ISTC МНТЦ

15 years

AEROSPACE RESEARCH

ISTC FUNDED PROJECTS 1994-2009

VOLUME 1

AERONAUTICS

INTERNATIONAL SCIENCE AND TECHNOLOGY CENTER

AEROSPACE RESEARCH

ISTC FUNDED PROJECTS 1994–2009

AERONAUTICS

VOLUME 1

Edited by

Waclaw Gudowski (ISTC)
Tatiana Ryzhova (ISTC)
Sergey Frolov (ICP RAS)

TORUS PRESS
Moscow – 2009

Aerospace Research: ISTC Funded Projects 1994–2009. Volume 1. Aeronautics / Edited by W. Gudowski, T. Ryzhova, S. Frolov. – 172 p.: 86 ill.

The book contains the synopses of 35 projects in Aeronautics funded by ISTC Funding Parties – the European Union, Japan, the United States of America, and Canada – during 15 years (1994–2009).

Project description gives a brief overview of its background, objectives, scope of work, and results – expected for ongoing projects and obtained for completed projects. Some administrative information including tech code/area/field, status and technology development phase according to ISTC taxonomy are also given, as well as information about funding parties, allocated funding, project duration, and commencement date.

The names of foreign organizations expressed interest in the project and participated in the project as Foreign Collaborators are presented in the synopses and provide an overview of the international cooperation in Aeronautics strengthened through ISTC projects.

The book also provides information on core and supplemental ISTC programs, including Partner program, and main ISTC partners in Aeronautics.

In addition, brief information on institutes – ISTC recipients in Aeronautics and a list of project proposals, which obtained good recommendation by ISTC scientific experts, but have not received funding yet, provide readers with an opportunity to meet their R&D needs through development cooperation/partnership with Russia/CIS.

The International Science and Technology Center is an international organization, created to serve the goal of international scientific cooperation. The European Union, Japan, the Russian Federation, and the United States of America started work on the basis of a multinational agreement established in 1992. Canada, Norway, and the Republic of Korea later became signatories to the ISTC Agreement, with Canada becoming a full Governing Board Member in 2004.

Consequently, ISTC started its work in 1994 based on the Decree of the President of Russian Federation and since then ISTC has funded and managed more than 2,650 projects with a total value of 816 million USD. Over $30 million USD has been used to fund aerospace and aircraft research, with many other projects completed or developed in related fields.

ISTC has today 39 member states and offers a wide spectrum of programs, services and activities. The ISTC Secretariat, based in Moscow, has about 150 staff members, among whom there are researchers, commercialization specialists, financial experts, and administrative staff.

Currently, the ISTC funds cooperative research projects in a wide range of scientific disciplines and technology areas. Future strategic priorities of ISTC are those that make the world safer and more secure – environment, renewable and environmental friendly energy, nuclear safety, and human health are at the first place. Obviously, many of these areas directly relate to the development of the aviation and aerospace industry and ISTC is proud of its record in developing projects and international relationships in this sphere.

ISTC has established strategic partnership with many Russian and other countries of the CIS innovation foundations and organizations, governmental organizations and agencies, business schools, legal companies, foundations, and investors that work to further strengthen the diversity of the national economies.

ISTC is also an organization that assists private industry in technology search, connecting international industry with high quality institutes in Russia and beyond. ISTC has over 400 commercial and governmental agency partners from around the globe, many of whom are engaged in R&D projects with experts from Russia and other countries of the CIS, and are developing technologies and applications that all of us will benefit from.

This book profiles many of the success stories resulting from the efforts of the Center and its many Partners, from breakthrough research in physics and aerodynamics, through to the investigation and development of greener and safer air transport. As an organization born of necessity and foresight back in the early nineties, I believe that ISTC has earned its reputation over 15 years as a respected, relevant, and progressive motor for international policy and peaceful science development. Where better to find justification for this view than in ISTC's work with the industries of the international aerospace and aviation sector and the many Russian and CIS experts in this field.

Adriaan van der Meer

Executive Director

Activity in Aeronautics

The ISTC projects portfolio in Aeronautics is a good example of scientific and technological capabilities of Russian/CIS research centers in such areas as enhancement of flight performance, economy and efficiency, improvement of safety and operational capacity and decrease of environmental impact.

The ISTC supports Russian and other CIS institutes not only by funding projects, but also through finding international partners for long-term R&D cooperation, supporting innovation in compliance with the international standards, improving communication systems in the institutes, personnel business training, and providing international travel grants for scientists to attend conferences and meetings.

The ISTC beneficiary institutes in Russia and elsewhere working for aerospace applications are ready to provide services to various companies in such fields as:

– flight physics: aerodynamics, aeroelasticity, aeroacoustics; physics and chemistry of high-speed gas flows; computational fluid dynamics (CFD); testing facilities; measurement techniques and instrumentation;

– flight dynamics and GNC: system architecture and avionics; on-board mission planning, advanced guidance; control techniques; flight and ground tests, including qualification, certification, and posttest analysis;

– turbomachinery and aeroengines, including new concepts of combustion and propulsion;

– alternative fuels, supersonic/hypersonic aircraft propulsion, scramjet/multi mode ramjet;

– helicopters, including new rotorcraft configurations;

– structures and materials: advanced materials, including high-performance steels, alloys, titanium and other metals, composites, etc.;

– design of advanced cockpit, including on-board software, cabin systems, and multimedia services;

– air-traffic management (ATM) and navigation systems;

– micro- and nanotechnologies applied to aerospace, industrial processes, integrated design and manufacturing, maintenance, etc.

Additional information on the ISTC activities: **http://www.istc.ru**

Tatiana Ryzhova

ISTC Senior Project Manager

ISTC Programs

The core ISTC programs are Science and Partner Project Programs.

Science Project Program

Funded through the ISTC budget (contribution of Funding Parties: European Union, United States of America, Japan, Canada).

Foreign organizations participate as collaborators.

Co-funding is possible for foreign collaborators.

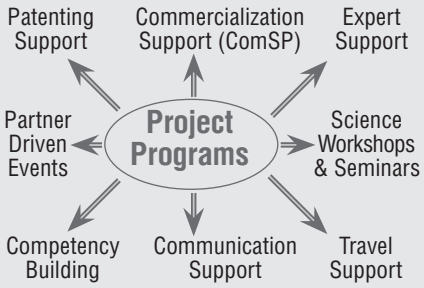
Partner Project Program

Foreign Partner funds through ISTC 100% of project expenses making advantage of the status of ISTC.

Supporting programs

Several programs were created at ISTC to improve projects performance and build sustainable capabilities and durable partnership.

Patenting Support



The Program goal is to provide financial support to the institutes participating in the ISTC projects. Program funds are used to pay costs associated with the initial stages of patenting in order to facilitate further national patent application processing at the territory of the ISTC Parties. Project managers routinely inform the Center of any patenting activity associated with an ISTC project and may submit an application for patent support in accordance with the procedures developed by the ISTC. A Patent Review Committee periodically reviews applications and reports on progress made in supporting patent applications.

Travel Support

The ISTC strongly encourages CIS scientific teams to develop their project proposals with the participation of foreign collaborating organizations.

The Travel Support program fosters collaboration by reimbursing travel and related expenses for CIS scientists who wish to begin or continue technical consultations on the proposals they submit to the ISTC.

Program funds also cover travel expenses for scientist participation in international meetings and conferences relevant to their specialization. Funding for the program is voluntary contributions provided by the ISTC Parties, Partners, and collaborators.

Commercialization Support

ISTC Commercialization Support Group is designed to act as the interface between the business world and Russian and CIS innovation. It is able to offer the international business community a unique service due to ISTC's international Agreement which aims to redirect the work of scientists previously engaged in weapons development toward peaceful scientific and sustainable commercial activity.

ISTC's main commercialization support tools are as follows:

- Innovation Initiatives
- Advanced Matchmaking (AMM)
- IPR Asset Inventory and Analysis
- Pre-commercialization support

Communication Support

The goal of the Communication Support Program is to provide financial support for hardware, software, and connectivity for eligible CIS institutes where the current capabilities inhibit the accomplishment of ISTC projects and the development of commercial opportunities.

Competency Building

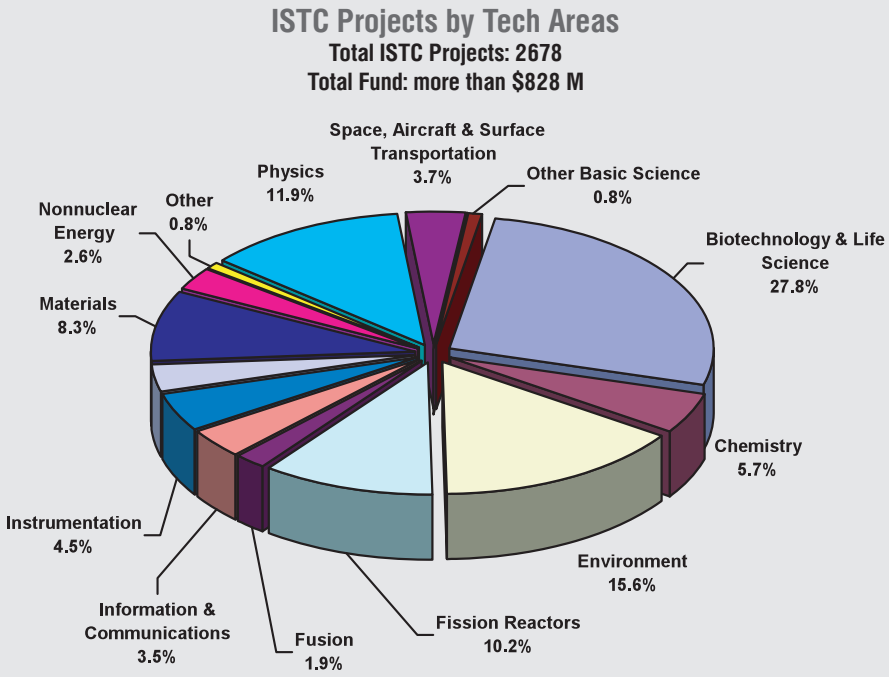
The Program assists CIS scientists participating in ISTC projects in their transition to long-term sustainability by providing expertise and knowledge needed for commercialization of R&D results.

Training forms (from short-term workshops to courses over many months).

Training modules (Innovative product marketing; Use of information technologies in marketing; IPR protection and commercialization; Business planning; Project and financial analysis for securing investment; Financial sources for R&D activities; Organizational forms of commercialization; Research project management; Business communication for commercialization; Strategy of effective presentations of a project to the business community; Quality standards and product certification; Export control; Market economy: general background; Other).

Science Workshops & Seminars

The Science Workshop Program is targeted on establishing effective collaboration and facilitating long-term scientific partnership through organizing direct conversations, meetings, and topical discussions between beneficiaries of the ISTC projects/programs and their colleagues from the territories of the ISTC Funding Parties. The program is implemented by organizing separate events in the form of a workshop dedicated to a particular technical area and involving limited number of the participants directly associated with the discussed topic. Scientific Workshops can be either specifically ISTC-dedicated events, ISTC sessions linked with topic-related workshops/conferences, supported by other organizations or industry groups, or mini-workshops for the purpose of developing project ideas or confirming basis of collaboration.



Research Projects in Aeronautics

Total funded projects related to aeronautics: 43

Total allocated fund: more than $11M

including:

funded by ISTC Funding Parties (EU, USA, Japan, Canada): 35 projects

funded by Partners: 8 projects

Main research areas

Flight Performance, Economy, and Efficiency

Aeroelasticity (Active and Nonlinear), Flow Control (subsonic/hypersonic flows), Testing Efficiency (wind tunnels, flying beds), Aerodynamic Efficiency (nontraditional configurations), Structural Strength & Efficiency.

Environmental Impact

Ecological aspects of SST-2, Engine emissions (including contrails), Local noise.

Safety

Wake Vortex, Crash landing & take off, Short gust of wind.

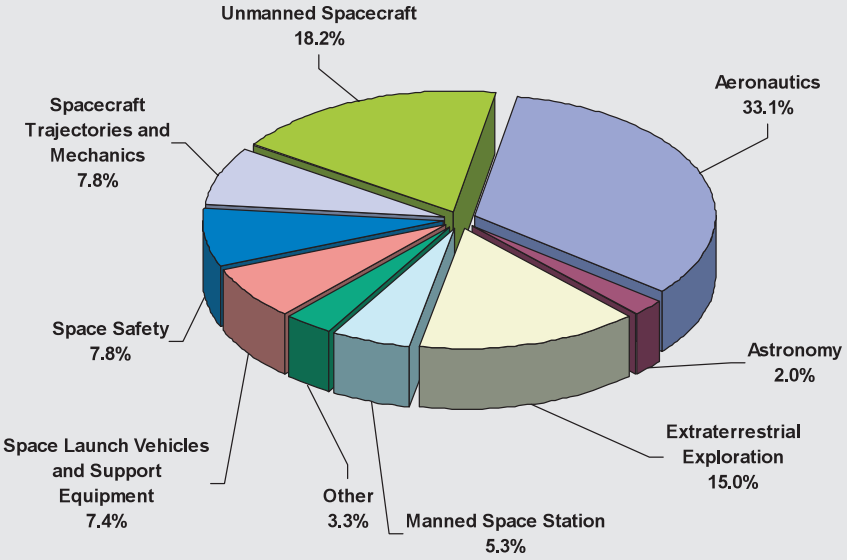
Main Project Recipients

- Central Aerohydrodynamic Institute (TsAGI), Russia
- Siberian Branch of RAS/Institute of Theoretical and Applied Mechanics (ITAM), Russia
- Central Institute of Aviation Motors (CIAM), Russia
- Moscow Aviation Institute (MAI), Russia
- Gromov Flight Research Institute (LII), Russia
- Georgian Technical University (GTU), Georgia

Aerospace Projects by Tech Fields

Total Projects: 103

Total Fund: more than $29 M



Partnership in Aeronautics Through ISTC

EU Partners:

AIRBUS

Snecma Moteurs, France

DFS German Air Navigation Services, Germany

Fraunhofer Gesellschaft, Germany

ONERA, France

U.S. Partners:

Boeing

European Office of Aerospace Research Development (EOARD)

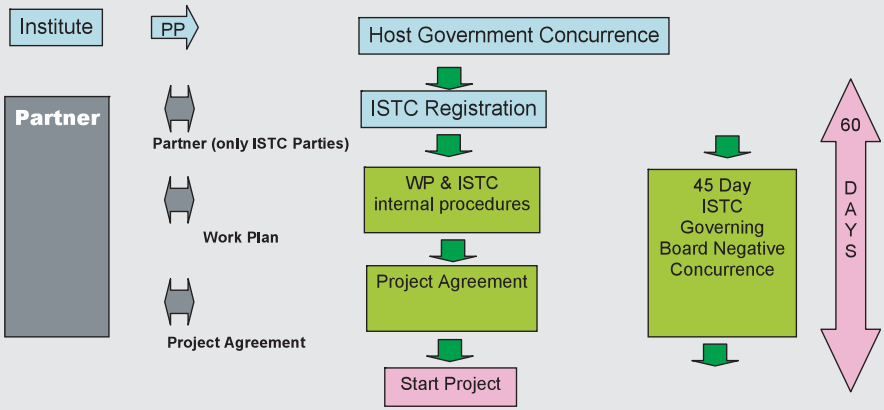
Partner Program Services

Technology Search: The ISTC database has more than 4,000 ISTC promising research, technology, and ongoing project abstracts. Technology areas include biotechnology and life sciences, chemistry, physics, materials, information technologies, etc. Talented teams from 750 R&D Institutes, with 60,000 scientists are involved (see website: **http://tech-db.istc.ru/**).

Project Management: Experienced management and good governance are essential to successful and accountable projects. ISTC assures financial and operational transparency audited by internationally recognized 3rd party consulting companies; Logistics and Monitoring – ISTC assists with project-associated logistics; project site visits, meeting project teams, and reviewing project performance.

Commercialization: For Russian/CIS technologies that demonstrate market potential, ISTC shares risk through co-funding to establish proof of concept, etc., as well as supports market research and business plans for CIS scientists, and develops near-market technologies to the point where they are ready for business opportunities.

Procedure of Partner Project approval



Contents

Enhancement of Flight Performance, Economy and Efficiency

Project Number:	**#0128**
Full and Short Title:	Experimental investigation of transition of supersonic boundary layers relevant to high-speed air transportation **Turbulent/Laminar Flow**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	$400,000 (US)
Commencement date:	(starting date) August 1, 1996
Duration:	36 months
Leading Institute:	Siberian Branch of RAS/Institute of Theoretical and Applied Mechanics (ITPMech), Novosibirsk, Russia
Contact Information:	Phone: +7 (3832) 350778, fax: +7 (3832) 352268, e-mail: admin@itam.nsc.ru, website: http://www.itam.nsc.ru
Supporting Institutes:	Federal State Unitary Enterprise “Russian Federal Nuclear Centre – Zababakhin All-Russia Research Institute of Technical Physics,” VNIITF, Snezhinsk, Chelyabinsk reg., Russia
Contact Information:	Phone: +7 (35146) 54367, fax: +7 (35146) 54499, e-mail: web-admin@vniitf.ru, website: http://www. vniitf.ru
Collaborators:	Rockwell International Corporation/Rockwell Science Center, Thousand Oaks, CA, USA
Project Manager:	MASLOV Anatoly
Contact Information:	Phone: +7 (383) 3303880, fax: +7 (383) 3300655, e-mail: maslov@itam.nsc.ru
ISTC Senior Project Manager:	TOCHENY Lev
Contact Information:	Phone: +7 (495) 9823113, fax: +7 (499) 9783603, e-mail: tocheny@istc.ru
ISTC Website:	http://www.istc.ru

Background

Laminar–turbulent transition in supersonic boundary layers is important for the design of laminar flow control systems for High-Speed Civil Transport.

Project Objectives

The objective of the Project is to investigate experimentally and analyze theoretically the origin of turbulence in supersonic and hypersonic boundary layers along with studies of fundamental processes and development of theoretical models. Laminar–turbulent transition has been studied in T-325 and T-326 wind tunnels on flat-plate, cone and swept-cylinder models. Constant-temperature anemometer and artificial wave train methods were used for this purpose. Experimental studies were supplemented with theoretical calculations.

Description of the Works

The following tasks were defined for the research work:

A1. Development of the experimental method of artificial wave packets (AWP) for investigating disturbance evolution in a supersonic boundary layer at Mach numbers typical for the high-speed civil transport.

A2. Experimental and theoretical studies of laminar–turbulent transition and stability of boundary layer on a swept cylinder at Mach number M = 2.

A3. Experimental investigation of physical mechanisms related to disturbance propagation over various roughness elements. Obtaining data on interaction between AWP and roughness elements using the method of Task A1.

A4. Experimental investigation of the nonlinear dynamics of two-dimensional (2D) and three-dimensional (3D) waves in supersonic boundary layers on a flat plate at Mach number M = 2.

A5. Numerical simulation of disturbance evolution in a supersonic boundary layer using the Craik theory and parabolized stability equations (PSE).

A6. Experimental study of wave packet evolution in a boundary layer on a blunt cone at Mach number M = 6.

A7. Development of numerical methods and implementation of supersonic flow calculations for the configurations relevant to experiments planned in the Project (swept cylinder and flat plate with 2D roughness elements), as well as calculations for hypersonic flow over blunt bodies.

A8. Investigation of multicomponent gas-mixture effects on the unsteady hypersonic flow over 2D roughness elements on a flat plate.

Task A1

Fluctuation measurements in the test section of supersonic wind tunnel T-325 at Mach number M = 2 have been performed using hot-wire anemometry. The level of mass flux fluctuations was shown to change linearly from 0.07% to 0.11% at the range of unit Reynolds numbers $Re_1 = 5.6 \cdot 10^6 – 34 \cdot 10^6$ m^{-1}. Compared with the early work, in the experiments at unit Reynolds numbers $Re_1 > 2 \cdot 10^7$ m^{-1}, the noise level in the test section was halved. The spectral structure of disturbances in the free stream has been measured. The maximum in amplitude spectra was shown to correspond to frequencies f = 4–5 kHz.

Task A2 To elucidate the reasons leading to a laminar–turbulent transition on the leading edge, the evolution of natural and artificial disturbances at the attachment line of a circular cylinder with a slip angle of 68° at Mach number M = 2 in supersonic wind tunnel T-325 has been studied. Numerical calculations pertaining to the experiments have been made. In accordance with the results of numerical calculations, the experimental data obtained in the course of implementing Task A2 were analyzed during the third year and additional tests were made. The numerical calculations showed that for the experimental flow conditions, the disturbances in the boundary layer on the attachment line were stable. This result was supported by authors' previous

experiments. The numerical results explained also the absence of laminar–turbulent transition in a wide range of unit Reynolds numbers. This result could be ascribed to a small size of the cylinder model. Reynolds numbers inherent in different flow regimes over cylinder were found experimentally. Experimentally based diagrams of laminar–turbulent transition with roughness elements (wires 0.07, 0.115, and 0.2 mm in diameter) were obtained. The latter data pertained to experimental data obtained in NASA Ames.

Task A3 The experimental investigation into the impact of 2D roughness on disturbance evolution in supersonic boundary layers has been performed. To this end, measurements of parameters characterizing development of modulated wave packets were conducted both on a smooth model and a model with roughness. The data for a smooth plate and for a model with roughness were compared. Those efforts allowed the authors to evaluate the changes in the transfer functions introduced by the influence of roughness. Disturbance wave spectra were obtained and variation of the transfer functions with the spanwise wave number was assessed for frequencies 10 and 20 kHz. The general inference which can be made from the results of the given studies is that the roughness elements used in the experiments affect quite insignificantly the evolution of unstable disturbances in a supersonic boundary layer. The transfer functions for a smooth surface and a surface with roughness elements had no basic qualitative differences and were quantitatively close.

Task A4 Nonlinear evolution of wave trains in boundary layer on a flat plate with sharp leading edge was studied experimentally at $Re_1 = 6.7 \cdot 10^6$ m^{-1} at x ranging from 60 to 200 mm. Absolute values of mass flux pulsations were detected for the case of controlled disturbances. Experiments conducted at low-level initial disturbances showed that parametrical resonance is a realistic mechanism of nonlinear interaction of unstable waves in a supersonic boundary layer. The major part of subharmonic energy was concentrated in waves with a propagation angle of about 80°. But it has been revealed in the experiments that when initial amplitudes increased, nonlinear excitation of quasi-2D subharmonic disturbances (acoustic waves) occured.

The experiments were conducted at a high amplitude level of controlled disturbances. The laminar–turbulent transition zone in these experiments was 20% closer to the leading edge. Excitation of controlled disturbances deformed the velocity profile, so that the boundary layer thickness increased. In the experiments,

(*i*) evolution of a nonlinear modulated large-amplitude wave train has been investigated; its evolution was shown to lead to degeneration of high-frequency harmonics and to downstream evolution of a quasi-harmonic wave train; and

(*ii*) strong amplification of 2D disturbances in a supersonic boundary layer has been observed which could not be explained within the framework of existing theoretical models and had no analogues in other experiments. The greatest amplification of 2D disturbances corresponded to the fundamental period of a modulated wave packet.

Task A5 Low-frequency disturbance-spectra filling at laminar–turbulent transition in a supersonic boundary layer was studied numerically. A resonant mechanism for energy transfer to subsequent subharmonics based on resonant parametrical interaction in the wave triads was suggested. An algorithm for the numerical solution of this problem was suggested. Numerical calculations were performed for the parameters used in controlled-disturbance experiments. The results obtained were compared with experimental data. Good qualitative and quantitative agreement has been achieved. Thus, it was shown that three wave resonance is a realistic mechanism for low-frequency

spectra filling in the laminar-to-turbulent transition zone in a supersonic boundary layer at low-level disturbances. Based on the appropriate estimates, the linearized Navier–Stokes equations were parabolized in the critical layer. The obtained set of equations was formally parabolic and free from restrictions imposed on steps of the marching scheme. The method for stability calculation was described and some numerical results were presented for the case with a flat plate.

Task A6 Laminar–turbulent transition in a hypersonic boundary layer over a 7 degree cone model at M_7 = 6 has been investigated. Experimental data on the influence of unit Reynolds number on transition zone location were obtained. Mean flow parameters were measured in the boundary layer at sharp and blunt cones. Natural disturbance evolution was studied in a sharp-cone boundary layer. Wave disturbances of the second instability mode were detected experimentally. Wave increments for the first and the second instability modes were assessed. The second-mode disturbances have been shown to be more unstable than the first-mode disturbances. The strong stabilizing effect of bluntness on the natural disturbances evolution in a hypersonic boundary layer was confirmed. A method for generation of oblique waves in a hypersonic boundary layer was suggested. The appropriate equipment and software have been developed, tests in T-326 wind tunnel have been carried out, and the ways of further development of the method were recommended. Evolution of artificial wave trains in a sharp-cone boundary layer was studied. Spatial structure of the first- and second-mode disturbances was investigated. For the first-mode disturbances, oblique waves with wave angles χ = 40°–49° were shown to be most unstable; the same is true for plane waves of the second mode. Growth increments for the most unstable disturbances were assessed; they agreed well with calculations. Only preliminary processing of the experimental data has been completed; more detailed information will be available later.

Task A7 New finite-difference techniques and codes intended to study the processes of boundary layer turbulization in the vicinity of an aerodynamic body were validated by numerical solution of appropriate equations and comparison of the results obtained with analytical solutions. Mathematical simulation of supersonic and subsonic flow parameters of an ideal or viscous gas using codes SPRUT-RAPID, TIGER, and TVD could be performed in 2D formulation. In case the Project is continued, the results of calculations using these codes for simulating the evolution of a small perturbation introduced through a narrow aperture in flat-plate boundary layer would be compared with experimental data obtained in the ITAM wind tunnel.

Task A8 Steady flow in the vicinity of a single roughness (Task A7) was studied at the free-stream Mach number up to M = 2. Air was treated either as a single-component gas or as a two-component gas mixture containing nitrogen and oxygen. Analysis of computations showed that the mean flow characteristics depend insignificantly on this issue.

Obtained Results

– Experimental AWP method was modified to meet requirements of Tasks A2–A4 and A6. The measurement system and data analysis were computerized.

– Capabilities of the method were extended to hypersonic flow velocities. Various types of the sources for generation of different artificial disturbances, such as sine waves as well as modulated and pulsing waves, have been designed. A technique for measuring the absolute pulsation level with a constant-temperature anemometer (CTA) has been developed. A CTA with the bandwidth of up to 500 kHz has been designed and manufactured.

– Experimental data on transition zone location at the attachment line past roughness elements have being obtained as a solution of Task A2. Using the AWP method, it was

demonstrated for the first time that disturbances arose in the boundary layer in the attachment line vicinity. Theoretical models of the attachment line stability and corresponding computational codes have been developed. The results of theoretical studies were in good agreement with experimental data.

– Concerning Task A3, the experimental data pertinent to the influence of roughness elements on the boundary-layer disturbance field and transition in a supersonic flow over a flat plate were obtained for the first time using the method developed in Task A1. These data allowed the mechanism for influence of roughness elements on laminar–turbulent transition in supersonic boundary layer to be understood.

– Experimental and theoretical investigation of weakly nonlinear phenomena inherent in laminar–turbulent transition in supersonic boundary layers have been carried out to implement Tasks A4 and A5. Linear and nonlinear evolution of disturbances was simulated numerically (task A5). The numerical methods used for investigations of disturbance evolution were based on three-wave approach and took into account nonlinear resonant wave interaction. New information on disturbance growth in the transition zone has been obtained. Numerical results have been compared with experiments. The absolute values of parameters characterizing interacting disturbances in a supersonic boundary layer were obtained for the first time (task A4) using the method of Task A1. Numerical data on the cascade scenario of laminar–turbulent transition in a supersonic boundary layer were obtained for the first time as well. New PSE were derived and used to simulate linear evolution of disturbances in a boundary layer at M = 2 and M = 5.

– According to task A6, the evolution of natural disturbances has been studied in the boundary layer of sharp and blunt cones at M = 6. Evolution of controllable first- and second-mode disturbances in the boundary layer over a cone model has been studied for the first time. The results for natural and controllable experiments have been compared. Experimental data have been also compared with theoretical results and the characteristic features of wave processes in a cone boundary layer have been ascertained at M = 6.

– When solving Tasks A7 and A8, the following results have been obtained. According to the subcontract with VNIITF, numerical methods have been developed and a number of model calculations of the flow in the vicinity of a standard aerodynamic body have been carried out. New versions of numerical codes for a flow around bodies of complex shape in 2D formulation were suggested. A new method with smooth, zero-dissipation solutions with minimum oscillations at strong discontinuities was developed.

Project Number:	**#0199**
Full and Short Title:	Development of New Methods of Laminar Flow Control and Turbulent Drag Reduction. **Turbulent Drag Reduction**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project underway
Technology Development Phase:	Technology development
Allocated Funding:	$572,995 (EU)
Commencement date:	(starting date) April 1, 1995
Duration:	36 months, extended by 9 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332, 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	AIRBUS Industrie, Blagnac, France (Hinsinger R); National Aerospace Laboratory NLR, Amsterdam, The Netherlands; ONERA, Clamart, France (Duc J M)
Project Manager:	KOGAN Mikhail
Contact Information:	Phone: +7 (495) 5564006, fax: +7 (495) 7776332, e-mail: mkogan@aerocentr.msk.su
ISTC Senior Project Manager:	TOCHENY Lev
Contact Information:	Phone: 7 (495) 9823113, fax: 7 (499) 9783603, e-mail: tocheny@istc.ru
ISTC Website:	http://www.istc.ru

Background

Understanding of general mechanisms of laminar flow breakdown and transition to turbulence is one of the basic problems of modern fluid dynamics. Knowledge of these mechanisms is of great importance for developing different methods for delaying laminar–turbulent transition and drag reduction. The use of laminar-flow control systems and methods of turbulent drag reduction would permit one to get a significant fuel economy and to decrease the harmful effect of airplane exhausts on the Earth atmosphere. Moreover, drag reduction for perspective supersonic passenger airplanes would permit the intensity of sonic boom to be reduced.

Project Objectives

The main objective of the project was to conduct theoretical and experimental investigations

leading to friction drag reduction of civil subsonic and prospective supersonic aircraft.

Description of the Work

Work Plan of the Project included seven tasks. Investigations were concentrated on new laminar-flow control techniques for straight and swept wings. Flow control mechanisms under investigation included vibratory and acoustic disturbances; energy supply into the boundary layer; introduction of solid and liquid particles into the flow; creation of periodic 3D flow disturbances; and local boundary layer suction.

For turbulent drag reduction, the study was focused on the influence of energy supply into the turbulent boundary layer; new Large Eddy Breakup Units (LEBU) in pipelines and external turbulent boundary layer; and the influence of riblets on the aft-body drag.

Obtained Results

• Analysis of leading-edge flow stability and possibilities of combined laminarization of swept-wing flow using heat/mass transfer and selection of surface pressure at subsonic and supersonic velocities

Numerical investigations of boundary layer stability on a high aspect-ratio swept wing have been carried out for various boundary conditions on the attachment line and various perturbations of parameters along the wing leading edge, namely: variable radius of leading-edge curvature along a wing span; nonuniform heating/cooling of the leading edge along the span; nonuniformly distributed gas suction; and various distributions of volumetric energy supply. It has been shown that for supersonic free-stream flow, the nonuniform surface temperature distribution along the leading edge could be used for delaying the laminar–turbulent transition on the swept wing attachment line.

Surface heating failed to allow cross-flow stabilization. The combination of surface pressure and suction distributions proved to be an optimal method of stabilizing the boundary layer cross-flow on a swept wing. Surface heating coupled with suction and particular pressure distribution was proved to be a promising solution for suppressing Tollmien–Schlichting instability in the swept-wing flow.

• Experimental study of surface noniso-thermicity influence on laminar–turbulent transition at subsonic velocities

In the low-turbulence T-36 wind tunnel (Fig. 1), the tests with a flat-plate model with heated blunt nose (with the heating capacity of 3 kW/m) were carried out at free-stream velocities up to 55 m/s and Reynolds number (based on the plate length) up to $6.6 \cdot 10^6$ for various heating distributions. Velocity and temperature profiles in various boundary layer cross sections as well as spatial location and statistical properties (intermittency factor and intermittency number) of transition region were measured. In all cases, the transition was determined by the evolution of Tollmien–Schlichting waves. The nose heating was found to lead to the significant growth of the transition Reynolds number even in the case of adiabatic surface. Leading edge heating eliminated the early laminar–turbulent transition caused by the roughness and unfavorable attachment-line location. The results of the tests were in agreement with the data of calculations based on the linear stability theory.

• Theoretical study of thermal methods of turbulent skin-friction reduction

Theoretical and numerical studies of turbulent drag reduction methods based on the local heat supply into turbulent boundary layer have shown that

– viscous drag reduction efficiency (ratio of the mechanical power gain due to drag reduction to the heat supply power) in a compressible turbulent boundary layer could be increased by means of localizing heat supply regions: at a fixed heat supply power, the smaller the length of each surface heating section and the ratio of the heating sections

length to the distance between them, the higher the amount of drag reduction;

– the account of the body material heat conductivity led to an essential decrease of the maximum surface temperature both within the heat supply regions and closely behind them. Variations of both local and total friction in comparison with the case of non-heat-conductive body were insignificant for high thermal resistance of intervals between the heating regions; and

– the allowance for the interaction between turbulent boundary layer and outer supersonic stream influenced essentially the local friction coefficient. Reduction in the total friction was smaller than that without viscous–inviscid interaction consideration.

The energy efficiency of turbulent drag reduction on the surface of a fixed length was virtually independent of the total capacity of heat supply and was approximately proportional to a free-stream Mach number. The location of heat sources across the boundary layer exerted an essential effect on the method efficiency.

Thus, the use of the turbulent drag reduction method based on the volumetric gas heating in boundary layer by burning a high calorific-

Fig. 1: Low-turbulence T-36 wind tunnel

power fuel was shown to allow an essential economy of fuel consumption at Mach number M > 4 to be achieved.

• Experimental study of turbulent drag reduction methods using energy supply at subsonic velocities

Experimental data on the influence of local surface heating on the turbulent friction coefficient were in qualitative agreement with the results of calculations using k–ε turbulence model. The local sections of heating provided the main part of friction reduction. The efficiency of local volumetric heating of a turbulent boundary layer increased when the heating position was closer to the body surface.

The effect of heating a cylindrical LEBU, installed at a distance from the body surface equal approximately to the half of boundary layer thickness, on the turbulent stresses has not been detected. The effect of friction reduction was detected when the LEBU was installed close to the body surface. The own drag of the LEBU was decreased appreciably in this case.

• Theoretical study of possibilities for reduction of laminar boundary layer receptivity with respect to acoustic, vortex, and vibration disturbances

The method of suppressing Tollmien–Schlichting waves in the swept wing boundary layer using an artificial 2D surface roughness has been developed. Such suppression appeared to be possible due to a special choice of roughness location and height. The natural and artificial Tollmien–Schlichting waves generated by the same external coherent forcing (sound or free-stream vortex perturbations) suppressed one another with automatic synchronization. Generalization of the method was suggested for the case when the spectrum of external forcing contained several frequencies. In this case, instability wave damping was ensured by a proper choice of artificial roughness shape. To prevent the laminar–turbulent transition of “by-pass” type close to the roughness, the method of shape optimization was suggested.

The method for suppressing instability of steady cross-flow vortices using crosswise periodic irregularity has been developed. Steady instability vortices generated by an “accidental” roughness were proved to be suppressed by an artificial roughness with selected amplitude and phase of transverse modulation without strict limitations imposed on its longitudinal location. The calculations showed that under the action of suppression the perturbation amplitude in the close vicinity to the roughness was a factor of 200 larger than that in the upstream vortices; this fact could be responsible for laminar–turbulent transition closely over the roughness (“by-pass”). To prevent this undesirable phenomenon, the distributed suction localized in longitudinal direction and periodic in transverse one was suggested to be applied. This modification of the method allowed the relative intensity of perturbations to be reduced more than by a factor of 30. Such suction introduced with the aim of receptivity control is capable of improving the stability properties of a 3D boundary layer.

• Experimental study of possibilities for reduction of laminar boundary layer receptivity with respect to acoustic disturbances

The tests aimed at verification of the developed method of laminarization were performed for a 2D boundary layer under acoustic forcing with spectrum containing several frequencies. In the simplest case of a two-frequency spectrum, the suppression method of acoustic Tollmien–Schlichting waves was evaluated using two and four roughness elements. In principle, such surface modification allows complete suppression of natural instability waves at two discrete frequencies. However, in the tests, these controlling roughness configurations exerted a general destabilizing effect on the boundary layer flow. The use of a single roughness element located closely to the position where natural instability waves attained

the maximal intensity was found to be most efficient. Such roughness allowed essential damping of unstable oscillations generated by acoustic waves of a wide-band spectrum and even by "natural" perturbations of free-stream in the absence of sound to be achieved.

- **Development of method of laminar boundary layer stabilization using fine-dispersed admixture input**

The problem of linear stability of dusty-gas laminar boundary layer with homogeneous distribution of particle density was considered. The 3D linearized Navier–Stokes equations governing the disturbed flow with allowance for the particle effect on the momentum transfer described by the Stokes force were transformed to the modified Orr–Sommerfeld equation which has been solved numerically. The dust was shown to suppress the instability waves in a wide range of particle sizes. The most efficient suppression was achieved when the relaxation length of particle velocity was close to the wavelength. In this case, dust with a 4 percent mass content reduced the maximum increment more than by one third.

The properties of linear stability of dusty-gas Poiseuille flow were investigated for inhomogeneous distribution of particle density. In this case, the particle effect on the instability wave was proved to be much higher than that for the homogeneous distribution and could be either stabilizing or destabilizing, depending on the position of the distributional maximum. The highest stabilizing effect was obtained for sharp distributions with the maximum close to the critical layer.

Dynamics of spherical particles moving parallel to the walls in a laminar Poiseuille flow was considered. The transverse force acting on a particle was evaluated as a function of three main parameters: (*i*) the distance from the channel wall; (*ii*) the particle slip velocity; and (*iii*) the flow Reynolds number. Particle equilibrium positions across the channel were evaluated.

- **Effect of spatial periodic flow inhomogeneity on laminar–turbulent transition**

The investigations were carried out in two ways. The first is the formation of an artificial span-wise periodic inhomogeneity leading to a delay in the growth of instability waves. The second is the study of laminar–turbulent transition in a flow with large-amplitude inhomogeneity simulating striped structures appeared at high turbulence in a free stream. The inhomogeneity shape leading to transition delay was found. However, the realization of such inhomogeneity by creating a simple periodic convexity/concavity or blowing/suction system always led to earlier transition.

Parameters of spanwise-harmonic, stream-wise-restricted inhomogeneity which led to essential flow destabilization were determined. In the flow with harmonic inhomogeneity, unstable perturbations of two main types were found, namely, the modes with symmetric and asymmetric spanwise velocity distributions. The modes of the first type had the phase velocity typical for Tollmien–Schlichting waves. They were the most fast-growing perturbations for a small-amplitude inhomogeneity. The instability related to the asymmetric modes dominated in the case of large-amplitude inhomogeneity. These modes differed qualitatively from Tollmien–Schlichting waves and propagated with a larger phase velocity.

- **Experimental study of riblet coating effect on afterbody flow separation**

Tests with a model revolution body with afterbodies of various length performed at free-stream Mach number from 0.25 to 0.85 and Reynolds number (based on the model length without afterbody) from 10^7 to $2.4 \cdot 10^7$ have shown that microribbing of the central cylindrical part of the model reduced the region of afterbody flow separation located at the narrowing tail without riblet coating. In the case of developed afterbody separation (for models with short tails), drag reduction caused

by the specified effect could be comparable with turbulent drag reduction on the ribbed part of the model.

• Experimental study of ring-shape LEBU effect on the flow in the duct of circular cross section

These investigations have performed at mean flow velocities up to 60 m/s and Reynolds numbers (based on the duct diameter) up to $2.2 \cdot 10^5$. The profiles of flow velocity and its streamwise fluctuations in various cross sections downstream of the LEBU have been obtained by means of hot-wire-probe and Pitot-tube measurements. The drag of the duct has been determined by static-pressure drop measurements. The tests were performed in a wide range of LEBU diameters, thicknesses, and chord lengths. The data have been obtained for two and three LEBUs installed in "tandem" configuration. The test results confirmed the reduction of viscous stress behind the LEBU, but no reduction of total drag has been detected.

• Numerical estimates of opportunity for laminar flow control by means of local boundary layer suction on swept wing at subsonic and transonic speeds

The studies of stability of 3D boundary layer on an infinite-span swept wing with and without boundary layer suction, performed on the basis of the linear theory of hydrodynamic instability and correlation between computed results and experimental data, have shown that the flow regimes investigated were dominated by cross-flow-type instability. Air suction from the boundary layer affected significantly both the direction of the wave vector of the fastest-growing disturbances and the distribution of the amplification factor. A generalization of Ellis and Poll criterion which characterizes the process of 3D boundary layer turbulization as a result of disturbing effects of a perforation with suction was proposed.

• Experimental investigations of flow laminarization on swept wing by means of local boundary layer suction

The investigations have been conducted in a T-107 transonic wind tunnel with test-section diameter of 2.7 m and length of the nonperforated portion of 3.5 m. The tests with the half-wing model of a 1.67-meter span, 0.73-meter chord in streamwise direction, 9.8 percent relative thickness of airfoil, and 35o sweep angle made it possible to (*i*) increase more than two-fold the length of the laminar flow region on the upper surface of the model due to local (0.03–0.11 of the chord) boundary layer suction and to decrease drag by up to 14% with a small suction flow coefficient ($1.1 \cdot 10^{-4}$); (*ii*) to establish the dependence of the critical Reynolds number (based on the orifice diameter) $Re_d = 114–76$ on the free-stream Reynolds number within a Mach number range M = 0.2–0.6; and (*iii*) to introduce a new generalized suction parameter which allows one to formulate some unified functions valid in wide ranges of the angle of attack and free-stream Reynolds number.

Project Number:	**#0501**
Full and Short Title:	Design Studies of the Very Large Commercial Transport (VLCT) Aircraft with Non-traditional Layout Configurations. **Large Commercial Aircraft**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$300,000 (EU)
Commencement date:	(starting date) May 1, 1998
Duration:	36 months
Leading Institute:	MAI (Moscow Aviation Institute), Moscow, Russia
Contact Information:	Phone: +7 (499) 1584264, fax: +7 (499) 1582927, e-mail: aet@mai.ru, website: http://www.mai.ru
Supporting Institutes:	**No**
Collaborators:	DaimlerChrysler Aerospace Airbus, Hamburg, Germany (Anger A) Deutsches Zentrum fur Luft- und Raumfahrt e.V. (DLR)/Institute of Design Aerodynamics, Braunschweig, Germany (Korner H)
Project Manager:	MALTCHEVSKY Victor
Contact Information:	Phone: +7 (499) 1584615, fax: +7 (499) 1582927, e-mail: design101@mai.ru
ISTC Senior Project Manager:	KULIKOV Gennady
Contact Information:	Phone: +7 (495) 9823154, fax: +7 (499) 9784637, e-mail: kulikov@istc.ru
ISTC Website:	http://www.istc.ru

Background

The interest to high-range heavy commercial aircraft is caused by many objective reasons. According to expert forecast, world companies need a considerable number of passenger aircraft with the commercial payload of 70–100 t and range exceeding 13,000 km in the next ten years.

Project Objectives

The project was focused on the design, definition, and comparative analysis of high-range heavy commercial aircraft characteristics with conventional and nontraditional “Polyplane” (Fig. 2) configuration with a complex lifting wing system.

Description of the Work

The design of aircraft under comparison was carried out according to technical requirements (TR) agreed with project collaborators and Airbus company partners.

According to the TR, the aircraft had to provide the transportation of 616 passengers with three class service on the estimated range 13,700 km with cruise Mach number M_{cr} = 0.85. The aircraft had to base at a first class airport. The latter limited the aircraft overall dimensions and the parameters of landing gear rough-field capacity.

The "Polyplane" and basic aircraft configurations were compared in terms of the following criteria: take-off mass, relative mass of empty aircraft with operational items, lift-to-drag ratio, and total fuel for the flight.

To increase comparison reliability, the following conditions and assumptions were adopted:

– the same techniques for estimating aerodynamic, mass, strength, and other characteristics, validated for modern aircraft, had to be used; and

– the same depth in the design development and the same level of structural and system parameters had to be obtained.

For the same reason, deep investigations were conducted for hydraulic and flight control systems exhibiting considerable differences for the aircraft configurations under comparison. The problems of passenger and crew evacuation in emergency situations were also investigated in detail.

Novel techniques for the analysis of the stressed-deformed state of the aircraft structure as well as for the estimation of the corresponding aerodynamic and mass characteristics, modified with taking into account specific features of the considered aircraft configurations, were implemented in the course of project performance. Aircraft layouts were made with the help of newly developed graphic models of combined element. When developing the aircraft layouts, other requirements like those related to aircraft family modifications were also taken into account.

On the basis of the newly developed technique of determining aeroelastic "Polyplane" wing characteristics, new **antiflutter** means providing the oscillatory damping margin and flutter safety were suggested.

The fulfilled investigations made it possible to obtain the corrected design parameters and to estimate mass and aerodynamic characteristics as well as flight performances required for complex comparison of different aircraft configurations. The results of the comparative analysis are presented below.

Comparison of aerodynamic characteristics

In the aerodynamic design of the "Polyplane" aircraft, the main efforts were focused on avoiding negative effects of this configuration, such as:

– the elevated level of the drag interference component caused by a considerable number of wing surfaces and volume elements in this configuration (e. g., fuselage, fuel tanks-fairing, etc.); and

– the elevated friction drag caused by increased washed surface due to fuel tank-fairing and joints of wings with fuselage.

The comparison of a "Polyplane" aircraft polar with that of the basic aircraft at specified altitude and velocity showed that despite relatively high minimum drag coefficient C_{Dmin}, the negative influence of increased washed surface was managed to be compensated by the decrease of the induced drag. Moreover, at M > 0.8, function $(C_L/C_D) = f(M)$ for the "Polyplane" configuration was more monotonous as compared with the basic aircraft configuration. At M = 0.87, the advantage of the basic aircraft configuration in terms of C_L/C_D ratio was found to disappear. Nevertheless, at C_L = 0.5 the lift-to-drag ratio of the "Polyplane" configuration was up to 4% less than for the basic aircraft configuration for specified flight altitude and velocity.

Comparison of weight characteristics

In terms of relative mass of empty aircraft with operational items, $m_{E\ EQ}$, the "Polyplane" aircraft had a considerable advantage against the basic configuration. The values of $m_{E\ EQ}$ were 0.4574 and 0.4824 for the "Polyplane" and basic aircraft configuration, respectively, that is by 5.18% lower. The advantage of the "Polyplane" configuration in terms of the airframe structure mass was caused first of all by a decreased (by a factor of 1.5) wing structure mass due to replacement of a console wing by a frame-structure lifting system. The fuselage mass decreased somewhat too.

This advantage compensated completely the insignificant increase of a flight-control system mass of the "Poiyplane" configuration. Despite the negative influence of lift-to-drag ratio on fuel consumption, the "Polyplane" aircraft estimated take-off mass was 488.21 t, which was 52.75 t (9.75%) less than the mass of the traditional-configuration aircraft (m_0 = 540.96 t). This was treated as a considerable advantage of the "Polyplane" aircraft configuration which could influence positively its economic parameters.

Comparison of fuel effectiveness and flight performances

Despite somewhat lower lift-to-drag ratio in cruise flight, the "Polyplane" aircraft was found to exhibit a noticeable advantage in comparison with the basic aircraft configuration in terms of fuel effectiveness.

For example, the flock fuel for the "Polyplane" aircraft was 206.2 t, whereas for the aircraft of basic configuration it amounted 221.3 t, that is 15.12 t higher. The estimated q_T for the "Polyplane" and basic aircraft was 23.060 and 24.927 g/p·km, respectively.

Fig. 2: "Polyplane" aircraft

According to the initial TR, the aircraft under comparison should have had the same main flight performances, i. e., payload, range, cruise flight velocity, as well as take-off and landing characteristics. Nevertheless, within the frame of the specified limitations, there were insignificant differences in the characteristics of flight profile. For example, because of a higher starting thrust-to-weight ratio, the "Polyplane" aircraft had better characteristics of climb than the aircraft of basic configuration and, in spite of lower $C_{L\max}$ at take-off and landing, it exhibited virtually the same take-off and landing characteristics.

Comparison of other characteristics

Because of lower take-off mass and higher thrust-to-weight ratio at take-off, the intensity of vortices for the "Polyplane" aircraft was shown to be considerably lower. The aircraft under comparison had approximately the same comfort and safety parameters. However, the "Polyplane" aircraft parameters relevant to manufacturing and operation service were shown to be lower than those for the aircraft with traditional configuration, which was caused by smaller nomenclature of airframe sections and onboard system components for the aircraft of basic configuration.

Conclusions

The scientific and methodological approaches to aircraft design developed within this project and a novel aircraft configuration with a system of lifting surfaces (protected by a patent) allowed the project team: to design a long-range aircraft with high passenger capacity based on both "Polyplane" and traditional vehicle configuration; and to determine flight performances of the aircraft and to perform their comparative analysis.

The comparative analysis demonstrated the advantage of the "Polyplane" configuration in terms of all main aircraft parameters. Despite 4 percent lower lift-to-drag ratio, the "Polyplane" aircraft was 9.75% lighter than the aircraft of basic configuration and had 7.5% higher fuel effectiveness because of the lower mass of airframe structure. This advantage could be even more pronounced if the most advanced technologies relevant to the subsonic flight were implemented in the design of the both aircraft under comparison. According to preliminary estimations, the "Polyplane" configuration can be considered as perspective for aircraft of many different intentions. Nevertheless, for decreasing the level of technical risk associated with the application of this aircraft configuration, validation experiments in wind tunnel are required.

Project Number:	**#0592**
Full and Short Title:	Development of a Complex Technique for Testing Highly-Economical, Ecologically-Promising Civil Aircraft in Transonic Wind Tunnels. **Wind Tunnels for Aircraft Testing**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	$150,000 (EU)
Commencement date:	(starting date) June 1, 1998
Duration:	24 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332, 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	Aicraft Research Association Ltd., Bedfort, UK (Stanniland D); European Transonic Windtunnel, Koln, Germany (Quest J)
Project Manager:	BOSNYAKOV Sergey
Contact Information:	Phone: +7 (495) 5563587, 5564323, 5563786, fax: +7 (495) 7776332, e-mail: bosn@progtech.ru
ISTC Senior Project Manager:	MALAKHOV Yuri
Contact Information:	Phone: +7 (495) 9823157, fax: +7 (499) 9784673, e-mail: malakhov@istc.ru
ISTC Website:	http://www.istc.ru

Background

The problem of ensuring ecological safety of modern civil and transport aircrafts is directly related to the problem of aerodynamic efficiency. Ground-based tests provide a wide gamut of opportunities for relevant investigations and for solution of arising problems. There is always the aspiration to test models of as large size as possible in available wind tunnels. However, systematic errors caused by the influence of test section walls in a Transonic Wind Tunnel (TWT) on the flow field around a model should be taken into account or eliminated. In particular, this issue is important for civil aircraft models as the

requirements imposed on the test data accuracy are very stringent. Depending on the specific features of wind tunnel design, this issue can be addressed in different ways, for example, by:

- making corrections in measured data using technologies of Computational Fluid Dynamics (CFD) or empirical relations;
- choosing, on the basis of preliminary investigations, optimal test conditions providing the minimal wall influence on specified aerodynamic performances (for example, by indicating *a priori* a certain distribution of wall porosity or by changing the plenum chamber pressure);
- choosing certain optimal parameter distributions in boundary conditions directly during the test, by iterations, and with the use of the results obtained at the preceding step on the basis of some CFD strategy for wall influence minimization (so-called adaptive wall technique).

Project Objectives

The project objective was to generalize previous experience and to develop on this basis a universal technique of model testing in TWT which could allow the results to be transferred to other aerodynamic test facilities. In particular, it was proposed to adapt high technologies to specific conditions of testing highly-economical, ecologically promising civil aircraft models. Implementation of such technologies would make it possible to evaluate more precisely the characteristics of such aircraft at the stage of ground-based tests.

Description of the Work

A wealth of experience on the development of measuring equipment and wind tunnel test techniques for vehicle models has been accumulated at TsAGI. The TWT-128 of TsAGI is an ideal object for comprehensive analysis of all the approaches mentioned above (Fig. 3). Its changeable test sections are equipped with remotely controlled perforated panels on the walls and it is equipped with a plenum chamber suction system. Over the period of its use, great experience was gained in terms of various technologies for taking into account and minimizing wall influence on the aerodynamic characteristics of models. Further extension of this experience would make it possible to obtain, in different wind tunnels, reliable data virtually free from wall influence.

The following Tasks were expected to be solved in the course of project implementation:

- to develop a TWT mathematical model and the corresponding software;
- to develop the technology capable of taking into account and excluding systematic errors caused by the influence of TWT walls on vehicle models;
- to develop the technology of performing wind-tunnel experiments in adaptive mode when optimal test conditions are attained by iterations during the run; and
- to increase in the accuracy of PSP technology by a factor of 2.

The TWT mathematical model was based on the second-order approximation and monotonic numerical method for solution of full Euler equation system developed by S. Godunov, V. Kolgan, and A. Rodionov. Solutions were obtained using multiblock computational grids adapted both to a TWT test section and to a tested model. Model geometry corresponded to a tested original and was imitated most precisely. The influence

Fig. 3: Airbus model in T-128 wind tunnel

of TWT walls was simulated within the framework of Darcy theory. *The advantage of calculations with realistic geometry for improving experimental accuracy as compared to the equivalent-body technologies widely used in European scientific centers has been demonstrated.*

The idea of TWT adaptive experiments implied complete elimination of or considerable decrease in the influence of test section walls on model performance by controlling the boundary conditions on porous walls. This can be achieved by varying the porosity of discrete TWT wall panels during the experiment and simultaneous control of plenum chamber pressure.

For realizing this adaptation procedure, a system capable of measuring flow parameters near test section walls, a computational methodology capable of predicting free-stream distributions of these parameters, and the coupling approach ensuring the convergence of the iterative process based on the control of plenum chamber pressure and boundary conditions on the walls had to be developed. The base distribution of flow parameters on a control surface was obtained using the Computational TWT. To choose the control algorithm for the iterative process, a special code imitating TWT operation was used.

The principle of PSP method is the measurement of pressure on the model surface using special paints. Local characteristics and optical properties of paints depend on the local partial pressure of oxygen. In tests, the radiated light was recorded by analogue or digital cameras and was processed by a computer. The method permitted visualization of local regions on the surfaces of tested model influenced by TWT walls. A key improvement was the use of a novel double-component PSP to provide more precise measurements.

All geometrical objects in the Computational TWT were divided into compartments, including aircraft model parts, wind tunnel walls, sting, etc. A compartment was a uniform part of an investigated object and was used to create an acceptable grid. As a rule, the compartment created the boundary of an appropriate grid block. For example, in the case of aircraft the nose part was one compartment whereas the intake served as another one. Sometimes, it was possible to divide one aircraft element, for example, rectangular intake, into several compartments. All the compartments had to fit each other and create a continuous surface. In practice, more than ten compartments were involved in a real geometry test in the Computational TWT. Therefore, the task of creating a continuous surface was quite complex. The best way to create the geometry was the use of Coons patches for joining the compartments with each other. This technology allowed a continuous but not smooth surface to be created. It brought about local mistakes in the solution due to the lack of continuous-derivative functions at all points. Using natural lines in projected geometry allowed the mistakes of this type to be diminished.

The numerical Godunov–Kolgan–Rodionov method applied for calculating a flow field around vehicle model in the Computational TWT called for generation of structured computational grids consisting of hexahedron cells. The neighboring cells had joint faces. Grid lines (lines formed by cell edges) had to be continuous and begin on the boundaries of a computational domain. It was found out that the best lines were those which satisfied a smoothness condition. As a rule, the computational domain in a Computational TWT had a complex topology hardly represented by analytical formulae. To gain the best results in approximating the boundary conditions, the computational domain was split in subdomains (blocks) and, as a result, a multiblock computational grid was generated (Fig. 4).

Grid blocks were built in such a way as to provide the use of bilinear functions for transformation of the physical space confined by block boundaries into unit cubes of mathematical space (index space). In reality, the blocks were curvilinear hexahedrons based on the model surface or on wind tunnel walls.

Each side of the hexahedron was a 3D surface split into cells by lines connecting the opposite boundaries of this surface. The volumetric grid inside the block was created taking into account the corresponding surface grids with the use of an algorithm described below. The use of multiblock grids permitted the aircraft geometry of arbitrary complexity to be approximated and the specific features of wall geometry and supporting devices to be taken into account. The solvers for multiblock grids were adopted for massive parallel calculations.

Each regime of wind tunnel tests was accompanied with two Computational TWT runs: the first for an unconfined and the second for Darcy-type conditions. The direct comparison of these regimes made it possible to properly correct experimental data (Fig. 5).

Obtained Results

1. A Computational TWT code has been developed and applied for studies of the influence of the computational-domain boundaries on the flow over a vehicle model. The influence of boundaries was shown to be significant: it can result in a crucial flow distortion in the vicinity of the model.

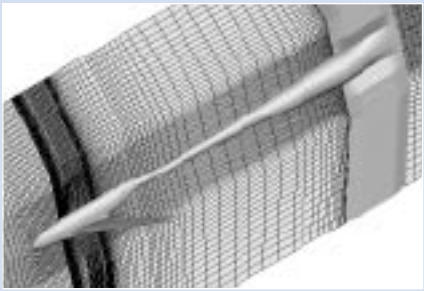


Fig. 4: Computer model of Airbus in T-128 wind tunnel

2. The TWT walls of different porosity were tested experimentally in TWT-128. The parametric dependencies of the Darcy coefficient were obtained and used in the Computational TWT code.

3. The effect of variable porosity of TWT walls was also studied experimentally in TWT-125. The experimental data were corrected using the suggested methodology. As a result, the data obtained in TWT-128 and TWT-125 were identical, which is indicative of method effectiveness.

4. Wall porosity, which is optimal in terms of diminishing the induction downwash, was ascertained. Its value equaled 3%–4%.

5. The technology of adaptive experiment has been developed.

6. Error sources in the PSP method were investigated and the technology of decreasing these errors has been developed. The experiments performed in TWT-125 proved effectiveness of the developed approach.

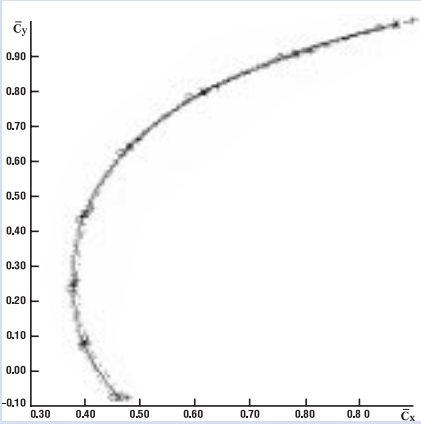


Fig. 5: Correction of experimental data

Project Number:	**#0548**
Full and Short Title:	Investigations of Technologies, Critical for Implementing an Airplane of Flying Wing Type with Superhigh Seating Capacity **Flying Wing Airplane**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	$695,000 (EU: $347,500, US: $347,500)
Commencement date:	(starting date) December 1, 1997
Duration:	36 months, extended by 3 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332, 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	AIRBUS Industrie/ET Engineering Directorate, Blagnac, France (Hinsinger R); Boeing Company, Long Beach, CA, USA (Liebeck R); DaimlerChrysler Aerospace (Satellites), Friedrichshafen, Germany (Hormann F); NASA/Lengley Research Center, Hampton, VA, USA (Bushnell D M)
Project Manager:	DENISOV Vladimir
Contact Information:	Phone: +7 (495) 5563162, fax: +7 (495) 7776332
ISTC Senior Project Manager:	MEYER Uwe
Contact Information:	Phone: +7 (495) 9823236, fax: +7 (499) 9780110
ISTC Website:	http://www.istc.ru

Background

Within recent years, a considerable progress has been achieved in improving aerodynamic efficiency of transport airplanes. The main technique used to improve the lift-to-drag ratio was the development of supercritical wings, which made it possible to increase wing thickness and *L/D* (aspect) ratio. Another method for increasing the *L/D* ratio is reduction of the relative wetted surface S_{ws}, that is, reduction of the airplane surface-area-to-the-wing-area ratio, which can be realized to a maximum degree in an airplane of flying-wing configuration with passengers and cargo fully or partly accommodated in the center-wing section (Fig. 6). The relative wetted surface in an airplane of conventional configuration S_{ws} is 5–6, whereas for the flying-wing configuration, S_{ws} = 2.3–2.5.

Such a decrease in S_{ws} results in the increase of the *L/D* ratio by 25% and corresponding improvement in fuel efficiency.

The advantages of the flying-wing configuration (lower fuel consumption and operating costs against a conventional airplane) can be realized in airplanes of large seating capacity.

There are a number of conceptual designs for superhigh-capacity airplanes of the conventional configuration: A–3XX (Airbus Industry), B-787 (Boeing), and Deutsche Aerospace concepts.

In the course of investigations of airplanes with superhigh-seating capacity, flying-wing designs (Aerospatiale – 1989, Deutsche Aerospace – 1990, McDonnell Douglas – 1995, Airbus Industry – 1995) were also considered.

Since the mid-1980s, TsAGI has been conducting research aimed at revealing possible advantages of flying-wing airplanes. Preliminary estimations of the flying wing effectiveness as compared to a conventional airplane showed that the fuel consumption per pass/mile could be reduced considerably (up to 20%); the direct operating costs could be also decreased.

However, the full-scale development of a flying-wing design calls for a comprehensive study including a number of "critical technologies" characteristic of this configuration. The main output intended to be achieved in the course of project implementation would be a stock of accumulated scientific and technical solutions enabling practical design of low-risk airplanes of the flying-wing configuration.

Fig. 6: Passenger cabin in a Flying Wing design

Project Objectives

The project objective was to develop critical technologies for a flying-wing aircraft with superhigh-seating capacity, including:

– assessment of possible cruise, take-off, and landing aerodynamic characteristics on the basis of theoretical and experimental investigations in TsAGI wind tunnels;

– exploration of stability and control characteristics, including the use of flight simulators;

– generation of the structural concept of a center-wing section and calculations of the stress-strained state by the finite element method;

– experimental studies of interference between the propulsion unit mounted over the upper wing surface and airplane airframe in wind-tunnels with simulation of engine jets; and

– design of a passenger cabin in the center-wing section with due regard for the requirements of FAR-25.

Description of the Work

The project was aimed at exploring and developing technologies needed to design a commercial flying-wing (FW) aircraft with a seating capacity of up to 1000 seats. Aircraft with such seating capacities, both of conventional and flying-wing configurations, are of significant interest to major airplane manufacturers. TsAGI has been investigating flying-wing aircraft since the mid-1980s, and this project was based on the gained experience. The works included studies of take-off and landing characteristics, investigations aimed at solution of accompanying stability and control problems, and the development of a baseline structural design, including engine mount and interference studies. Theoretical models were developed and experimental mock-ups were built and tested in large wind-tunnel facilities available in TsAGI.

An integrated analysis was made by separate directions:

– ascertaining a rational aerodynamic airframe configuration, including rational wingplan, shapes of airfoil sections and other airplane components, such as units of control and trim, with the use of up-to-shape numerical methods of aerodynamics;

– development and manufacturing of aerodynamic models as well as a drained wing compartment, ejector suction system, air intake simulator and nozzle for experimental investigations of powerplant/airframe interference;

– experimental tests in TsAGI wind tunnels (T-102, T-106) aimed at refining take-off–landing aerodynamic characteristics and determining their achievable level more precisely (Fig. 7);

– studies of the interference effect of the propulsion unit mounted on the upper wing surface, near the trailing edge, as applied to airplanes with turbojet engine T-129;

– formulation of a rational airframe structural concept on the basis of finite element methods, analysis of stressed-strained state, stiffness, and weight characteristics;

– exploration of possibilities to use the structure elasticity and mass distribution for enhancing the aerodynamic characteristics of the airplane, its lift qualities, reducing the aeroelastic aerodynamic center shift, increasing control effectiveness and critical flutter speed;

– formulation of recommendations on passive and active reduction of wing bending moments and increase in the load ratio;

– generation of controls with due regard for their multifunctional application, selection of a rational structure and parameters of the fly-by-wire-control system and active control systems with consideration for the requirements providing the comfort of passengers and crew;

– analysis of the agreement between the requirements of aeroelstic stability of the airplane and the automatic flight control in all regimes;

– experimental studies of stability and controllability characteristics using piloted simulators of TsAGI;

– configurational studies related to accommodation of passengers and cargo to verify the possibility of meeting the airworthiness standards; and

– comparative analysis of fuel and cost efficiency of flying-wing and conventional airplanes similar in their purposes.

Obtained Results

The major Project result is generation of technologies that enable designing of full-scale FW airplanes with a low technical risk.

The comparison with a conventional configuration has revealed that the FW design offered the following advantages:

Take-off weight 13,4% lower

Operating empty weight 6,4% lower

Engine thrust 12% lower

L/D ratio 19% higher

Fuel consumption per flight 24% lower

DOC 7%–9% lower (depending on fuel price)

Fig. 7: Flying Wing model in TsAGI wind-tunnel

Project Number:	**#0672**
Full and Short Title:	Experimental Installation for Research of Unstable Processes and Means for Increasing of Efficiency of Compressors **Compressors Efficiency**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Market ready technology
Allocated Funding:	$200,000 (EU)
Commencement date:	(starting date) April 1, 1998
Duration:	36 months
Leading Institute:	Central Institute of Aviation Motors (CIAM) Moscow, Russia
Contact Information:	Phone: +7 (499) 7635747, +7 (495) 3624928, 3616481, fax: +7 (499) 7636110, e-mail: avim@ciam.ru, ved@ciam.ru, website: http://www.ciam.ru
Supporting Institutes:	**No**
Collaborators:	Royal Institute of Technology/Division of Heat and Power Technology, Stockholm, Sweden (Torsten F); University of Cambridge/Whittle Laboratory, Cambridge, UK (Cumpsty N)
Project Manager:	SAREN Victor
Contact Information:	Phone: +7 (495) 3629323, fax: +7 (495) 3616696, e-mail: saren@ciam.ru
ISTC Senior Project Manager:	TOCHENY Lev
Contact Information:	Phone: +7 (495) 9823113, fax: +7 (499) 9783603, e-mail: tocheny@istc.ru
ISTC Website:	http://www.istc.ru

Background

Development of modern turbomachines widely used both in aircraft engines and in power plants applied in power engineering is impeded because of poor knowledge of gasdynamic properties of rotor–stator interaction. Many periodical processes taking place in turbomachines are not sufficiently studied and can be understood only based on a combined theoretical and experimental approach. The problem the Project was aimed at developing a special test facility for performing investigations of rotor–stator interaction physics in axial compressors.

Project Objectives

The objective of the Project was to create the experimental basis for developing approaches to improve efficiency and reliability of turbomachines.

Description of the Work

The technical approach was based on manufacturing a large-scale, low-speed, research axial compressor equipped with modern measuring instrumentation including laser flow anemometry. Experimental investigations of various effects of rotor–stator interaction was performed in the stator–rotor–stator row system.

Obtained Results

To study rotor–stator interactions in turbomachines, large-scale experimental facilities were designed and manufactured. A patent was filed, namely, the Patent of the Russian Federation for the invention № 2255319 “Experimental setup for studying gasdynamic interaction of rotor and stator blade rows in axial turbomachines” (Patenter: Federal State Unitary Enterprise “Central Institute of Aviation Motors” (RU), Authors: Saren V. E. (RU), Savin N. M. (RU), Zverev V. F. (RU), Suslennikov L. A. (RU)); the application № 2003133384 with the priority date of November 18, 2003.

A set of experiments was performed to study the stator clocking effect in the stator–rotor–stator row system in an axial compressor at various axial gaps between the rows and various numbers of blades in the rows. Experimental and theoretical studies performed allowed the basic gasdynamic mechanism responsible for the influence of stator clocking on the level of pressure fluctuations in the working channel, total pressure ratio, and efficiency of the axial compressor to be elucidated. Optimization of the mutual circumferential positions of stators and the numbers of their blades allowed the level of pressure fluctuations in the flow to be halved and the efficiency to be increased by 1% or 1.5% as compared with a nonoptimized row system.

Project Number:	**#0672.2**
Full and Short Title:	Experimental Installation for Research of Unstable Processes and Means for Increasing of Efficiency of Compressors. **Compressors Efficiency**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	150,000 € (EU)
Commencement date:	(starting date) November 1, 2002
Duration:	34 months, extended by 5 months
Leading Institute:	Central Institute of Aviation Motors (CIAM) Moscow, Russia
Contact Information:	Phone: +7 (499) 7635747, +7 (495) 3624928, 3616481, fax: +7 (499) 7636110, e-mail: avim@ciam.ru, ved@ciam.ru, website: http://www.ciam.ru
Supporting Institutes:	**No**
Collaborators:	Rolls-Royce, London, UK (Cumpsty N A); SNECMA, Moissy Cramayel, France (Caron S)
Project Manager:	SAREN Victor
Contact Information:	Phone: +7 (495) 3629323, fax: +7 (495) 3616696, e-mail: saren@ciam.ru
ISTC Senior Project Manager:	TOCHENY Lev
Contact Information:	Phone: +7 (495) 9823113, fax: +7 (499) 9783603, e-mail: tocheny@istc.ru
ISTC Website:	http://www.istc.ru

Background

This Project was the direct continuation of the study performed in the framework of ISTC #0672 Project. The new Project was aimed at practical application of developed means of noise reduction and compressor efficiency and reliability increase by controlling rotor–stator interaction. The issues addressed are important for ecological and economic aspects in compressor-engineering, in particular, for peak-load gas-turbine power plants and gas-pumping stations.

Project Objectives

The objective of the Project was to develop new approaches for decreasing the level of pressure pulsations and the radiated noise caused by rotor–stator interactions in axial compressors. In particular, clocking of stators in the stator–rotor–stator blade-row system and tangential stator-vane bowing in one of the stators were studied both experimentally and theoretically.

Description of the Work

The experimental setup comprised a large-scale subsonic stage of an axial compressor including inlet guide vanes (IGV), rotor, and stator (Figs. 8 and 9). The entrance receiver (smoothing chamber) of the setup has been certified as a reverberation chamber. Experimental studies allowed the sources of generated interaction noise to be ascertained and the effect of IGV and stator clocking as well as tangential bowing of stator vanes on the noise level to be assessed. The experiments have been made for 6 assemblies of the setup with different shapes of longitudinal axes of the stator vanes.

To provide hydrodynamic explanation of the experimentally found influence of tangential stator-vane bowing on the rotor flow, the following theoretical studies of the following phenomena were carried out:

– diffusion of free vortices in turbulent wakes behind turbomachine blades; and

– rotor–stator interaction employing the generalized axisymmetric flow theory.

Obtained Results

The clocking effect for all compared compressor assemblies manifested themselves most remarkably in pressure pulsations on rotor blades, in the intensity of free vortices behind the blades, and in the intensity of radiated noise on individual rotor-blade passing frequencies. Based on this finding, a patent was filed, namely, the Patent of the Russian Federation for the invention № 2280169 “An axial turbomachine with a lowered level of the pressure pulsations, exciting blade vibrations and radiated noise” (Patenter: Federal State Unitary Enterprise “Central Institute of Aviation Motors” (RU); Authors: Saren V. E. (RU), Savin N. M. (RU)); the application № 2004128965 with the priority date of October 5, 2004.

The tangential stator-vane bowing in the stator–rotor–stator row system of a subsonic axial compressor was found to affect the stator clocking insignificantly. The experiments demonstrated that the tangential stator-vane bowing entailed essential redistribution of time-averaged flow parameters both in stator and rotor. However, the overall pressure ratio for a particular stage was found to change insignificantly. The tangential bowing of stator vanes of crescent and sabre shapes resulted in essential decrease, as compared to radial stator vanes, of the total pressure losses caused by rotor–stator interaction, in the mid-span radius. In the hub and case areas, the losses caused by unsteady rotor–stator interaction were less significant.

Fig. 8: Axial compressor (in the middle), inlet plenum (right) and gas collector (left)

Fig. 9: Window in axial compressor for laser flow anemometry

Project Number:	**#0761**
Full and Short Title:	Multidisciplinary Approach to Preparing the Concept of Second-generation Supersonic Transport Airplane (SST-2) Ensuring Perfect Aerodynamic, High Static/Fatigue Strength, Good Structural Efficiency and Safe Flights **Supersonic Transport Airplane**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	$60,000 +301,877 € (EU: 301,877 €, Other Funding Sources: $60,000)
Commencement date:	(starting date) June 1, 1999
Duration:	24 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	Aerospatiale Airbus, Toulouse, France; DaimlerChrysler Aerospace Airbus, Hamburg, Germany; British Aerospace, Bristol, UK
Project Manager:	SCHERBAN Konstantin
Contact Information:	Phone: +7 (495) 5564297, 5564002, fax: +7 (495) 7776332, e-mail: scherban@tsagi.ru
ISTC Senior Project Manager:	TYURIN Igor
Contact Information:	Phone: +7 (495) 9823196, fax: +7 (499) 9783603, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

Works on second-generation supersonic passenger-carrying airplanes SST-2 are currently conducted by major aircraft companies and research centers in the UK, France, USA, and Russia. In the course of investigations conducted in TsAGI, possible approaches to enhance structural efficiency, to increase lifetime, and to improve aeroelastic stability characteristics at high lift-to-drag ratio of two-mode SST-2 at flight Mach number M < 1 and M > 1 were suggested. To simplify the search for and utilization of the ways of implementing these approaches at the design stage, it is reasonable to start from considering only key SST-2 characteristics.

The aim of the project was to investigate the gamut of possible solutions for the European supersonic commercial transport airplane (ESCT). The development of highly economic and effective ESCT requires a multidisciplinary approach and should meet many constraints in terms of strength, weight, and service life requirements, as well as requirements to the aeroelastic stability of the airplane structure aimed at airplane shape optimization. Among the parameters whose selection requires such a multidisciplinary approach are an increased outer wing sweep angle, reduced airfoil thickness-to-chord ratio, and greater aspect ratio which could be useful in terms of aerodynamics, on the one hand, but could increase the airframe structure weight and shorten its lifetime, on the other hand.

An increase in the supersonic cruise flight Mach number advisable in terms of economics complicates the task of ensuring high static/ fatigue strength due to more intense aerodynamic heating and can necessitate replacement of cheap Al-alloys by more expensive Ti-alloys and composites and deteriorate the airplane economic merit figures.

Project Objectives

The objective of the project was to develop the SCT-2 structural concept meeting the requirements imposed on static strength, aeroelasticity, and service life at strict weight constraints. In the course of project implementation for the ESCT in accordance with the FAR25 and JAR25 requirements on ensuring airframe strength with regard for the structural effect of elevated temperatures arising in the supersonic flight, the comprehensive strength estimates should be made, including:

– loads for flight and ground segments;

– structural configuration of the airframe and structural elements;

– load-carrying material distribution in the structure;

– structural stressed-strained state based on a finite-element airframe model in the basic design cases; and

– shapes and frequencies of oscillations, as well as characteristics of aeroelasticity.

Description of the Work

1.1 Design basis and conditions

The problems of design selection in terms of the loads affecting the supersonic passenger airplane of second generation were considered. Experience of TsAGI in designing supersonic passenger and military airplanes as well as in harmonising home and foreign standard requirements to airplane strength was widely used. The requirements developed for the supersonic passenger airplane Tu-144 (VNLGSS-76) were compared to the appropriate requirements for the Concord airplane (Concord TSS Standards). Several loading cases were considered for the flight Mach number ranging from 0.5 to 2.1 and impact pressure ranging from 1500 to 3500 kgf/ mm^2. For the subsonic flight conditions, the flight mass was assumed to be 340 t whereas for the supersonic flight conditions it was taken equal to 325 t with regard for 15 t fuel consumed for climbing and speeding-up. The maximum loading was found to be realized:

- for positive overload n = 2.5, at M = 1.1–1.5 and minimum flight speeds appropriate to the maximum lift coefficient of an airplane or critical elevon deviation angle;
- for negative overload n = – 1, at M = 1.1–1.5 and maximum flight speeds.

1.2 Analysis of inertial and aerodynamic span and chord distributed loads

To determine the aerodynamic loads, three design cases with limit load factor n_y = 2.5 were selected exhibiting the following characteristics:

– $q_{\max\max}$ at Mach number M_d = 2.2;

– subsonic flight at $C_N^{\max}$ = 1; and

– flight at $C_N^{\max}$ = 1, M = 0.95.

For these cases, the aerodynamic loads on a rigid airplane and the appropriate inertia unloading were calculated. Some attempts were undertaken to improve the methods

for calculating aerodynamic loads on the deformed structure applying various procedures of optimising the design nets. A new method has been developed to calculate static aerodynamic loads on the deformed structure in a supersonic flow in the form of circulation distribution. The validity of all the proposed methods was checked by comparing the calculated data with measurements for a model of tested type.

The loads on the landing gear unit during landing of a rigid plane were preliminary estimated. Possible structural layouts for landing gear units were considered with the appropriate hydrodynamic characteristics of shock absorption and diagrams of vertical shock-absorber deflection under standard conditions were plotted. Based on the experience collected with the supersonic passenger transport and on the required properties of ESCT-2, a novel design of the landing-gear shock absorber was suggested.

1.3 Selection of structural concept and structural materials

Based on the experience in the development of Tupolev Tu-144 as well as on main requirements to the second-generation supersonic transport, the design strength concepts and design criteria for ESCT-2 airframe structure have been formulated. It was shown to be expedient to fabricate the wing box structure from titanium rather than aluminium alloys because of very small construction heights in the box and difficulties in assembling structural joints. According to weight estimates of wing structure, the stringer structure of a wing central part and the wall structure of a separated wing part were preferable. The multiwall structure was considered in three options depending on the wall number (19, 24, 31). As a result, the optimum option in terms of weight was the stringer wing box made of Ti alloy at the wing central part, the wall made of high-strength composite for the separated wing part, and the traditional fuselage layout made of heat-resistant Al alloy.

1.4 Developments of airframe finite-element model for the sake of structural analysis, stress-strain state analysis and structural weight definition

A finite-element (FE) model was developed for the airframe with a wing, empennage, and fuselage essentially resembling the structural layout taken from BAE. The geometrical data were obtained from data processing of CADDS-5 contents. The FE model of a half aircraft structure consisted of 8549 elements and 3366 nodes. The wing, fuselage, and fin skins as well as the frame, spar, and rib webs were simulated by membrane elements, while the spar, rib and frame caps were represented by rod elements. The structural layout for main wing components (spars, ribs, skins, etc.) was assumed to be close to BAE drawings. The wing was divided into separate blocks including elevon structures, wingbox, front wing, leading edge, tip part of the wing, and landing gear cutout. In order to transfer mass loads from the engine structures to the primary wingbox, some rough FE models of the engines have been developed. The outer wing was connected with the fuselage through a centerwing.

The aircraft fuselage consisted of a central part of a nearly cylindrical cross section, while its nose and tail parts had conical narrowing of cross section. The skin, primary frames, longitudinal webs and stringers, as well as the floor were considered as the primary structural elements. The fin structure was assumed to transfer forces to the aft-fuselage under asymmetric loads.

1.5 Optimization of selecting load-carrying material in the assumed structural concept

The aircraft primary structure was studied in detail using athe FE model. The design analysis was performed using the FE block of the ARGON multidisciplinary design system.

In the design analysis, the following strength allowable stresses were selected for aircraft metallic parts:

– upper skin and stringers (titanium) – 80 kgf/ mm^2;

– lower skin and stringers (titanium) – 60 kgf/ mm^2; and
– wing and fuselage elements of Al alloy – 40 kgf/ mm^2.

The number of stringers in the panel and the panel sizes were taken as the most important parameters to be considered when determining the thicknesses required to prevent buckling. Therefore a parametric optimization study was performed with variation of their values. For the flight load spectrum considered in the project, the wing was found to be the most loaded structure. Fig. 10 illustrates the predicted wing displacement distribution.

1.6 Aeroelasticity characteristics

Standard calculations of aeroelasticity characteristics were performed using the prescribed form method (PFM), i. e., the polynomial Ritz method. Provision of the required SST aeroelastic characteristics was found to be important. On the basis of parametric studies, a new approach for solving the problems of dynamic and static aeroelasticity has been envisaged. The calculations of static aeroelasticity characteristics have demonstrated a significant unfavourable effect of the structural elasticity on the elevon efficiency in the roll motion. The main trouble was the bending-bending flutter shape with the frequency of 2 Hz for both types of fuel loadings (Fig. 11).

The comprehensive parametric study resulted in the conclusion that the most effective means to increase the critical dynamic pressure of such flutter type is to replace the engines forward towards the wing leading edge. Due to the fact that the forward engine displacement results in increasing of the critical dynamic pressure of the bending-bending flutter and in decreasing that of the bending-torsion flutter, the optimal engine location in terms of flatter should be found.

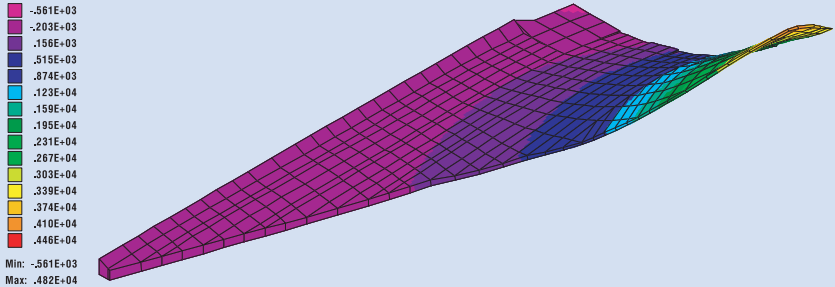


Fig. 10: Predicted wing displacement distribution. Maximum stresses are attained in the main wing box where the skin is made of Titanium alloy

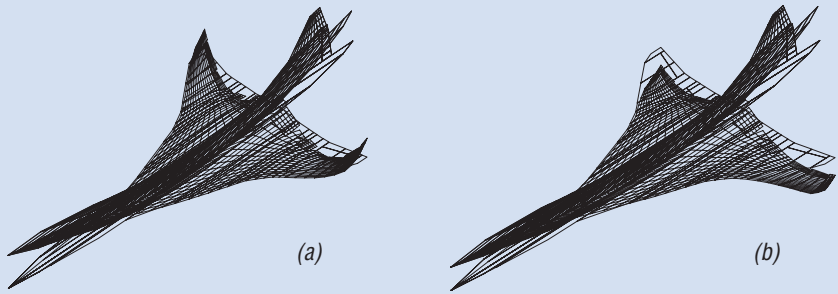


Fig. 11: Flutter mode f = 2 Hz with phase 0 (a) and 0.25 (b)

1.7 Structural Weight Analysis

For evaluating airframe weight, a particular WGS procedure has been developed within the FE model with making a provision for refining sequentially the weight breakdown among finite elements. The weights had to be corrected by applying certain coefficients to take into account main stages of both fabricating the individual parts and assembling the airframe. Fig. 12 demonstrates the methodology of weight computations for basic units in a wing, fuselage, and vertical stabilizer as well as shows the resulting weights.

Obtained Results

Comprehensive estimates of strength characteristics have been obtained for the second generation of supersonic passenger-carrying airplane ESCT. These estimates could be used to ensure airframe strength with regard for the effect of elevated temperatures arising in the supersonic flight on the aircraft structure, including:

– loads for flight and ground segments;

– structural configuration of the airframe and structural elements;

– load-carrying material distribution in the structure;

– structural stress-strain state based on the FE airframe model in the principal design cases; and

– modes and frequencies of oscillations, as well as aeroelasticity characteristics.

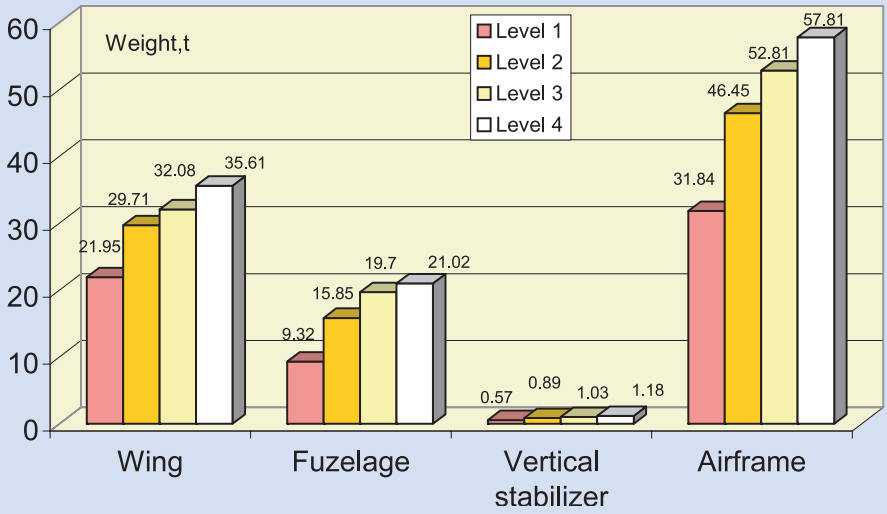


Fig. 12: Evaluation of airframe weight

Number:	**#0808**
Full and Short Title:	New Approaches to Predictive Joints Design Based on a Detailed Description of Local Elasto-Plastic Strain History by Combining the Holographic Interferometry Data and Numerical Simulation **Predictive Design of Joints**
Tech Code/Area/Field:	MAN-MAT/Manufacturing Technology/Engineering Materials SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	229,655 € (EU)
Commencement date:	(starting date) April 1, 1999
Duration:	18 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	Aeronautical Research Institute of Sweden, Bromma, Sweden (Blom A F); Bremer Institute of Aplied Beam Technology (BIAS), Bremen, Germany (Juptner I W)
Project Manager:	PISAREV Vladimir
Contact Information:	Phone: +7 (495) 5564150; 5563656, fax: +7 (495) 7776332, e-mail: pisarev@tsagi.ru
ISTC Senior Project Manager:	KULIKOV Gennady
Contact Information:	Phone: +7 (495) 9823154, fax: +7 (499) 9784637, e-mail: kulikov@istc.ru
ISTC Website:	http://www.istc.ru

Background

In many cases, joints are the primary sources of structural weakness because they bear the most part of applied load. The following illustrates the importance of this issue. In modern passenger airplanes of airbus type, the number of rivets varies from 1,500,000 to 2,000,000 and the average number of bolts is about 300,000. A total mass of joints comprises about 25% of the airframe mass. The number of joint elements to be tested for validating the airframe fatigue strength can be as great as 1000. Such tests contribute considerably to a total cost of airplane production and service. Moreover, it is well

known that about 85% of aircraft structure failures occur at joint elements of pin and rivet joints. Recent trends are directed toward substitution of traditional pin or rivet joints of airframe structures with analogous welded joints. However, in 2009, this process is still far from its completion. Thus, tackling the problem of reliable lifetime prediction for various high-loaded joints and their optimal design would be an essential step forward in the development of advanced structural elements with higher reliability.

Project Objectives

The main objective of the project was to develop and implement new design techniques capable of increasing the reliability and lifetime of permanent joints at low-cyclic fatigue conditions. The proposed techniques were based on the unique information obtained by the application of the holographic interferometry method. The method provides information on local elastoplastic strains and crack history in contact interaction zones of bolted and rivet joints. The techniques also involved modern powerful computational tools and sophisticated algorithms capable of detailed simulation of both local and general deformation processes in real joints of various design for any loading cycle investigated, including random loading.

Description of the Work

The proposed techniques were based on unique information on the evolution of local elastoplastic strain fields near irregular zones of various joints prior to crack appearance with taking into account both initial/residual redistribution of stresses and the character of actual contact interaction. The required data were obtained by the holographic interferometry method. Similar data related to processes of fatigue crack appearance and propagation in residual stress fields was also available. The second essential component of the techniques dealt with modern powerful computational tools capable of detailed and accurate numerical simulating of both local and general deformation process in real joints of various design for any loading cycle of interest.

Progress in predictive design of joints demands the development and implementation of novel approaches to quantitatively describe local elastoplastic strain and crack history near each separate joint element at any possible loading cycle. The techniques to be developed must take into account at least the actual character of contact interaction and evolution of local mechanical properties of the material under cyclic in-service loading. The solution of similar problems for welded joints has to be based on quantitative data on the level of initial residual stresses and on the accurate description of evolution of these stresses under operation conditions.

The holographic interferometry technique was used as methodological and metrological basis of the experimental part of the project. Essential features of this approach are that it provides noncontact and highly accurate measurements of local displacement fields on the surface of real objects. Of great importance is that such measurements can be performed in both elastic and elastoplastic deformation regime in a similar way. The initial experimental information which was essential for optimal design of various pin-loaded joints was represented by the values of local strains in the vicinity of individual joint elements. Some novel measurement techniques based on reflection hologram interferometry served for deriving the required information. Most of these approaches were developed by the project authors and have no analogues so far.

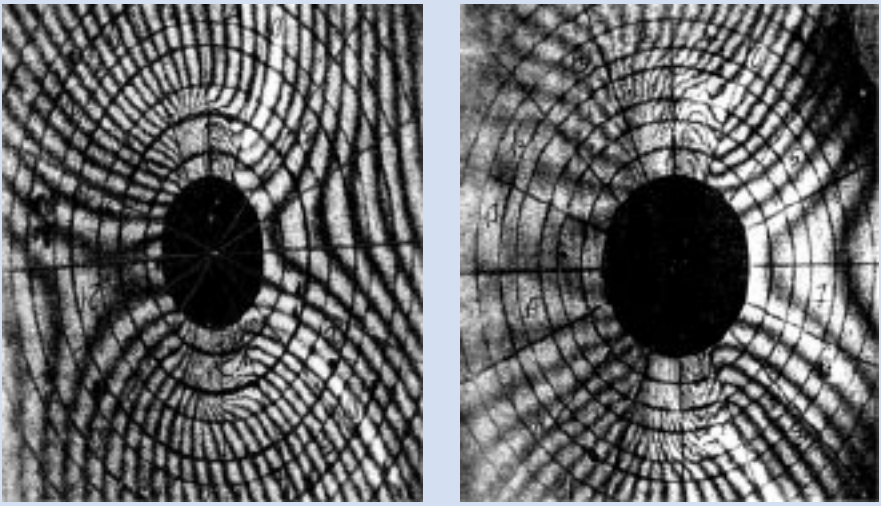
The other essential component of the project was a set of mathematical models of different complexity. Most of traditional approaches to the analysis of local strain evolution are restricted by oversimplified models. Availability of holographic interferometry data provides remarkable

opportunities for creating novel hybrid techniques for the numerical simulation of local deformation processes under cyclic loading based on the most advanced mathematical models. The numerical procedures were realized in the project using the MSC/NASTRAN software code.

The idea of using an overlay holographic interferometer in combination with visualization of zero-order fringes was proposed and realized for obtaining required experimental data for the first time. Such an approach allowed the local deformation processes to be studied in the course of loading plane specimens of dimensions $260 \times 60 \times t$ mm in a real testing machine. Samples with thickness of 3 (Nos.2 and 3) and 6 mm (Nos.1, 4, 5, and 6) and hole radius of 9 (No.3) and 6 mm (others) were the main objects of investigations and loading programs. The testing conditions involved an open hole (Nos.1, 2, and 3), a hole filled by steel inclusion with interference fit (Nos.4 and 5) and without clearance or interference (push fit) (No.6).

The types and ranges of loading involved cyclic loading in net stress range $-120 \leq \sigma_0 \leq 230$ MPa with different loading shape (Nos.1, 4, 5, and 6), single static tension in net stress ranges $0 \leq \sigma_0 \leq 244$ MPa (No.2) and $0 \leq \sigma_0 \leq 232$ MPa (No.3).

More than 1000 holographic interferograms which became a source of more than 9000 interference fringe patterns were recorded during the study of local deformation processes inherent in tested specimens. Great volume of obtained experimental data provided a unique opportunity for developing mathematical models needed for quantitative description of the evolution of local elastoplastic strains near joint elements. Single static tension tests were used for validating the models of the first complexity level (for Specimens Nos.2 and 3) describing a deformation process in elastoplastic range, with both specimens loaded up to plastic yielding. Figures 13*a* and 13*b* show the typical fringe patterns caused by tension of Specimens No.2 and No.3, respectively,



(a) *(b)*

Fig. 13 Typical interference fringe patterns obtained at tension of plane specimens with open holes in the range of highly developed plastic strains: (a) Specimen No.2 for net stress interval σ_0 from 198 to 223 MPa; and (b) Specimen No.3 for net stress interval σ_0 from 208 to 222 MPa

in a region of high elastoplastic strains. Note that the maximum values of local strains were determined for the first time based on the measured fields of local displacement components. The “local strain vs. net stress” diagrams obtained both experimentally and numerically appeared to agree with each other within 5 percent accuracy. The numerical model of such a high predictive capability was possible to develop only due to the use of experimental distributions of local displacement components.

The mathematical model of the second complexity level (MM-2) was applied for describing local deformation processes at cyclic loading. It was validated against the experimental data obtained for Specimen No.1. Figure 14 compares the results with the experimental data denoted by dots and the numerical simulation represented by curves. Availability of MM-2 made it possible to derive the dependencies of the maximum acting stresses on the open-hole edge on the corresponding local strains (“maximum local stress vs. maximum local strain” diagram). Such dependencies were the key points for the optimal design of pin and rivet joints. The developed approach can be reliably used for obtaining a set of “maximum local stress vs. maximum local strain” diagrams for different loading cycles for elements with different hole diameter. In fact, such a set itself is a foundation of an engineering technique for evaluating the fatigue lifetime of joints. Moreover, the research tools developed and the experimental data obtained allow the following step to be made, namely, they allow taking into account contact interaction (geometrical nonlinearity) in the analysis of local deformation process at cyclic loading.

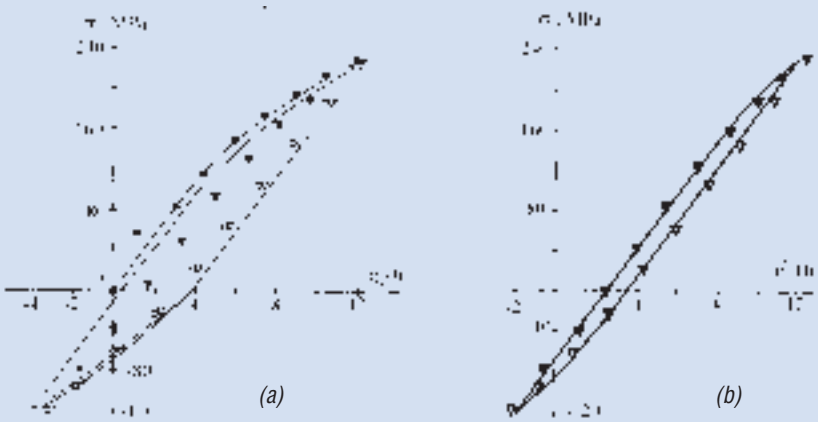
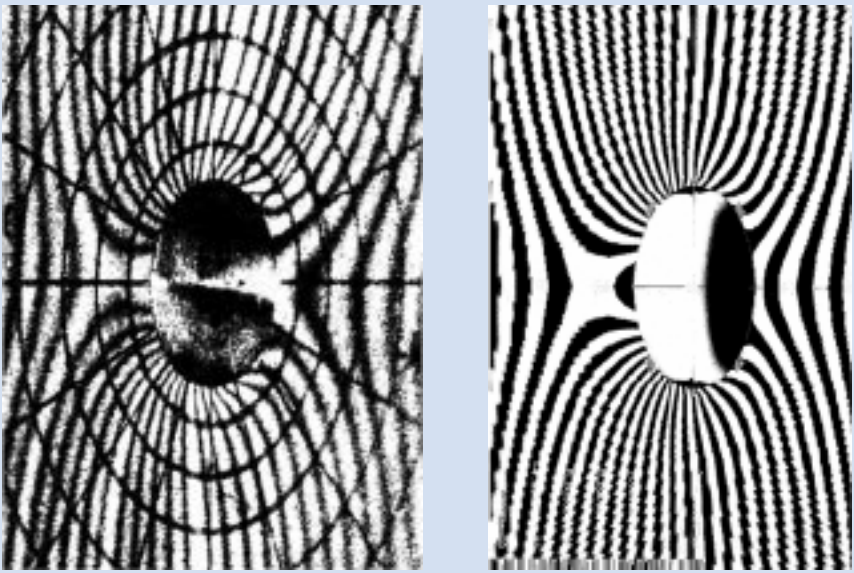


Fig. 14: Maximum local strain vs. net stress diagrams obtained for Specimen No.1 using the standard combined hardening law included in the MSC/NASTRAN software code: (a) first two loading cycles; and (b) the 14th cycle

Unfortunately, with the computational tools, which were available during project performance terms (1999-2000), the numerical simulation was limited with only local contact interaction in a joint element with push fit (Specimen No.6). Figure 15*a* shows typical realistic interferograms recorded for Specimen No.6 at the 14th (σ_0 ranging from 174 to 203 MPa) loading cycle. Nearly perfect quality of fringe patterns in the figure has to be pointed out. The experimental information of this kind was used for validation of the mathematical model of the 3rd complexity level (MM-3), which was applied for numerical simulation of local deformation processes in contact interaction zones at cyclic loading. The performance of the model was perfectly demonstrated by so-called reference fringe patterns. The artificial image of local displacement component fields obtained by numerical simulation for the case of Fig. 15*a* is presented in Fig. 15*b*. Virtually perfect agreement of real interferograms and reference fringe patterns illustrates a very high quality of MM-3. In addition, Fig. 16 compares experimental (dots) and numerical (curve) "local strain vs. net stress" diagrams for the 14th loading cycle.

Obtained Results

Novel experimental, numerical, and hybrid research tools capable of providing the optimal design of highly-loaded pin/rivet joints with increased fatigue lifetime have



(a) *(b)*

Fig. 15: Real interferogram (a) and reference fringe patterns (b) obtained in the range of elastoplastic strains and contact interaction at the 14th loading cycle for net stress interval σ_0 from 174 to 203 MPa

been developed and validated. Experimental techniques for determining local displacement component fields by electronic speckle-pattern interferometry and powerful computational tools which are currently available open up unique opportunities for implementing these approaches in the design of advanced airframe structures.

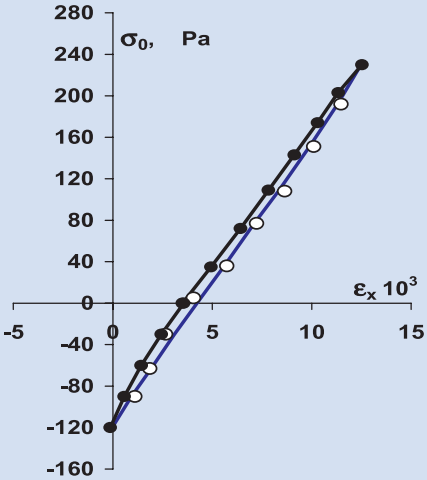


Fig. 16: Maximum local strain vs. net stress diagram obtained for Specimen No.6 at the 14th loading cycle

A general approach to determine membrane and bending res dual stress components based on the combined hole drilling method and reflection hologram interferometry and surpasses all known techniques in terms of the accuracy and reliability has been developed. A capability of recording high-quality interferograms with high fringe density at small hole proximity (Fig. 17) is a key point of this approach.

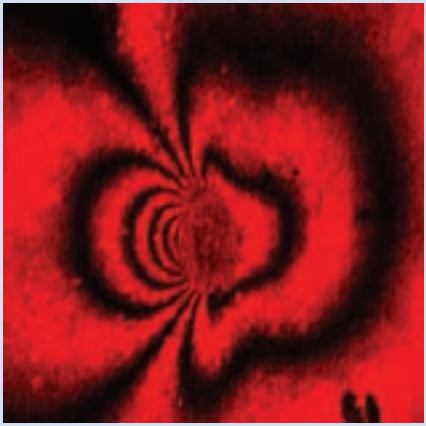


Fig. 17: Typical interference fringe pattern obtained in the course of residual characterization by combining the hole-drilling method and reflection hologram interferometry with high resolution

Number:	**#0887**
Full and Short Title:	Experimental Investigation Concerning the Optimitisation of Supersonic Inlets **Supersonic Inlets**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$250,000 +235,715 € (EU: 235,715 €, Other Funding Sources: $250,000)
Commencement date:	(starting date) July 1, 2001
Duration:	18 months, extended by 32 months
Leading Institute:	Siberian Branch of RAS/Institute of Theoretical and Applied Mechanics (ITPMech), Novosibirsk, Russia
Contact Information:	Phone: +7 (3832) 350778, fax: +7 (3832) 352268, e-mail: admin@itam.nsc.ru, website: http://www.itam.nsc.ru
Supporting Institutes:	**No**
Collaborators:	Aerospatiale, Les Mureaux, France Rutgers University, Piscataway, NJ, USA; MBDA France, Chatillon, France
Project Manager:	MASLOV Anatoly
Contact Information:	Phone: +7 (383) 3303880, fax: +7 (383) 2342268; 2352268, e-mail: maslov@itam.nsc.ru
ISTC Senior Project Manager:	TOCHENY Lev
Contact Information:	Phone: 7 (495) 9823113, fax: 7 (499) 9783603, e-mail: tocheny@istc.ru
ISTC Website:	http://www.istc.ru

Background

Investigations of operation process and characteristics of air-jet power plants for high-speed flying vehicles of different purposes are important for further development of civil transport. The project is closely connected with the ISTC Project #128 “Experimental Investigation of Transition of Supersonic Boundary Layers Relevant to High-Speed Air Transportation” dealing with the development of turbulent and laminar flow theory.

Project Objectives

The objective of this project was the experimental investigation of supersonic inlet optimization, as well as the study of fundamental processes in gasdynamic flows and validation of theoretical models.

Description of the Work

The special attention was paid to investigations of flows in inlet channels and to the possibility

of flow control for providing acceptable levels of flow rate and total pressure recovery, as well as flow nonuniformity and total pressure pulsations. The conditions of flow separation and the possibility of preventing flow separation by proper changing of diffuser configuration, boundary layer bleed, or fluid injection were also investigated.

All elements of the model (forebody, inlet, flowmeter) were manufactured, control and regulation systems were assembled and adjusted, and the systems of gas supply into the model channel and boundary layer bleed (control) were fabricated. The calibrating tests of the measuring and control systems were performed.

The blow down (T-313) and hot-shot (IT-302M) wind tunnels were used for experiments. The flow field parameters in the test sections of the wind tunnels were measured.

At the first stage of the work, experiments with an inlet model combined with a flowmeter device were performed in the blow wind tunnel T-313. At the second stage, the inlet model tests were performed with a new forebody. These tests included model tests at Mach numbers ranging from 2 to 6 within the range of unit Reynolds numbers from 10 to 60 million/m. The main purpose was to ascertain the airflow rate, total pressure coefficient, and inlet start (nonstart) conditions. The results obtained served as a basis for the choice of configurations and parameters for tests with an inlet model in the hot-shot wind tunnel, including experiments with hydrogen combustion.

During the experiments, the measurements of the following flow parameters were performed: static pressure distribution on the walls; total pressure distribution in the control sections; air flow rate; total pressure recovery; and nonuniformity of total pressure fields. In all runs, the flow around the model channel entrance and flow in the inlet channel were visualized.

Ten main modifications of the inlet model were tested in wind tunnel T-313:

– extra bleed of boundary layer was realized in the model nose part (deverter);

– bleeding of the boundary layer was modified in the inlet throat;

– a deflector was mounted in the flowmeter;

– cowl size, configuration, and rotation angle were changed;

– new model forebody was manufactured (new geometry);

– cowl sizes and configuration were changed and longitudinal displacement was realized;

– the boundary layer bleed was implemented before the first wedge and at the inlet throat;

– an additional boundary layer bleed was implemented on the model forebody before the inlet throat;

– the boundary layer bleed was modified at the model throat; and

– a device was fabricated for inlet shock start in the blow-down wind tunnel.

Totally 18 configurations have been tested. The experiments performed furnished throttle characteristics for all Mach numbers.

One way to control effectively the boundary layer and to reduce its influence on the inlet characteristics was to test the inlet without sidewalls or to vary their sizes (configurations). The tests of the model without side walls at Mach numbers 5 and 6 resulted in a much higher air flow rate.

Another way to control the boundary layer was to arrange the boundary layer bleed through a slot ahead of the first compression surface (diverter) or through a cavity in the inlet throat. The boundary layer bleed through the diverter was used at Mach number M = 4. It turned out that such a kind of boundary layer bleed was not efficient for this configuration. There was no inlet start, no growth of the airflow rate or full pressure recovery coefficient. Combined boundary layer bleed at the central body and in the inlet throat did not lead to significantly better characteristics of the inlet, either.

According to the studies performed, the porous bleed appeared to be an effective approach to achieve inlet start. The inlet with sidewalls was started at Mach number M = 4

along with a flow rate approaching the designed value and a full pressure recovery coefficient being quite high. The porous bleed permitted the increase of the airflow rate in the model with sidewalls to be more than doubled. This flow rate was more than 30% higher than the airflow rate in the model without sidewalls. It was also found that the downstream porous bleed was the most efficient. The upstream bleed closing exerted virtually no effect on the airflow rate and did not entail reduction in the flow rate. The efficiency of the porous bleed increased with the flow Mach number. At the same time, it was found that, after inlet start, porous bleed closing did not result in the inlet nonstart, i. e., the inlet remained in the started state. It was natural that the inlet flow rate increased when the boundary layer bleed was closed.

Concurrently, the pressure distribution over the model channel walls and Pitot pressure fields in the typical channel cross sections behind the inlet throat, airflow rate and full pressure recovery coefficient were measured. Evidently, modification of the geometrical configuration of the model or shape of the boundary layer bleed entailed a significant change in the pressure distribution in the model channel. The pressure distributions in the models with and without side walls, being compared, showed that the inlet start was accompanied by a decrease of the static pressure in the channel and corresponding increase of the airflow rate owing to the absence of a shock wave at the inlet entrance and side spreading reduction.

It should be noticed that the pressure distribution differed not only quantitatively but also qualitatively in the case of inlet nonstart. Such a difference in the pressure distributions at the inlet nonstart was typical at any Mach number studied.

Tests with the inlet were carried out using 0, 2, and 4 degree angles of attack (Figs. 18 and 19). The measurement results have revealed that at any Mach number the air flow rates and full pressure recovery coefficients were smaller for 0 degree angle of attack. This was caused by the decreasing angle of compression on the first compression surface and by corresponding reduction of the entrapped jet in the undisturbed stream.

The effect of the position of the cowl leading edge on the varying air was studied (Fig. 20). The upstream movement of the cowl resulted in more air captured and more intense inner compression, i.e., the mass flow rate and total pressure recovery coefficient increased (Fig. 21). It is evident that in this case there was a certain optimum position of the cowl leading edge, which would provide inlet start and maximum value of the airflow rate and full pressure recovery coefficients.

The model tests in hot-shot wind tunnel IT-302M were conducted at Mach numbers ranging from 5 to 8 within the range of Reynolds numbers from $5 \cdot 10^6$ to $30 \cdot 10^6$. The main goal of the investigations of the inlet model was to check the adequacy of results of tests in different wind tunnels, to obtain the experimental data at Mach numbers from 5 to 8, to ascertain the inlet start (nonstart)

Fig. 18: Photo of the model with starting device

conditions, and to study ignition and combustion in the channel at hydrogen supply. In these investigations, the adequacy of results of tests in different wind tunnels was checked and experimental data at Mach numbers from 5 to 8, inlet start (nonstart) conditions were accumulated, effectiveness of different methods of inlet control was assessed, and ignition and combustion in the channel at hydrogen supply were studied

In spite of the change in the free stream parameters during the operation regime, a quasi-stationary flow regime was realized in the hot-shot wind tunnel. Free stream Mach number dependence on time can prove this fact. The quasi-stationary flow regime was realized at all Mach numbers within the time range from 15 to 80 ms. The Mach number value was constant during the regime.

Because of the short time of the operation regime defining the angle of cowl installation, which resulted in the inlet start, was of particular interest. The fact of inlet start was checked individually in every run. It was found that the values of self-start angles were smaller in the hot-shot wind tunnel than those in the blow-down wind tunnel, and they were closely related to the minimum angles of the start with control.

The comparison of the results of pressure distribution measurements on the model compression surfaces in two wind tunnels has proved the effect of Reynolds number on the pressure distribution in the channel. The pressure distribution at Mach number of 5 showed virtually complete identity of the pressure fields on the external compression surfaces, and a certain discrepancy between them in the channel. An especially significant difference was observed at the channel exit. When the Reynolds number decreased during the wind tunnel operation, the pressure at the channel exit (X = 745 mm) varied from the full identity to the data in wind tunnel T-313 to a twofold difference.

Two main configurations without injection have been studied in the wind tunnel: with and without cavity. The results of the experiments have demonstrated that the static pressure distribution over the model differed only insignificantly. The presence of a cavity (closed throat bleed) slightly affected the inlet flow rate. It is evident that the difference in the flow rate was small.

At the same time, during these tests it has been founded that the change of pressure in the channel at Reynolds number variation and flow structure in the inlet channel entailed no changes in the pressure distribution on the external compression surfaces ahead of the entrance in the inlet channel. In each case, the pressure on the external compression surfaces was virtually invariable and very similar in both wind tunnels. Therefore, the identity of flow rate values should be expected, too.

The comparison of obtained flow rate coefficients in the hot-shot and blow-down wind tunnels has confirmed their good agreement if the experiments were carried out with profiled nozzles at M = 5 and 6. At the same time, it was found that tests of a long model in the hot-shot wind tunnel

Fig. 19: Forebody units

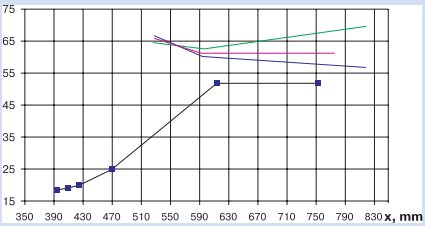


Fig. 20: Channel configuration at various cowl rotation angles

with a conical nozzle failed to obtain the correct results because of the considerable Mach number increase along the jet (along model nose part). As a result, the regularity of variation of the flow rate coefficient dependence on Mach number was broken. It was confirmed by the data for the same angles of cowl position. These data were obtained at Mach number equal to 6 in the hot-shot wind tunnel with a conic and profiled nozzle at the same parameters of the model and wind tunnel. They suggest that the tests with models of such a configuration in the wind tunnel with the conical nozzle failed to provide correct results. This was caused by considerable changes in the Mach number along the model and, as a result, by changes in the compression conditions and indeterminacy in the free stream. At the same time, such tests allowed one to arrive at qualitatively correct dependencies of the flow rate on cowl installation angle and angle of attack. It was also demonstrated by the data for Mach number of 7.

The effect of conical flow in the wind tunnel can be seen in the pressure distribution on the model nose part. The pressure in the model symmetry plane decreased downstream. The pressure was lower on the second compression surface than that at the first point on the model forebody. The comparison of the results at Mach number M = 6 confirmed the effect of the conical flow on the pressure distribution along the surfaces of external compression. It was also found that the level of pressure increase in the channel was appreciably smaller in tests with the conical nozzle than that in tests with the profiled nozzle.

Injection of air into the inlet channel did not change the flow structure in the channel or airflow rate. The pressure distribution in the channel showed that the air injection resulted in a pressure rise in the channel but did not affect the pressure distribution ahead of the channel entrance. A slight increase in the flow rate during the regime was dictated by the relative increase of the injected air flow rate arising from the decrease of the air flow rate through the inlet.

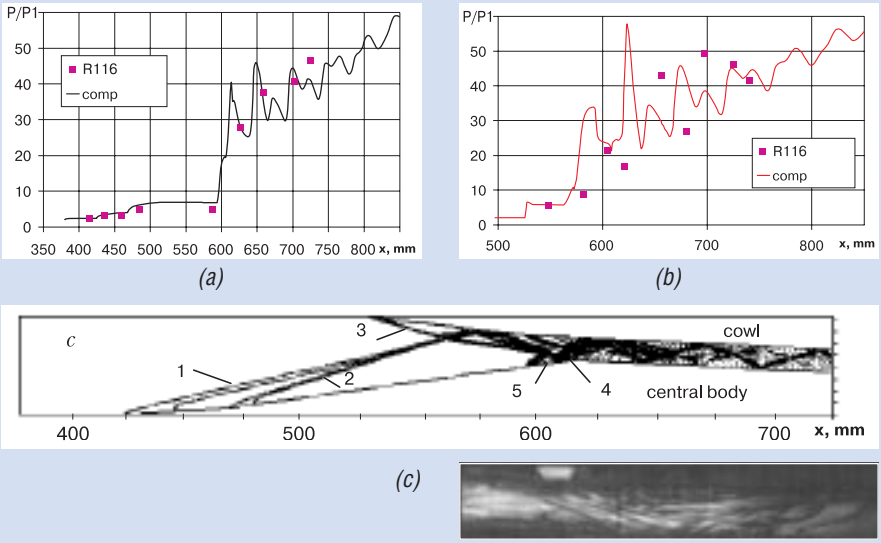


Fig. 21: Computed and experimental pressure distributions along the central body (a) and the cowl (b) at M = 7 and pressure contours (c)

At Mach number M = 8, air injection into the channel through the second injector row on the central body and cowl caused inlet choking even by 5th ms and a drastic decrease of the air flow rate. A change in the injector row on the central body (4th row) has eliminated channel choking and resulted in airflow rate increase.

The experiments with hydrogen combustion were carried out with the purpose of exploring the possibility of self-ignition and combustion stabilization in the diverging channel when fuel was supplied from the wall without extra combustion stabilization means. First experiments at Mach number M = 8 demonstrated that ignition took place at the wind tunnel beginning starting from 5th ms and the flow in the channel choked after 15th ms. The pressure was increasing on the external compression surface and decreasing in the channel.

At the same value of the fuel equivalence ratio, an increase in the cowl installation angle by 2° (the expanding channel) increased the combustion process duration up to 100 milliseconds with no channel choking. Comparison of the pressure distributions for the flows with and without combustion demonstrated a more than 4-fold increase of the pressure. The flow regime obtained was thought to be closely related to the choking regime because combustion increased the pressure before the channel entrance. This assumption was confirmed by the data for the divergent channel obtained at the fuel–air equivalence ratio close to 1. The channel choking was observed after 6th ms.

The channel throttling at hydrogen combustion, i. e., transition to a subsonic combustion regime, caused the channel choking already at 16th ms and intense pulsating combustion after the choking, whereas combustion in the supersonic regime continued up to 60 ms with no flow choking. At the same time, it can be seen that in the subsonic combustion regime, the pressure increase level is higher at equal values of the equivalence ratio and the parameters at the combustion chamber entrance.

The data obtained in the experiments with hydrogen combustion have demonstrated that the minimum angle of cowl installation (according to the start conditions) does not allow one to guarantee fuel combustion without channel choking, in spite of the fact that Mach number at the combustion chamber entrance increased with the cowl installation angle.

The skin friction gauge was tested in a hot-shot wind tunnel at a total pressure of 100 bar and total temperature of 1500 K. The results of these tests pertain to the range of Reynolds numbers from 10.6 up to 3.2 million. These data show a fairly good consistency between the calculation and experimental results without inflow breaking.

The computations performed demonstrated the opportunity of mathematical modeling of the mixed external/internal flows in inlets. The results of the computations agreed with available experimental data. The joint analysis of computed and experimental results permitted the wave picture of complex flows with multiple shock waves and expansion fans/turbulent boundary layer Interactions to be constructed and its specific features to be explained.

The results obtained have allowed determining the main characteristics of the inlet, pressure distribution, and start conditions, and possible ways of modification of the inlet model. At the same time, the data made it possible to choose a fixed geometry and/or the bounds of inlet adjustment depending on the requirements for propulsion.

Based on the investigations performed it can be concluded that:

– the extra efforts are needed to increase the flow rate, especially at small Mach numbers up to M = 4;

– there is a significant influence of the subsonic diffuser on the flow structure in the inlet channel. The back facing step is not typical for a real inlet and has been produced by virtue of necessary cowl motion;

– application of the boundary layer bleeding in the inlet throat failed to provide considerable improvement of inlet characteristics.

Bleed of the boundary layer on the model forebody can be more effective at small Mach numbers.

The results obtained served as a basis for the choice of configurations and parameters for testing the inlet model in the hot-shot wind tunnel, including experiments with hydrogen combustion.

The adequacy of the results of experiments with the inlet model in the wind tunnels of two types: blow-down wind tunnel and hot-shot wind tunnel, has been proved.

Injection of air in the channel at the minimum angles of cowl installation did not cause channel choking when the injected airflow rate did not exceed 10% of the inlet flow rate. The efficient method of choking prevention was to change the injector row positions. This modification has been realized at Mach number of 8 in a constant-area channel.

Self-ignition and intense hydrogen burning was realized in the hot-shot wind tunnel when hydrogen was supplied from the top and bottom walls. It has been ascertained that channel choking occurred at such cowl installation angles which corresponded to the inlet self-starting if the fuel–air equivalence ratio was higher than 0.8. A proper increase of the cowl installation angle allowed realizing the combustion process in a divergent channel without flow choking

It has been found that the tests with long models in the wind tunnel with a conic nozzle did not provide correct quantitative results because of the strong effect of the lengthwise Mach number gradient, and hence of subsequent changes in the compression conditions and pressure distribution over the external compression surfaces. Investigations of this class models should be carried out in wind tunnels with profiled nozzles.

Investigations of the inlet with a new forebody configuration have demonstrated that the start was realizable at Mach number of 5 and 6 only without sidewalls. At the same time, the air flow rate in these tests was much lower than that predicted by the calculations. It can be assumed that the decreased flow rate resulted from:

– the effect of the thick boundary layer at the inlet channel entrance; and

– the inlet nonstart due to the high level of the inner compression.

These two reasons, combined or not, led to boundary layer separation and to a decrease in the effective open flow area. Because of this, some extra means were applied to control the boundary layer and flow rate growth.

According to the studies performed, the porous bleed was an effective procedure to achieve inlet start. With the use of this procedure, the inlet with sidewalls was started at all Mach numbers, the flow rate approached the designed value and the total pressure recovery coefficient was quite high. The porous bleed permitted more than twice as high increase of the airflow rate in the model with sidewalls to be achieved. It was also established that the downstream porous bleed was the most efficient.

The possibility of shock start was explored in the blow down-wind tunnel. The tests performed showed that, in spite of the evacuated inlet inner channel, the shock start could be realized only at a Mach number equal to 6. The characteristics obtained in the blow-down wind tunnel were identical to the data obtained in the hot-shot wind tunnel IT-302M. In the latter case, the shock start happenned naturally and simultaneously with the shock start of the wind tunnel.

The series of computations of the flows in inlets were carried out at M = 6, 7, and 8, for conditions corresponding to experimental runs performed in IT-302M. The fields of all the gasdynamics parameters have been obtained together with the pressure, skin friction and heat flux distributions over the channel walls. The results of computations were compared with experimental data showing satisfactory agreement. The influence of inlet geometry and Reynolds number on the flow parameters was studied.

Obtained Results

1. The model tests in hot-shot wind tunnel IT-302M were carried out at Mach numbers ranging from 5 to 8 within the range of Reynolds numbers from $5 \cdot 10^6$ to $30 \cdot 10^6$. Adequacy of the test results acquired in different wind tunnels was checked. Inlet start (nonstart) conditions, effectiveness of different methods of inlet control and feasibility of ignition and combustion in the channel when hydrogen was injected in it were ascertained.

2. The results of measurements performed in two types of the wind tunnels: blow-wind tunnel and hot-shot wind tunnel on the inlet model were proven to be adequate. Hydrogen self-ignited and burned intensively when injected at the bottom and top walls of the hot-shot wind tunnel.

3. The skin friction gauge was tested in the hot-shot wind tunnel at a total pressure of 100 bar and total temperature of 1500 K. The results of these tests were obtained at Reynolds numbers ranging from 10.6 up to 3.2 million. The data show the accordance between the calculation and experimental results without inflow breaking.

4. The computations performed demonstrated the opportunity of mathematical modeling of the mixed external/internal flows in inlets. The results of computations agreed with the available experimental data. The joint analysis of computed and experimental results permitted the wave picture of complex flows with interaction of multiple shock waves and expansion fans with the turbulent boundary layer to be constructed and its specific features to be explained.

Project Number:	**#0935**
Full and Short Title:	Problem Investigation of Onboard Measurement System of Hypersonic Flying Test Bed Intended to Attack Hypersonic Flight Problems **Onboard Measurements for Hypersonic Flights**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Basic research
Allocated Funding:	337,462 € (EU)
Commencement date:	(starting date) December 1, 1999
Duration:	24 months, extended by 3 months
Leading Institute:	Central Institute of Aviation Motors (CIAM) Moscow, Russia
Contact Information:	Phone: +7 (499) 7635747, +7 (495) 3624928; 3616481, fax: +7 (499) 7636110, e-mail: avim@ciam.ru, ved@ciam.ru, website: http://www.ciam.ru
Supporting Institutes:	Gromov Flight Research Institute, Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5565544; 5565607, fax: +7 (495) 5565334, website: http://www.lii.ru
Collaborators:	Aerospatiale, Les Mureaux, France (Laruelle G); European Space Agency, Noordwijk, The Netherlands
Project Manager:	SEMENOV Vjacheslav
Contact Information:	Phone: +7 (495) 3624950, fax: +7 (495) 2671354, e-mail: semenov@ciam.ru
ISTC Senior Project Manager:	RUDNEVA Valentina
Contact Information:	Phone: +7 (495) 9823206, fax: +7 (499) 9784637, e-mail: rudneva@istc.ru
ISTC Website:	http://www.istc.ru

Background

Hypersonic flight of a vehicle in the atmosphere is a complex physical process. The complexity is caused by high-enthalpy air flow around vehicle airframe with a complex structure of boundary layers, laminar–turbulent transition, interaction of shock waves, ionization of gas molecules, and recombination of atoms and radicals on the vehicle surface. These processes affect strongly hypersonic-vehicle stability and controllability, particularly, the heat shielding of airframe and engine. In view of it, as distinct from airplanes and missiles, onboard measurement system in a hypersonic flying vehicle is of primary significance.

As every flight of the hypersonic flying test bed is rather expensive and is still considered as a unique experiment, it is desirable to use high-precision transducers and measurement system units for obtaining the most reliable information on parameters measured on the Hypersonic Flying Test Bed (HFTB) board. However, a limited volume of the internal compartment in HFTB fuselage along with the severe effects of external factors accompanying the flight make problematic the use of standard high-precision measurement equipment. Therefore, exploration of the service conditions of measurement instrumentation in flight on board of HFTB, of the effect of external factors along the flight path, and of physical processes taking place in the flow around hypersonic flight laboratory (HFL) airframe in flight is a significant and important part of the Work Plan of the present Project. As a result of work, special requirements to be imposed on transducers and other measuring instruments that can be used on HFTB board were formulated.

The main results of experimental and computational investigations of hypersonic vehicle flight along trajectory as well as the processes in the flow around the airframe and heating of critical structure elements permitted parameters and positions of measurements points which furnished maximal information on real physical processes to be determined.

Analysis of the domains in which various types of hypersonic flying vehicles can be applied has shown that though various types of hypersonic flying vehicles are at present being developed in USA, Japan, and Germany, the development of an unmanned hypersonic flying vehicle with fuselage shorter than 10 m in length and mass of about 2 t delivered to a prescribed trajectory point by a rocket booster is the most expedient way of obtaining required scientific information at minimal costs. In the investigations planned within the Project, a HFL "ARES" (Figs. 22 to 24) developed by EADS LV with mass and dimension parameters close to those mentioned above was chosen as a HFTB prototype.

Project Objectives

The objective of the Project was to develop an optimal scheme of HFTB onboard measurement system for solving hypersonic flight problems.

Fig. 22: Original geometry of "ARES" hypersonic flight laboratory

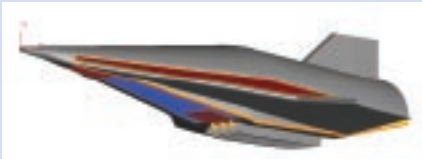


Fig. 23: Modified geometry of "ARES" hypersonic flight laboratory (side view)

Fig. 24: Modified geometry of "ARES" HFL (bottom view)

Description of the Work

Within the framework of the Project, computational investigations of the aerodynamic flow over HFTB airframe and laminar–turbulent transition in the boundary layer at hypersonic flight were conducted with the aim of determining the optimal positions and number of gauges measuring pressure and temperature on the fuselage; performing the comparative analysis of the possibility to use gauges of loads, pressure, and temperature of various design for the HFTB onboard measuring system at real flight conditions; developing technique and instrumentation for measuring real thrust of an engine similar to a scramjet integrated with airframe; and developing special tools for monitoring the combustion efficiency in the engine (Figs. 25 and 26).

Several types of measurements included in the HFTB onboard system were studied. They permitted the following conclusions to be drawn:

– HFL "ARES" flight trajectory parameters were found to be measured most expediently with the use of at least two independent methods: radar measurements using ground facilities and measurements with the use of satellite navigation systems "GLONASS" and "NAVSTAR." In addition, it was found to be expedient to measure some parameters, for example, flight velocity, acceleration,

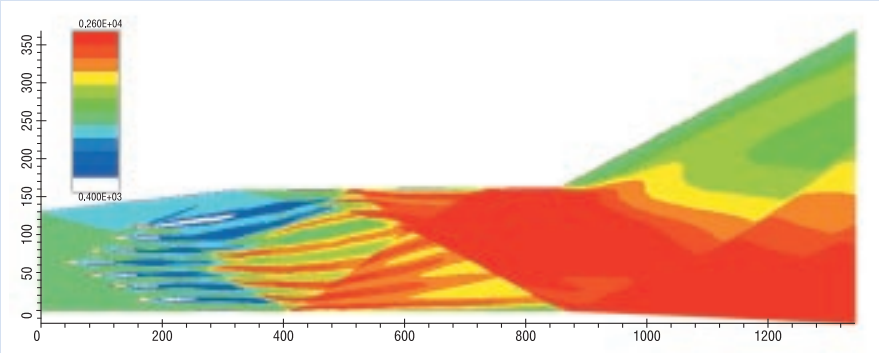


Fig. 25: Predicted static temperature field (in K) for "ARES" scramjet in a hypersonic flight

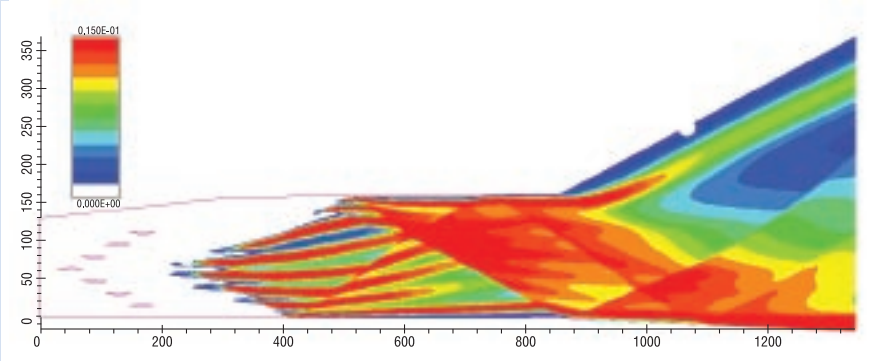


Fig. 26: Predicted OH mass fraction field for "ARES" scramjet in a hypersonic flight

angle of attack, and slide angle of HFL by gasdynamic techniques and with an inertial flight control system. The interrelated analysis of the results of all trajectory measurements allowed the measurement accuracy of 1% for flight velocity, 1.5% for flight altitude, and 2% for airframe situation angles to be achieved;

– gasdynamic measurements of flow parameters around the HFL airframe is fairly well developed in terms of available instruments. An ample number of pressure transducers manufactured by several companies are available that differ in cost, construction, measurement accuracy, and operation principle. Therefore, the main efforts in the development of an onboard system of gasdynamic measurements should be focused on determining measurement point positions on the airframe surface based on the computational results for pressure distribution over the airframe surface in a hypersonic flow, shock wave interactions, and boundary layer structure. Measurement accuracy of available transducers can change in a wide range from 0.1% to 3%; the cost of transducers can also vary appreciably. High-accuracy (and high cost) sensors are to be used for pressure measurements in the flight control system or for exploring physical processes under investigation. In addition, it was found to be expedient to range and duplicate pressure transducers to increase measurement accuracy;

– temperature distributions in structural units subjected to thermal loads and hypersonic vehicle heat shielding are worth to be measured concurrently applying several methods. Standard thermocouples made from different materials for corresponding temperature ranges are used most widely. The errors of temperature measurements with standard thermocouples usually do not exceed 0.8% of the upper limit. To measure the heat shielding temperature, it was found to be expedient to use crystalline transducers, temperature indicators of melting and thermally sensitive paints. These sensors are most efficient for the conditions of vehicle landing on the ground in the absence of water. Currently available crystalline transducers and temperature indicators with a very narrow temperature range for the transformation reaction possess quite high accuracy of temperature measurements with an error of about 1%;

– measurements of loads on rudders with the use of resistive-strain sensors pasted on force-transmitting elements of constructions are usually carried out individually for every kind of a force-transmitting device. Thus, the methods of sensor calibration and estimations of measurement errors have to be developed for any specific case. Authors' estimations showed that measurement error could attain at least 2% or 3%;

– measurements of hypersonic vehicle propulsion performance can be performed using both direct and indirect methods. Direct measurements of loads provide high accuracy on the level of 0.5%. However, in order to install standard transducers for load measurements, significant complications in terms of engine mounting on the airframe system are required. To obviate this difficulty, it is necessary to develop a fundamentally new design of load measurement transducers which could be compatible with the system of engine fastening to fuselage or could be one of the units of this system; and

– special techniques for measurements of specific parameters inherent in hypersonic flows were developed on the basis of the experience with "Bor" and "Kholod" HFL flights. Among them are the measurements of gas friction on the airframe surface, gas ionization degree in the boundary layer, heat fluxes into heat shielding, pressure pulsations on airframe surface, etc. These measurements are well justified as they are needed for theoretical and computational analyses of physical processes inherent in hypersonic flight. Nevertheless, the design of transducers must be properly modified to be used aboard of any particular vehicle.

Obtained Results

The following results were obtained in the course of project implementation:

• at present, the required set of transducers for measuring all main parameters inherent in "ARES"-type hypersonic vehicle flight is available;

• it is necessary to make a provision for mounting various transducers of an onboard measurement system at the earliest stages of vehicle design;

• despite the possibility of using transducers of different types in the onboard measurement system has been shown, the practical application of transducers calls for special investigations aimed at design refining;

• to acquire the planned measurement information, the onboard measurement system must involve at least 650 transducers, among them:

Pressure transducers	175
Thermocouples	200
Thermistors	30
Crystal thermometer probes	100
Pressure pulsation transducers	20
Transducers of motion acceleration	20
Transducers of angular rotation velocities	10
Vibration transducers	10
Transducers for special measurements	70

– The main aspects of construction of the onboard measurement system were ascertained.

– The values of flow parameters on the hypersonic vehicle surface and the parameters of ambient atmosphere (with fluctuations taken into account) under flight conditions were estimated.

– Calibration tests of special tools for measurements of hypersonic flight parameters were accomplished.

– Telemetry systems for transmitting and receiving measured parameters under hypersonic flight conditions were considered.

– The testing programs of onboard measurement system channels were formulated.

– The values of power potential needed for radio signal transmitting links and coverage areas by ground stations along the hypersonic vehicle flight route ensuring required noise immunity and minimum errors of data channels were estimated.

– A system of onboard measurements in a hypersonic vehicle of "ARES" type with positioning of the measurement points on the vehicle airframe and in flow passage of propulsion unit was developed.

Number:	**#1978**
Full and Short Title:	Development of a Complex Technique for Testing Highly-Economical Civil Aircraft in Transonic Wind Tunnels with Slotted Walls **Civil Aircraft Testing Technique**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	330,000 € (EU)
Commencement date:	(starting date) July 1, 2001
Duration:	24 months, extended by 3 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	European Transonic Windtunnel, Koln, Germany (Quest J)
Project Manager:	BOSNYAKOV Sergey
Contact Information:	Phone: +7 (495) 5563587; 5564323; 5563786, fax: +7 (495) 7776332, e-mail: bosn@progtech.ru
ISTC Senior Project Manager:	KULIKOV Gennady
Contact Information:	Phone: +7 (495) 9823154, fax: +7 (499) 9784637, e-mail: kulikov@istc.ru
ISTC Website:	http://www.istc.ru

Background

This study deals with cryogenic tests in the European Transonic Wind tunnel (ETW). It was supposed to summarize the present experience and to create a linear calculation method that could take into account slotted boundary conditions in direct accordance with ETW geometrical parameters. Special experimental and computational studies and literature reviews were supposed to be performed for the formulation of slotted boundary conditions.

The essential direction of investigations was to formulate the “smooth” slotted boundary conditions and to present it in linear approximation. These conditions were the key for developing the linear method. A computer code realizing the nonlinear method for direct fitting the shape of slots with “plenum chamber” had to be developed. This code was referred to as “sharp fitting” procedure.

Project Objectives

The objective of the project was to summarize the previous experience and to develop on its basis a universal technique for correcting experimental data.

Description of the Work

The mathematical model of transonic wind tunnel (TWT) was based on the second-order approximation and monotonic numerical method for solution of full Euler equation system developed by S. Godunov, V. Kolgan, and A. Rodionov. Solutions were obtained using multiblock computational grids adapted to a TWT test section (including slots) and to a tested model. Model geometry corresponded to a tested original and was imitated most precisely.

The computer code allowed the flow around a model to be calculated in two cases: (*i*) in the presence of slotted walls, and (*ii*) in free-stream conditions. Comparison of the computational results for both flow configurations in a control section made it possible to determine additional blockage and additional upwash caused by the presence of the model in a wind tunnel. These values were used for correcting experimental data.

All geometrical objects in the "Computational" wind tunnel were divided into compartments including aircraft model parts, wind tunnel walls, sting, etc. (Fig. 27).

All tested surfaces were covered by the surface grid. The numerical method required generation of the structured computational grid comprising hexahedron cells. The faces of neighboring cells should coincide with each other. Grid lines (lines formed by cell edges) had to be continuous and begin on the boundaries of the computational domain. It was found that the best grid lines were those which satisfied the smoothness condition. As a rule, the computational domain of the wind tunnel had a complex topology which could not be represented by analytical formulae. To gain the best approximation of boundary conditions, the computational domain was split into

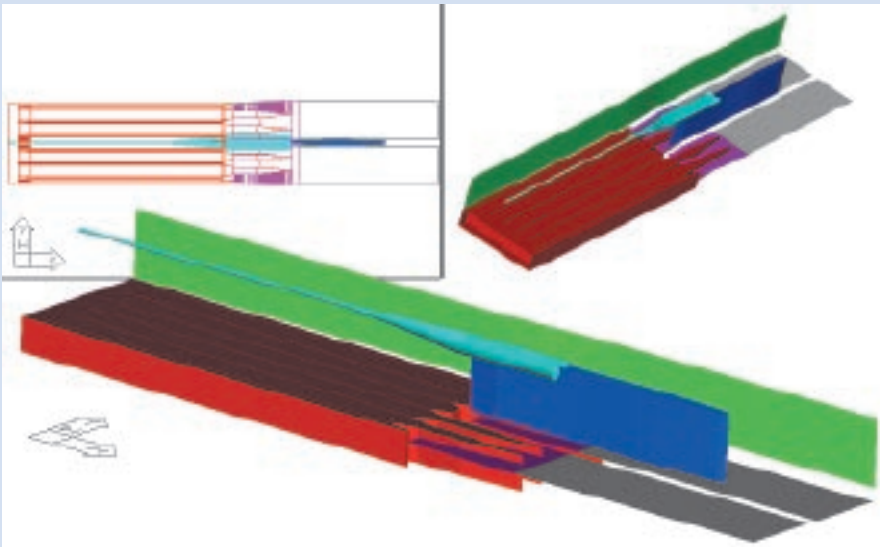


Fig. 27: Compartments in the "Computational" wind tunnel model

subdomains (blocks) and, as a result, a multiblock computational grid was generated (Fig. 28).

Based on the data provided by ETW, a computational grid of the ETW test section geometry has been developed. The ETW test section was assumed to be symmetrical with respect to vertical and horizontal planes passing through the ETW longitudinal axis. Therefore, the computational grid contained only lower quarters of the following elements: Bottom Wall, Center Body, Centerline Probe, Reentry Flap, Horizontal Wall, Side Wall, Plate, Partitions, and Plenum chamber (Fig. 29).

The approach used for simulating the flow in the ETW test section was as follows: The flow was calculated on the basis of Euler equations; however, the geometry of the test section (including slotted walls) was corrected by the displacement thickness of the boundary layer. As a matter of fact, the equivalent-length method proposed by Prof. E. Repick, was used.

The first series of ETW flow calculations implied closed slots. The main goal of these calculations was to test the capabilities of the Basic Approach (Euler calculations with boundary-layer corrections of geometry) to predict the characteristics of this simplest flow in the ETW.

The second series of ETW flow calculations was implied open slots. The geometry of slots, reentry flaps, short axial probe, and sting was reproduced as accurately as possible.

The analysis of the results showed that flow unsteadiness always existed in the case with open slots. The prolonged calculations showed that flow oscillations were periodic. Thus, in this case, the numerical solutions were time-averaged. Time-averaged pressure distributions on the ETW walls were in a good agreement with available experimental data.

The parametrical calculations of the ETW test section with an aircraft model were performed. The geometry of the model was provided by AIRBUS-UK. The model was

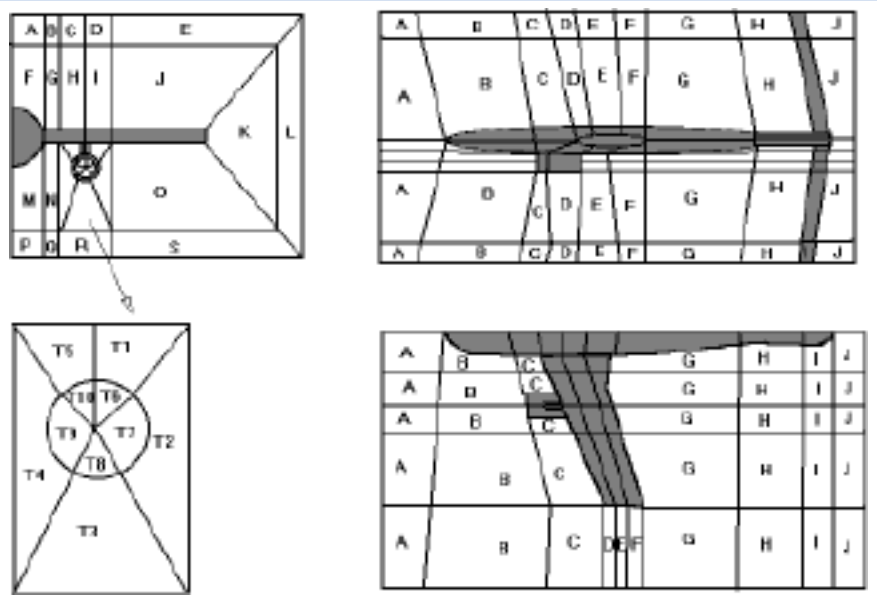


Fig. 28: Multiblock computational grid

mounted on a cylindrical sting with a conical part. For each flow regime, Euler calculations were performed for a flow in the EWT and for a free flow. The comparison of the results obtained allowed the influence of ETW walls on the flow around the model to be estimated.

For subsonic flows, the differences between the flow around an isolated model and the flow in the ETW test section were distributed allover the wing surface. For flow regimes with supersonic zones, significant shock "smoothing" in the time-averaged solution was the most important difference.

Concurrently, within the framework of Project #1978, a possibility of simulating the flow in slotted ETW walls in Navier-Stokes calculations with a differential model of turbulence were investigated. A computer code was developed and tested. Preliminary calculations of a single-slot flow were performed.

The computational grid included detailed geometry of a single slot, with reentry region (including the reentry flap inclined at a needed angle), with the exact depth and cross-section contour of the slot duct, and with an additional bottom panel below the slot duct (Fig. 30).

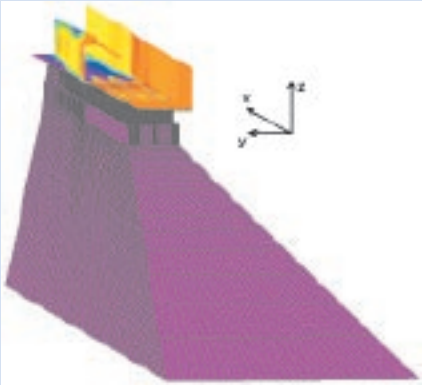


Fig. 29: The computational grid of the European Transonic Wind tunnel

As the basic experimental part of the work, experiments in TsAGI wind tunnel T-125 simulating a flow in the ETW were planned within the ISTC Project #1978. Before starting the work, at the stage of searching for an appropriate wind tunnel, a general approach to solve the problem experimentally was developed and the main simulation criteria were formulated. It was obvious from the outset that flow regimes in ETW cannot be simulated completely because of extremely high Reynolds numbers of cryogenic flow. Therefore, this problem was not assigned. The similarity parameters used in experiments resulted mainly from the previous experience and from the analysis of the literature on slotted boundaries.

Wind tunnel T-125 at TsAGI is a continuously operating setup utilizing bottled gas. It was developed as a wind tunnel of low turbulence. Its compression ratio exceeds 20 and it is equipped with deturbulizing grids and noise-suppression systems. The first test section is intended for smooth nozzle inserts providing

Fig. 30: Computational grid for a single-slot tunnel configuration

subsonic regimes and supersonic regimes of up to M = 4.0 with a 0.5 discontinuity. The second test section has perforated and slotted subsonic inserts. The total prechamber pressure can be varied in a wide range (from $2 \cdot 10^4$ to $4 \cdot 10^5$ Pa) at appropriately constant total temperature (about 270 K). Wind tunnel T-125 is equipped with optical glasses for visualizing the model by photo and video shooting.

The test section of T-125 was modified. A new bottom subsonic insert simulating a half of ETW bottom wall was fabricated and mounted without changing a smooth upper subsonic insert. The test section height, length, and width were 180, 1500, and 200 mm, respectively. Thus, only a quarter of the ETW section could be simulated; therefore, the arising asymmetry with respect to the tunnel axis was not important. In the region of the first optical window, two types of models could be mounted, namely, 2D wing profiles and half-models. These models were mounted on a α-mechanism with hand drive. Figure 31 shows three slots on the bottom wall in plane.

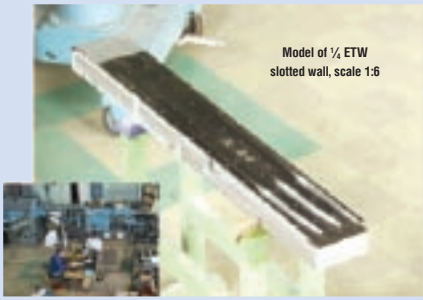


Fig. 31: Modified test section of T-125 wind tunnel at TsAGI

The geometry of these slots corresponded to slots in the ETW.

For more correct interpretation of the results obtained in T-125 tests and for more accurate simulation of the flow with the use of modern numerical methods, it was necessary to get information on nonstationary characteristics of the wind-tunnel flow. Because investigations of pulse flow characteristics in the wind tunnel were beyond the scope of the project, it was decided to use available wind tunnel data.

The test program implied investigation of flow fields both with and without a model. In both cases, it was supposed to perform detailed pressure measurements along the longitudinal generatrixes of walls and in the cross sections of slots. The results of these measurements were supplemented with data on the near-wall boundary layer.

Electronic scanners with multichannel pressure modules applied in T-125 served as a recording system. Pressure at different locations was measured with differential Kistler type probes. The most important part of the program was scanning the flow fields near the slots with the use of combined microprobes.

The most interesting flow zones were visualized with the use of color oils and silk thread. The visualization results were extracted from the photos and videotape and subjected to subsequentdecoding and interpretation.

Obtained Results

- Development of a “Computational ETW wind tunnel” software code for a PC.
- Development of linear methodology for taking into account the influence of slotted wind tunnel walls on experimental results.

Project Number:	**#2050**
Full and Short Title:	Theoretical and numerical investigations of active/passiveconcepts to demonstrate the impacts from aeroelasticity on the improvement of aircraft performance **Active Air-elasticity**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	175,000 € (EU)
Commencement date:	(starting date) April 1, 2002
Duration:	36 months, extended by 12 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 556 43 37, website: http://www.tsagi.ru
Supporting Institutes:	No
Collaborators:	Airbus Deutschland GmbH, Munich, Germany (Schweiger J); Deutsches Zentrum fur Luft- und Raumfahrt e.V., Institut fur Aeroelastik, Gottingen, Germany (Honlinger H)
Project Manager:	KUZMINA Svetlana
Contact Information:	Phone: +7 (495) 5563216, fax: +7 (495) 7776332, e-mail: kuzmina@tsagi.ru
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: Ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

Aeroelasticity implies the behavior of an elastic body or vehicle in airflow wherein there is significant interaction or feedback between structure deformation and flow (Fig. 32). Aeroelasticity plays a crucial role both in the design of modern aerospace vehicles and in design of such civil objects as bridges or tall buildings.

On the one hand, in terms of aeroelasticity, airplanes suffer from aeroelastic degradation of aerodynamic performance; aeroelastic degradation of longitudinal and lateral stability and maneuverability; adverse coupling effects between a flexible structure and a flight control system; increased static and dynamic loads; and aeroelastic instabilities.

"Aeroelastic weight penalty" is therefore a frequently used expression in aeronautical engineering.

On the other hand, structural elasticity sometimes can produce a positive effect on flight performance, e. g., reduce the root bending moment at a swept wing. Such favorable effects can be achieved when special measures are undertaken in construction design to control elastic deformations. The project was aimed at exploiting such effects to solve aeromechanical problems based on the "passive and active aeroelasticity" concept. The essence of the "active and passive" concept was to reduce structure weight with keeping aircraft safety with respect to flutter, controls reversal, divergence, strength, as well as to improve design performance with the aid of favorable deformations.

Project Objectives

The main Project objective was to develop recommendations aimed at improving flight performance, economy, and efficiency of aircraft by exploiting the concept of "active and passive aeroelasticity," including:

- improving characteristics of static aeroelasticity;
- increasing lift-to-drag ratio by means of changing elastic deformations in flight;
- providing favorable redistribution of aerodynamic loads; and
- improving characteristics of dynamic aeroelasticity, particularly to increase flutter speed.

The main expected result was recommendation on how to reduce the lifting surface weight by 5%–15% and tail lifting surface area by 10%–20%.

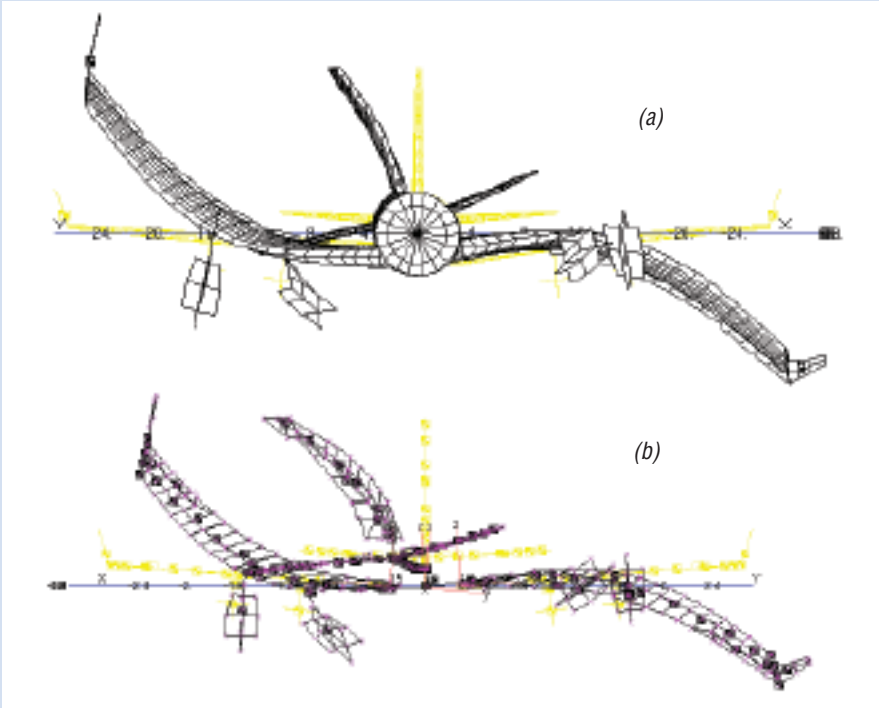


Fig. 32 Comparison of the second elastic vibration shape for FS airplane (a) and wind-tunnel model (b)

Description of the Work

The following four tasks were included in the Work Plan:

A. Selection of the baseline configuration of a civil aircraft and its aeroelastic analysis.

B. Investigation of an "active and passive aeroelasticity" concept to improve aircraft performance.

C. Assessment of the parameters of elastically scaled and dynamically scaled models of an aircraft to demonstrate the effectiveness of the "active and passive aeroelasticity" concept in wind tunnels. Elaboration of recommendations to improve flight performance.

D. Development of an active control system to enhance the dynamic characteristics of aircraft.

The baseline configuration has been selected in agreement with collaborators. The results of analysis were compared with those obtained by collaborators. The means to realize the "active and passive aeroelasticity" concept have been investigated on the selected baseline configuration (EuRAM). The effects to be demonstrated in wind tunnel tests were selected based on the solution of Task B. The results of solution of Task C were transferred to collaborators for manufacturing a EuRAM model and performing experimental studies within European Project 3AS (EU FP 5), Figs. 33 and 34. The theoretical and experimental results obtained were used for further validation of the concept. The recommendations on application of the aeroelasticity effects in aircraft design were among the major results. Additional task D was planned in order to develop an active control system to enhance airplane dynamic characteristics. Preliminary recommendations were refined.

Obtained Results

1. The weight of wing construction panels with nontraditional tip aileron can be reduced by 4% taking into account the stress and aeroelasticity constraints and providing the required roll aileron effectiveness when the area of the wing-tip lifting surface is 30% of the regular aileron area.

2. Reduction of the vertical tail lifting surface by 35% for the required rotation stiffness allows the acceptable flight dynamics characteristics to be attained in all operational regimes.

3. Roll effectiveness has been increased when using additional wing tip and out-of-plane ailerons, which are most efficient at the maximum flow velocity. In this case, the roll effectiveness can be increased by a factor of two when the area of the wing tip aileron is 2% of the wing area.

4. Wing tip and out-of-plane ailerons can be used for active alleviation of dynamic loads (bending moments) caused by a single discrete air gust. A simple control law was derived that provided a 10-15 percent reduction of the bending-moment maximum in the wing root under discrete sinusoidal air gust.

The use of selective deformable structures in fabrication of an adaptive inner aileron allowed the lift-to-drag ratio coefficients of the compartment for adaptive aileron to be increased by approximately 15% with respect to a conventional aileron.

Fig. 33: Design of an adaptive aileron

Fig. 34: EuRAM model in wind tunnel T-104

Number:	**#2633**
Full and Short Title:	Investigation and Development of New Methods of Flow Control for Modern Passenger Aircraft Aerodynamics Improvement **Flow Control for Modern Passenger Aircraft**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project underway
Technology Development Phase:	Basic and Applied Reserach
Allocated Funding:	EU: 152,010 €, Other Funding Sources: $68,245
Commencement date:	(starting date) May 1, 2007
Duration:	24 months, extended by 6 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	AIRBUS Industrie, Blagnac, France (Hinsinger R)
Project Manager:	KOGAN Mikhail
Contact Information:	Phone: +7 (495) 5564006, fax: +7 (495) 7776332, e-mail: mkogan@aerocentr.msk.su
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

Progress in modern aircraft design depends to a considerable extent on new methods for flow control. In view of it, one has to know flow receptivity to different governing natural and artificial influences. Nowadays, various flow control methods are known and used (geometry optimization, boundary layer suction, blowing/jets, etc.). Nevertheless, further progress in commercial efficiency, safety, and ecology of aviation calls for the development of new flow control methods.

Project Objectives

The objective of the project was to study mainly theoretically several new flow control methods and to estimate their aerodynamic efficiency.

Description of the Work

In the main part, the project dealt with control of laminar–turbulent transition in a boundary layer, the phenomenon known to be very complex. Novel approaches to control

turbulent boundary layers and boundary layer – shock wave interaction on a transonic airfoil were considered as well. To elaborate the novel control methods, it was intended to refine physical and mathematical models of some flow configurations, to develop relevant computational methods, and to carry out appropriate parametric studies.

The project was considered as continuation of investigations within the ISTC project #199-95 dedicated to civil aircraft drag reduction enabling decrease in fuel consumption.

Boundary layer receptivity to free-stream vortical disturbances (natural and wind tunnel) for straight and swept wing: Receptivity control

Investigations included the study of interaction of steady vorticity normal to the leading edge of straight and swept wings with a boundary layer. The flow outside the boundary layer was determined using the rapid distortion theory. Evolution of disturbances in the boundary layer was studied by the PSE-method. Generation of cross-flow instability modes due to steady-flow nonuniformity/swept wing interaction was studied as well. The knowledge of the receptivity mechanisms obtained was employed to elaborate transition delay methods.

Control of cross-flow dominated transition

Cross-flow instability is one of important factors controlling laminar–turbulent transition in the boundary layer at swept wings of modern transport aircrafts. Boundary layer suction is the most thoroughly investigated technique applied for transition delay. However, there are still many issues to be addressed before its efficient practical use. This is the reason why elaboration of new alternative methods of cross-flow dominated transition delay is an urgent task. This part of the project was devoted to theoretical development of such an alternative technique based on introduction of artificial disturbances in the boundary layer. Under natural conditions, laminar–turbulent transition is triggered by a steady cross-flow instability mode. This mode will be referred to as the basic mode. The investigations were aimed at demonstration of basic mode growth suppression by means of generation of other cross-flow instability modes. The artificial disturbances should change the basic flow properties in such a way as to prevent the basic mode growth. Artificial disturbances themselves should be chosen so that their growth levels off and does not result in transition. It was proposed to study both steady and nonsteady artificial disturbances (produced by MEMS). The parameters of artificial disturbances (amplitude, frequency, and spanwise period) providing the best suppression of the basic mode growth were chosen in the course of theoretical studies of interactions between different cross-flow instability modes. Direct numerical simulation (DNS) and nonlinear PSE codes were used in these studies. The efficiency of the suggested methods of transition delay by the artificial disturbances was assessed.

Semiactive control of laminar–turbulent transition in three-dimensional compressible boundary layer

This part of the project was devoted to theoretical investigation of laminarization of boundary layer on a swept wing using a steady artificial irregularity (semiactive control). Laminar–turbulent transition was assumed to be caused by free-stream disturbances (sound or flow vorticity) or roughness of the wing surface. The general idea of the laminarization method was to attain mutual cancellation of unstable modes excited by external disturbances in the vicinity of the leading wing edge and over artificial irregularity of the wing surface. This cancellation becomes possible because of the special choice of the irregularity location and amplitude (in order to achieve opposite phases of the incoming and artificial instabilities). As these two modes are excited by the same external disturbance, the adjustment of irregularity parameters is independent of the disturbance amplitude and phase.

Thus, the physical mechanisms of the method consist in total receptivity relaxation.

Various types of artificial (MEMS) irregularities were considered. The optimum type and the longitudinal shape of the irregularity were found capable of preventing the generation of 'by-pass' transition immediately over the controlling MEMS irregularity.

Investigation of thermal transpiration phenomenon

Thermal transpiration method is based on the thermal slip effect: slip velocity arises along the surface whenever a tangential gradient on it exists. If a surface is the inner surface of a pore in a porous membrane, then the gas flow arises once a temperature difference is imposed across the membrane. The important feature of this flow control method is high uniformity of flow rate through membrane, which results from the small pore diameter in the membrane. The mathematical model of a gas flow in such small channels and porous membrane was based on the kinetic theory of gases (Boltzmann equation). Numerical investigation of the flow through a porous medium with the help of the kinetic approach was carried out by the direct simulation Monte-Carlo method (DSMC) and other Monte-Carlo methods. Asymptotic limiting flow regime in a porous medium and flow in connecting channels was investigated using Navier-Stokes equations.

The numerical and analytical results permitted the optimal values of the flow rate, temperature, geometrical and other parameters of a thermomolecular (Knudsen) pump to be determined and the energy efficiency of the thermal-transpiration boundary-layer control method with conjugated heat and mass transfer processes to be estimated.

Flow control by electrogasdynamic methods

Different electrogasdynamic (EGD) methods were investigated to assess a possibility of both laminar and turbulent boundary layer flow control. Influence of direct current (DC) plasma actuators on evolution of Tollmien-Schlichting disturbances in a laminar boundary layer on a flat plate was studied. The boundary value problem modeling effect of spatially-periodic bulk force generated by plasma actuators on cross-flow type disturbances in a boundary layer on an infinite span swept wing was formulated and solved. The efficiency of the EGD methods for laminar–turbulent transition delay was assessed.

A physical model of plasma actuators based on a dielectric barrier discharge (DBD) and operating in air flows as well as appropriate computer codes were developed. Using these codes, an impact of DBD plasma actuators on laminar and turbulent boundary layers was studied.

A qualitative theoretical estimation of DC plasma actuator influence on a turbulent boundary layer is expected to be obtained. A model for turbulent skin friction involving consideration of quasi-streamwise vortices in the cross-stream plane will be developed to study the effect on the skin friction of EGD-interaction generated by the DC plasma actuator.

The efficiency of such flow control as EGD-forcing, caused by local heating and bulk force additions, and relaxation processes, on shock wave/boundary layer interaction in transonic flows will be studied based on solution of time-dependent Reynolds averaged Navier-Stokes equations (URANS-method) with the use of the popular two-equation SST model of turbulence.

Obtained and Expected Results

Several new methods of boundary layer control were investigated and their efficiency for drag reduction and buffet onset delay was assessed. The most effective and beneficial methods will be chosen and recommended for subsequent experimental verification and refinement. The positive results will promote fuel consumption reduction and increase of flight safety in passenger aviation.

Project Number:	**#3085**
Full and Short Title:	Investigation of Steady and Unsteady Phenomena in Transonic Wind Tunnels with Slotted Walls to Improve a Complex Technique for Testing Highly-Economical Civil Aircrafts **Civil Aircraft Testing**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research/Technology development
Allocated Funding:	240,000 € (EU)
Commencement date:	(starting date) March 3, 2005
Duration:	24 months, extended by 3 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	Aerospatiale Airbus, Toulouse, France (Collercandy R); European Transonic Windtunnel, Koln, Germany (Quest J)
Project Manager:	BOSNYAKOV Sergey
Contact Information:	Phone: +7 (495) 5563587; 5564323; 5563786, fax: +7 (495) 7776332, e-mail: bosn@progtech.ru
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

This Project is the direct continuation of the study performed within the ISTC Project #1978. It was concluded at the final workshop on the Project #1978 that the Computational Fluid Dynamics (CFD) model of European Transonic Wind tunnel (ETW) based on Euler equations could be used for correcting experimental data. A new approach for simulating flows in ETW and T-128 (working part No.3) has been proposed within the present Project. The new approach allows stationary and nonstationary phenomena in the aforesaid wind tunnels to be investigated with taking into account the effects of viscosity and turbulence. For this purpose, it was necessary to develop a CFD code based on Reynolds-averaged Navier-Stokes equations (RANS). A preliminary version of this code was presented as complimentary to the ISTC Project #1978. Verification of this code against

experimental data confirmed the reliability of the method suggested. It was also proposed to apply the method for correcting the experimental data obtained in the course of civil-aircraft model testing in transonic wind tunnels with slotted walls. The method developed within Project #1978 was based on a linear computer code permitting one to correct the experimental results obtained in model tests by taking into account the influence of wind tunnel walls. It applied "distributed" boundary conditions. These boundary conditions were formulated on the basis of experimental data. It was proposed to increase the range of linear technology implementation up to transonic Mach numbers (M ~ 0.85). This investigation was closely related and consistent with requirements of ETW in Cologne and T-128 in TsAGI.

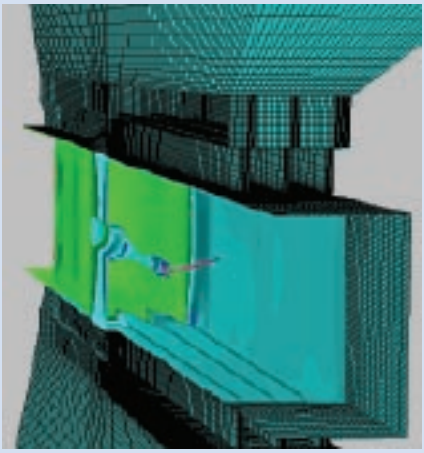


Fig. 35: CFD model of ETW based on Navier–Stokes equations

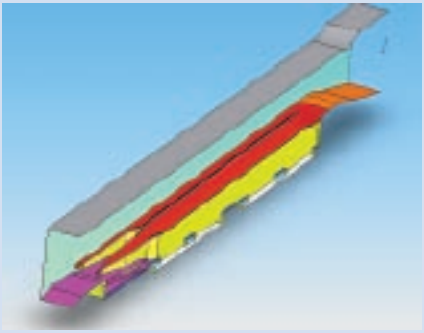


Fig. 36: Fine structure of slots in the CFD model of ETW

Project Objectives

The objective of the Project was to develop and verify the universal technique for calculating stationary and nonstationary phenomena in a wind tunnel (WT) with slotted walls permitting the improvement of a Complex Technique for Testing Civil Aircrafts in wind tunnels.

Description of the Work

To achieve the Project objective, three mutually connected problems were solved:

(1) Reynolds-averaged Navier-Stokes equation system (closed by differential models of turbulence) was solved and Large Eddy Simulation (LES) approach was used (Figs. 35 to 37);

(2) the approach suggested was verified and the range of subsonic and transonic regimes where the linear method (called "estimation of the influence of slotted boundaries on the flow around models in wind tunnels") could be applied was extended (Figs. 38 to 40);

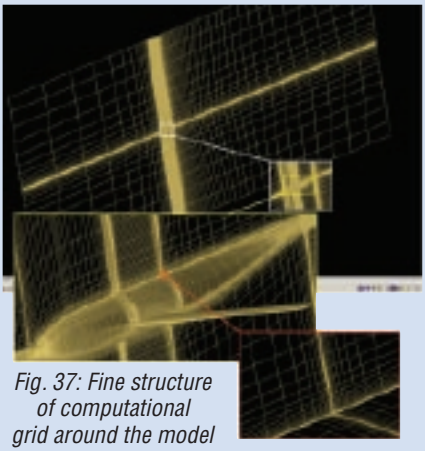
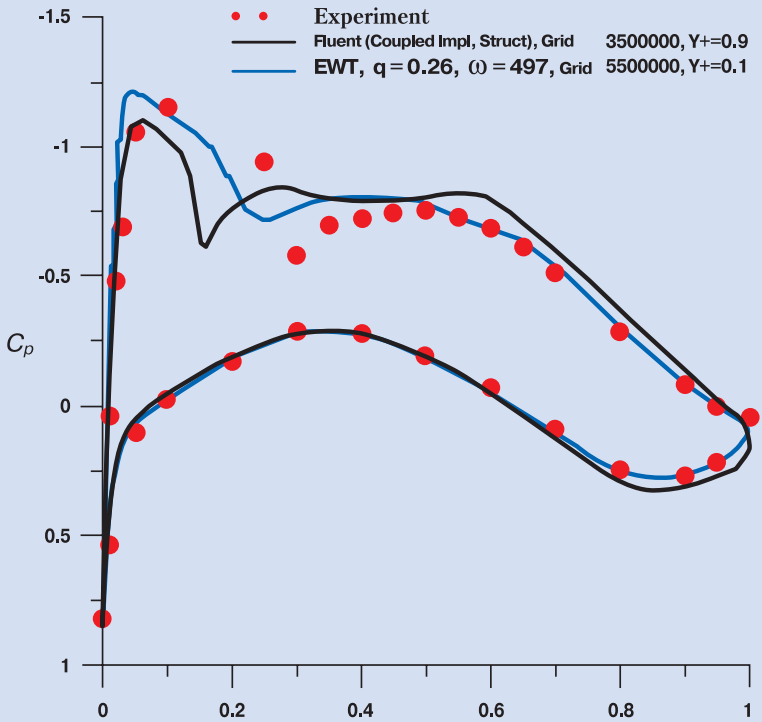


Fig. 37: Fine structure of computational grid around the model



M = 0.75, C_y = 0.5, P_0 = 190470, T_0 = 336.64, z = 0.514

Fig. 38: Comparison of computational results with experimental data

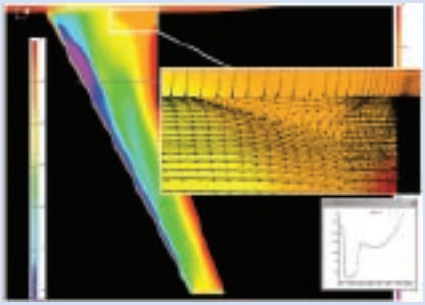


Fig. 39: Prediction of a separation zone

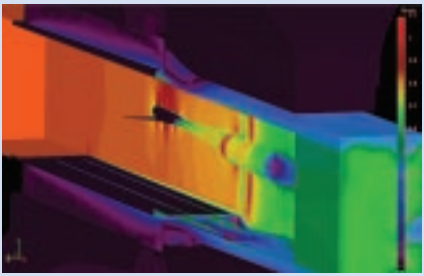


Fig. 40: Predicted filed of flow Mach number in EWT

(3) numerical and experimental investigations of nonstationary flows were performed for an isolated slot representing a copy of the appropriate element in ETW wall.

The objective of experiments was to investigate fine features of nonstationary slot flows. The task formulation was simplified due to the fact that the experimental model already existed: it was designed and manufactured during implementation of Project #1978. It was proposed to modify this model by installing additional tools for investigating unsteady phenomena in the slots. It was also planned to modify the model for additional optical observations. Measurements of nonstationary flow parameters were performed using small-size fluctuation gauges and thermoanemometers.

The main component of the proposed numerical methodology was a special algorithm of computational grid generation with fitting of various geometry features (both of wind tunnel and aircraft model) referred below as to the "sharp-fitting" approach. In calculations, all main geometry elements were taken into account, namely, test section of wind tunnel, plenum chamber, slots in the walls, reentry flap, sting, model, etc. The computational grids were compressed towards the surfaces of all investigated bodies to allow for computation of the near-wall viscid flow (boundary layer). As a basic numerical approach, the point-implicit monotonic numerical method of 2nd approximation order was used. To accelerate calculations, the method of fractional timesteps was developed. This method ensured the correct description of nonstationary processes. In the framework of this approach, one global timestep (the same for all computational cells) was divided into many local timesteps (with different number of local timesteps in different cells). The number of local timesteps in a particular cell depended upon the local stability condition. This method can be realized using multiprocessor computers. It was proposed to compose a cluster from Pentium computers and to develop a new code on the basis of the MPI technology.

The CFD code was verified using a four-step procedure. At Step 1, solutions at different grids were compared. At Step 2, an idea that the solution of the same task provided by different codes must be the same was verified. At Step 3, the numerical solution convergence to a known theoretical solution (e. g., asymptotic solution) was investigated. At Step 4, consistency of the CFD solution with experimental data was verified. Verification answered two types of questions: (*i*) Are there mistakes in the code? (*ii*) Do the mathematical models (for example, turbulence model) comply with the requirements to the flows under study?

The presence of an aircraft model in the wind tunnel gave rise to the following main effects: (*i*) variation of flow Mach number at a reference point in the wind tunnel and in the vicinity of the model (blockage); and (*ii*) variation of the effective angle of attack (additional upwash). The computational data were used to estimate these effects. Experimental data were corrected with the use of the estimates and were recalculated to "free-stream conditions." Nonstationary effects arising around slotted walls were investigated as well.

The main steps in the work can be formulated as follows:

- development of a RANS CFD code taking into account the real geometry of ETW and T-128 wind tunnels;
- experimental study of nonstationary flow characteristics near the slotted walls;
- ascertaining of applicability limits of the linear method at high subsonic velocities by comparing its results with the CFD data obtained with the RANS code;
- using CFD code for correction of the experimental data for free-stream conditions.

The ETW mathematical model was based on the numerical method for solving a full system of Reynolds equations closed by the differential model of turbulence. This method was developed within the framework of the present Project. This method had a second order of approximation and was monotonic. The solution was obtained using a multiblock

computational grid adapted to a WT test section with slots. The model geometry was simulated with the maximal accuracy and corresponded to the original tested. The effect of slotted walls was simulated by means of exact formulation of boundary conditions.

The methodology described above made it possible to calculate flowfields around an aircraft model in two cases: (*i*) with slotted walls, and (*ii*) in free flow. Direct comparison of the numerical data for these two cases permits the influence of slotted boundaries on the distribution of local parameters near the model to be assessed.

One can anticipate that the results obtained take correctly into account major specific features of nonstationary phenomena in slots of wind tunnel walls and permit the technology of civil aircraft tests to be improved.

Obtained Results

1. A new method for calculating stationary and nonstationary flows in WT based on solution of Reynolds-averaged Navier–Stokes equations and using the LES approach has been developed.

2. Structure of nonstationary flow near slots has been investigated and methods for diminishing the level of flow parameter pulsations have been proposed.

3. The calculation method has been verified.

In addition:

4. The border induction correction coefficients obtained for linear case were compared with the CFD data.

5. The correction calculated using different methods based on linear aerodynamics were in good agreement with each other.

6. Linear methods for perforated walls were valid up to flow Mach number M = 0.85.

7. For wind tunnels with slotted walls, new “integral” boundary conditions taking into account the influence of slots on the experimental results were recommended.

Number:	**#3319**
Full and Short Title:	Stress determination on a base of advanced interferometric measurements of deformation response induced by local mechanical influence **Experimental Determination of Residual Stresses**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics INS-MEA/Instrumentation/Measuring Instruments PHY-OPL/ Physics/Optics and Lasers
Status:	Project underway
Technology Development Phase:	Technology development
Allocated Funding:	82,781 € (EU)
Commencement date:	(starting date) August 1, 2006
Duration:	24 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 77763 32; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	Deutsches Zentrum fur Luft- und Raumfahrt e.V./Institute of Materials Research, Koln, Germany (Doeker H); Universitat Stuttgart/Institut fuer Technische Optik, Stuttgart, Germany (Osten W)
Project Manager:	PISAREV Vladimir
Contact Information:	Phone: +7 (495) 5564150; 5563656, fax: +7 (495) 7776332, e-mail: pisarev@tsagi.ru
ISTC Senior Project Manager:	KULIKOV Gennady
Contact Information:	Phone: +7 (495) 9823154, fax: +7 (499) 9784637, e-mail: kulikov@istc.ru
ISTC Website:	http://www.istc.ru

Background

The use of welding joints is currently considered as the most promising way for decreasing a weight of advanced airplane structures. However, the availability of residual stresses is a serious barrier of their wide application. Numerical methods related to residual stress characterization are quite complex and unreliable. Traditional experimental techniques of residual stress determination are inaccurate and time consuming. That is why current research efforts are mainly directed toward the development and implementation of new methods of residual stress determination

possessing metrological parameters exceeding those for traditional approaches. The essential feature of the techniques involved is their capability to reliably identify a type of stress field of interest based on the initial experimental data obtained in the form of local residual stress fields.

The general approach to determine both membrane and bending residual stress components based on combining the hole drilling method and reflection hologram interferometry and possessing unique metrological parameters, has been developed and carefully verified earlier within the ISTC Project #0808.

Project Objectives

The main objective of the Project was to develop new methods for determining stresses whose metrological parameters exceed considerably those pertinent to known techniques, in particular, for curved cylindrical shells and tubes. A remarkable feature of the new technique under consideration is its capability of recognizing a stress state type based on the whole-field initial experimental data.

Description of the Work

The validity of the general approach developed in the previous ISTC Project was further supported in investigations of residual stress fields near welded joints of different types. It has been shown that an error in determining the values of residual stress components was within only 5%. The key point of the novel technique is a capability of recording high-quality holographic interferograms with high fringe density at small hole proximities.

The research tools developed within the Project became a basis for a cooperation with DLR Institute of Material Research in studies of mechanical behavior and strength parameters of friction stir welded (FSW) joints. Friction stir welding is a novel solid-state joining process with a high potential in many modern industrial applications, especially those dealing with joining aluminum alloys in aerospace engineering. The emphasis is made on characterization of initial residual-stress level and its influence on fatigue crack propagation in welded structures under cyclic loading.

A set of residual stress distributions inherent in FSW joints of thin plate made from 2024 Aluminum alloy were obtained for the first time by combining the hole drilling method and optical interferometric measurements of local mechanical response. The studies performed are related to a regular plane specimen with FSW joint taking into account temporal relaxation of initial stress values, FSW joint in transverse compact tension specimen, and FSW T-joint.

Figure 41 shows the typical fringe patterns obtained by reflection hologram interferometry at the proximity of FSW T-joint. Figure 42 presents the typical distribution of maximum residual stress component in the direction normal to the weld line. All specimens were provided by DLR Institute of Material Research, where they were used for investigations of fatigue crack propagation in residual stress fields by the crack compliance method.

This was the reason why special attention was paid to characterization of initial residual stress level and its influence on fatigue crack

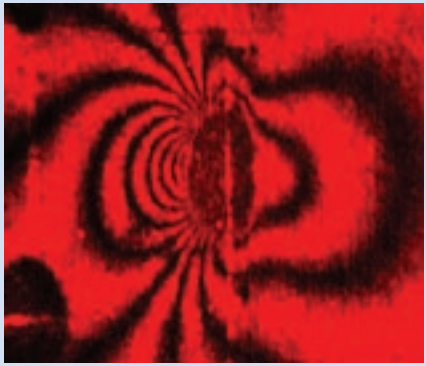


Fig. 41: Typical interference fringe pattern obtained in the course of residual stress characterization based on the combination of the hole-drilling method and high-resolution reflection hologram interferometry

propagation in welded structures under cyclic loading. Both these problems were of decisive importance for predicting airplane lifetime. Practical applications of optical interferometric techniques in this field has to be based on an automated measurement procedure. To solve this problem, an optical system of electronic speckle-pattern interferometer capable of obtaining required interferograms in digital format was designed, fabricated, and carefully tested. The measurement accuracy was estimated in the course of residual stress determination by combining the hole drilling method and electronic speckle-pattern interferometry. Figure 43 shows the typical interferogram with a high fringe density and resolution recorded near a drilled small hole. It is worth noting that the quality of these interferograms is comparable with the quality of perfect interference fringe patterns presented in Fig. 41.

Availability of the electronic speckle-pattern interferometer is an essential condition for developing a novel technique based on combining the crack compliance method and optical interferometric measurements of local mechanical response. The initial experimental information is presented in the form of interference fringe patterns corresponding to a local increment of crack length (Fig. 44).

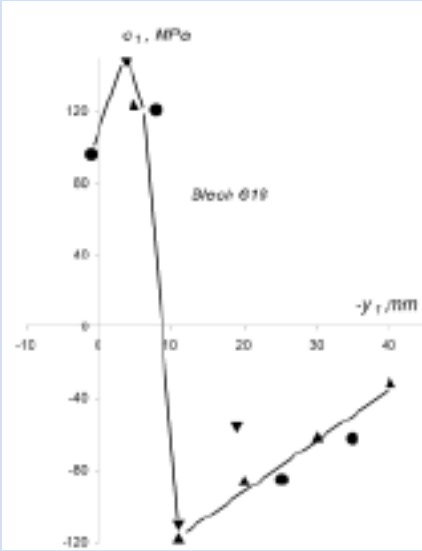


Fig. 42: Distribution of σ_1 residual stress component near FSW T-joint in direction normal to the weld line

A wide set of unique interference fringe patterns describing the fields of in-plane displacement components at the crack tip proximity was obtained for the first time. All cracks propagated under mode-I conditions. Both edge cracks and nonsymmetrical cracks with the initial point located near the welding seam axis were studied.

The available experimental database is needed for describing fatigue crack propagation in residual stress fields of different nature by a combined approach using the crack compliance method and electronic speckle-pattern interferometry. A wide set of unique investigations has been performed for the first time. They include:

- a study of edge crack propagation in residual stress fields inherent in FSW in T-joint specimen and compact tension specimen 4 mm thick and made from 2024 Aluminum alloys. The dependencies of “crack closer *vs.* total crack length” type were obtained for both specimens. Such dependencies were shown to be useful for quantitative description of crack growth process in residual stress field; and

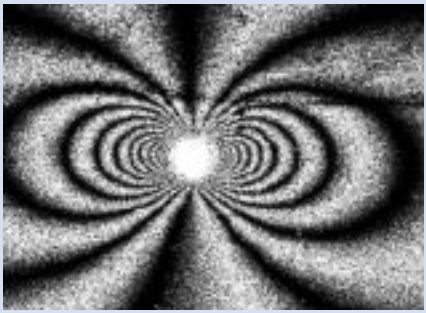


Fig. 43: Typical interference fringe pattern obtained in the course of residual stress characterization by the hole-drilling method and high-resolution electronic interferometry

• a study of nonsymmetrical crack propagation in residual stress fields of different nature. The initial points of these cracks were located near the welding seam axis. Three electronically welded plane specimens served for developing and refining the experimental procedure. In the case considered, the dependencies of "crack opening *vs*. total crack length" type allowed revealing a point of crack stopping. It was also shown that there was a limit of the maximum residual stress value σ_1, after reaching of which a crack had no barriers for growth up to a fracture of structural element. A process of central crack propagation inherent in FSW was investigated for plane specimen (Blech 469) and T-joint specimen (Blech 616) 4 mm thick and made from 2024 Aluminum alloys. As an example, Fig. 45 shows the dependencies of "crack opening *vs*. total crack length" type obtained in both cases. Revealed deviations between crack stopping instants quantitatively demonstrate a role of the stiffener in slowing down the crack growth process. It is, however, seen that the rate of crack propagation is virtually the same in both cases.

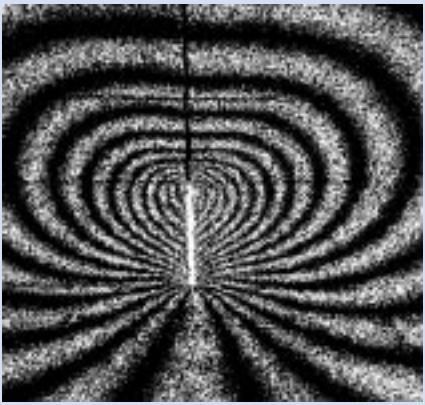


Fig. 44: Typical interference fringe pattern related to a process of crack propagation in residual stress field obtained by combining the cut compliance technique and high-resolution electronic speckle-pattern interferometry

Obtained Results

The form of dependency "crack opening (closer) vs. total crack length" was shown to be mainly determined by the type of welding technology if the compared specimens are made from the same material. This fact means that the developed approach can be implemented for studies of fatigue crack propagation at any loading cycle without interpreting initial experimental data in terms of force parameters such as residual stress values σ_1, stress intensity factors K_I, or *J*-integrals.

Joint patent application "Determination of stress intensity factor and crack stopping instant in stress field from data of optical interferometric measurements" has been prepared by TsAGI and DLR. Further works will be directed toward promoting the technique developed and implementation of the obtained results in aerospace industry.

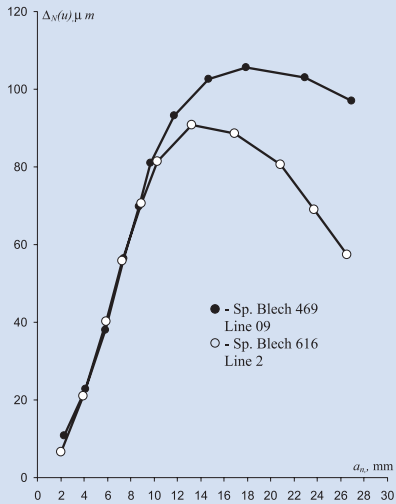


Fig. 45: Dependencies of crack opening on the total crack length for Specimen Blech 469 and Specimen Blech 616

Number:	**#3622**
Full and Short Title:	Analysis of Aircraft Aeroelasticity with Taking into Account Nonlinearities and Uncertainties **Nonlinear Aeroelasticity**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project underway
Technology Development Phase:	Applied research
Allocated Funding:	$240,000 (Canada)
Commencement date:	(starting date) April 1, 2007
Duration:	30 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	No
Collaborators:	National Research Council Canada/Institute for Aerospace Research/Structures and Materials Performance Laboratory, Ottawa, ON, Canada (Zimcik D G)
Project Manager:	KUZMINA Svetlana
Contact Information:	Phone: +7 (495) 5563216, fax: +7 (495) 7776332, e-mail: kuzmina@tsagi.ru
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

Virtually, all structures of a flight vehicle are nonlinear systems. The main nonlinearities in the aircraft structure are local nonlinearities which include, for example, free-play and dry friction in mounting components of controls, engines, nonlinearity of actuators, antiflutter dampers, etc. In most cases, the nonlinear dependencies can be linearized; therefore, their dynamic characteristics can be studied with the help of relevant approximate linear mathematical models. Nevertheless, only the boundaries of the stability domain of relevant linearized systems can be explored by this method.

For example, free-play can arise in modern airplanes due to technological reasons or in operational regimes of a control system. The value of the free-play can exceed the values, regulated by normal requirements. Therefore, the important problem to be investigated is the assessment of the influence of free-play on the aeroelastic performance and dynamic response of an airplane for estimating a danger of flutter onset and for getting the confirmation that the normal requirements are satisfied for the expected values of free-play in the system. Airplane self-oscillations in flight can affect the strength and resource of the structure at large values of free-play in the control surfaces. It is necessary to specify the maximum permissible values of free-play based on the results of studies of structure stress-deformation conditions for various flatter modes.

There are several sources of nonlinearity either in the aerodynamic flow or in the elastic structure of a flying vehicle and in a control system. The main types of nonlinearities are listed below.

Aerodynamics:

I. Oscillatory motion of shock waves in transonic flow.

II. Stalled phenomena such as buffets.

III. Consideration of large deformations in calculations of the aerodynamic flow.

Structure:

I. Free-play in connection units resulting in nonlinear stiffness.

II. Geometrical nonlinearity arising from large displacement gradients and/or loss of skin stability.

III. Dry friction – nonlinear damping arising from structural components in sliding contacts.

Control system:

I. Limitation of the actuator-rod motion velocity (saturation) and dead zone.

II. Nonlinear filters in control laws.

One of the most important problems in the analysis of aeroelasticity is the great many inevitable uncertainties existing in mathematical models of real aircraft structures. They include: dispersion of material properties, irregularity of weight report, idealization of various boundary conditions, etc. In view of it, prediction of effects of possible uncertainties on aeroelasticity characteristics at the design stage of flying-vehicle is the issue of primary importance.

Project Objectives

The main objective of the project was to develop the methodology for studying new aspects of aeroelasticity phenomena for advanced passenger airplanes taking into account nonlinearities and uncertainties.

Description of the Work

The methodology proposed is applicable for studying not only flutter boundaries of an airplane, but also for calculating the parameters of both limit-cycle oscillations (LCO) and flutter onset and evolution in the supercritical domain (Figs. 46 and 47).

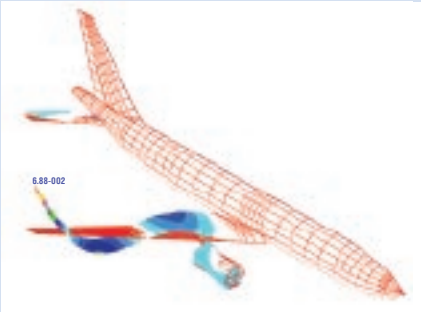


Fig. 46: Example of a symmetrical flutter mode

The development of the methodology was based on the solution of the following tasks:

- formulating mathematical models of flutter to study oscillations of controls with local nonlinearity, for example, with free-play;
- calculating flutter margins for an airplane considered as a linear system;
- determining the dependence of limit cycle on flow parameters;
- calculating a response of an airplane with nonlinearities in a controls actuator to normalized effects;
- formulating a computational model of flatter taking into account nonlinearity caused by motion of shock waves in a transonic flow;
- investigating nonlinear flutter in the time domain by a numerical integration method.

On the basis of existing experience in design and certification of passenger aircraft, the following problems of nonlinear aeroelasticity had to be considered:

– free-play and friction in the controls mounting portiobs;

– transonic oscillations connected with motion of shock waves on lifting surfaces; and

– geometrical nonlinearity arising from large wing deformations.

Within the project, novel methods, algorithms, and software dealing with the new aeroelasticity aspects will be developed to include

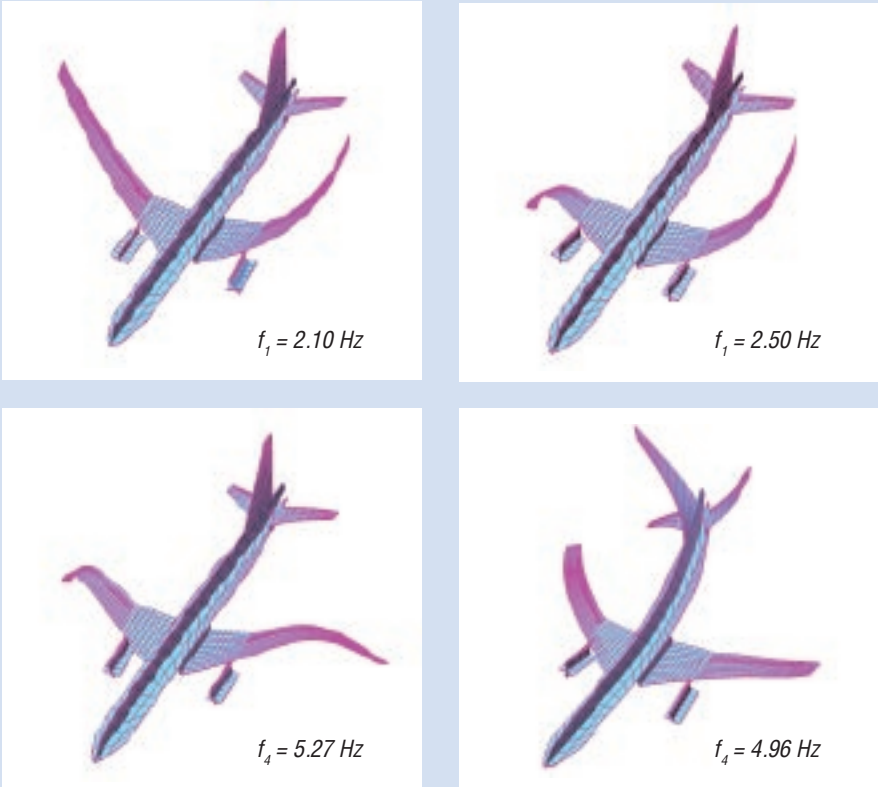


Fig. 47: Natural vibration modes of airplane

nonlinearities and uncertainties. The strength and aeroelasticity of the considered structures of a baseline passenger regional airplane will be studied theoretically. The sensitivity of main aeroelastic characteristics to structural parameters will be estimated and the most critical combination of parameters will be ascertained during the design stage of an airplane investigated with taking into account their possible uncertainties.

As a whole, the project should allow the most useful approaches to be suggested and recommendations on the application of the results obtained in various situations to be developed.

During implementation of the project:

- the possible types of nonlinearities and spread of parameter values will be ascertained and investigated for a structure of an airplane selected;
- the flutter margins and parameters of limit-cycle oscillations of a baseline airplane will be determined with allowance for nonlinearities and uncertainties;
- calculation approaches capable of increasing the accuracy of the limit-cycle oscillation level and corresponding load predictions by 20%–30% will be proposed;
- the procedure for optimization and reduction by 10%–20% of the number of tests needed to assess safety of the proposed perspective regional airplanes in terms of aeroelasticity requirements will be proposed; and
- in-flight wing deformations will be updated with due regard for nonlinearities by approximately 10%.

Expected Results

The main expected benefits would be:

- improved quality of analytical investigations of airplane structures at the design stage;
- prevention of possible costly changes in the airplane structure elements related to flying vehicle safety due to aeroelasticity requirements at the design stage; and
- reduced duration of the certification test program associated with safety of regional passenger airplanes in terms of aeroelasticity requirements and corresponding reduction of costs of airplane creation by 0.05%–0.08%.

Project Number:	**#3872**
Full and Short Title:	Comprehensive Study of Shock Wave Interference with a Turbulent Boundary Layer, High-Enthalpy Layer, and Vortex Structure **Shock Wave and Vortex Interference with the Body Surface**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project underway
Technology Development Phase:	Basic research
Allocated Funding:	222,250 € (EU)
Commencement date:	(starting date) January 1, 2009
Duration:	36 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	Siberian Branch of RAS/Institute of Theoretical and Applied Mechanics (ITPMech), Novosibirsk, Russia
Contact Information:	Phone: +7 (3832) 350778, fax: +7 (3832) 352268, e-mail: admin@itam.nsc.ru, website: http://www.itam.nsc.ru
Collaborators:	ONERA, Chatillon, France (Chanetz B); Rheinisch-Westfalische Technische Hochschule/Stoβwellenlabor, Aachen, Germany (Olivier H); Universite Libre de Bruxelles/Faculte des Sciences Appliquees, Brussels, Belgium (Degrez G)
Project Manager:	SKURATOV Arkady
Contact Information:	Phone: +7 (495) 5564720; 5564064, fax: +7 (495) 7776332, e-mail: skuratov@progtech.ru
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

Shock wave/boundary layer interaction is one of the most complex problems of modern aerodynamics. Intense research in this field has been performed for almost 60 years. Some fundamental features of interference flows have been identified. A great bulk of quantitative information has been accumulated, and the dependence of the maximum pressure and heat-transfer coefficient on free-stream parameters and shock-wave intensity has

been found. Research of interference flows has been substantially intensified for the past two decades. Much attention is paid to three-dimensional (3D) flows in the vicinity of an isolated wedge or a pair of wedges generating intersecting shock waves, which is typical of the inlet entrance. The main challenge here is the development of adequate methods for numerical simulations of interference flows. Various approaches and various turbulence models are used for turbulent flow calculations. Significant progress has been achieved due to using advanced computational capabilities. Nevertheless, the distributions of heat transfer and friction in developed separation zones formed by strong shock waves impinging the body surface cannot yet be calculated with acceptable accuracy. It has been recognized that the amount of experimental data has to be substantially increased to solve the problem.

Almost all activities aimed at studying interference flows deal with shock-wave interaction with a boundary layer on a flat plate with a sharp leading edge (or a sharp cone). The effect of small-radius bluntness of the body on the gas flow and heat transfer in the interference zone was ignored. On the one hand, the leading edges of the flying body are bounded to have certain bluntness: it is necessary to reduce the heat flux from the gas toward the leading edge and to restrict the maximum temperature. On the other hand, the radius of bluntness of the leading edges has also to be restricted to avoid an increase in drag.

The influence of small-radius bluntness on the flow past a flat plate or a cone in the absence of any incident shock waves was comprehensively studied in the 1950–1960s. It was demonstrated that the high-entropy layer generated by bluntness exerted a large effect on the distributions of pressure and heat-transfer coefficients on the plate (or cone) surface even at a large distance from the leading edge (or cone tip). The similarity criteria determining the influence of small-radius bluntness on the pressure and heat-flux distributions were established. The influence of small-radius bluntness on the flow in the interference zone, however, was first studied only recently by the participants of the present project. Some gasdynamic effects were found which could facilitate solving the thermal problem of the hypersonic inlet without significant deterioration of its aerodynamic performance. The effects observed were explained on the basis of considering the high-entropy layer characteristics; the influence of the Mach number on the threshold value of bluntness and the maximum heat-transfer coefficient in the interference zone was estimated.

In the works performed, the undisturbed boundary layer was laminar, and the laminar–turbulent transition occurred only inside the separation zone generated by the incident shock wave. At the same time, of the greatest practical interest is the influence of bluntness on interference between the shock wave and the turbulent boundary layer. One can assume that plate bluntness will reduce the heat inflow in the interference region in the turbulent flow as well. Probably, there is also a certain threshold value of bluntness above which the heat transfer is not attenuated and only additional losses of pressure are ensured. The planned study has to provide an answer to this question, as applied to two-dimensional (2D) and 3D flows. Obviously, the transition of the boundary layer to the turbulent state ahead of the interference zone will also affect the quantitative characteristics that describe the influence of bluntness on the gas flow and heat transfer in the interference zone.

Project Objectives

The objective of the Project was a comprehensive experimental and theoretical (numerical) study of gas flows in regions of shock wave and vortex interference with the body surface. The study of interference zones is of great interest for two reasons. First, interference zones are critical regions of the surface of flying vehicles, because these are the zones with intense heating of the surface and a manifold increase in pressure. Second,

despite significant achievements of computer technologies and computational methods, it is still impossible to get reliable computations in interference zones, as it could be done for other parts of the flying body. Particularly large difficulties are encountered in calculating turbulent interference flows. Experimental investigations still remain the only means for obtaining principally new information in this field of knowledge.

Description of the Work

The project implies experimental investigations of the flow in the zone of incidence of an oblique shock wave at Mach numbers M = 6 and 8 in a wide range of Reynolds numbers (up to 25 million, based on the model length), predominantly with a turbulent boundary layer. These experiments will be performed in short-duration wind tunnels of TsAGI and ITAM SB RAS, which provide high flow parameters in moderate-cost experiments. Various methods of research will be used: both conventional methods and new techniques developed by the project participants. The experimental studies will be supported by numerical simulations of the flow within the framework of Reynolds equations, which will give additional information about the flow and elucidate the capabilities and constraints of numerical codes used.

Another important problem is the streamwise vortex/shock wave interaction. Interference of a vortex with shock waves often leads to vortex breakdown, which, in turn, can deteriorate the lifting capacity of aerodynamic surfaces, to inadequate regimes of engine operation, and to a drastic increase in heat transfer. Despite the adverse features of this phenomenon, it can be used as one of the methods for improving mixing in the combustor. Therefore, it is also planned to study this type of interaction within the framework of the present project.

One specific feature of interaction of a vortex wake with a shock wave is the unsteadiness of this process. There is an obvious lack of experimental data for quantitative estimates of unsteadiness. The lack of numerical and experimental data for hypersonic velocities should be particularly mentioned. Preliminary results of experiments performed in T-313 and T-326 wind tunnels at ITAM SB RAS by the project participants at M = 6 demonstrated qualitative and quantitative differences of hypersonic interaction from the data for supersonic velocities at M = 2–4. The project participants also found that the streamwise vortex can qualitatively change heat transfer on the surface of a blunted body at M = 3. This effect can be logically expected to become stronger at hypersonic velocities.

The project proposed includes the study of hypersonic interaction of a streamwise vortex with normal and oblique shocks and obtaining systematic data for Mach numbers M = 6 and 8 on the influence of the angle of attack of the vortex generator, vortex strength, and slope of the shock wave on the interaction process. It is also planned to study the effect of vortex strength and the shape of the forebody interacting with the vortex on heat-transfer characteristics. Special attention will be paid to unsteady effects during the interaction process.

The project is intended to help one to understand specific features of shock-wave interaction with a turbulent boundary layer on a slightly blunted body. Information will be obtained on the possibility of reducing heating of the body surface in the region of shock-wave incidence and on the rational size of bluntness with allowance for the influence on heat transfer and on pressure losses caused by formation of an entropy layer. New experimental data will be obtained related to a supersonic streamwise vortex, its structure, its interaction with the shock wave, specific features of interaction at hypersonic velocities, vortex breakdown phenomenon, and its effect on body heating.

A database of new experimental results will be obtained, including information on pressure, heat-transfer coefficient, and structure of interference flows. It can be used for

verification of numerical codes designed for computing the turbulent flow around various bodies under complicated conditions: incident shock waves, entropy layer, and vortices.

The project proposed is consistent with ISTC goals. It will allow former weapon scientists from TsAGI and ITAM to conduct basic research in peaceful areas, for instance, in creating cost-efficient means for launching payloads to the near-Earth orbit with the use of an air-breathing engine. Close collaboration between TsAGI and ITAM scientists and European partners will be reached.

At all stages, the project will be performed in close cooperation with foreign collaborators, who will participate in the development and approval of the test program, choosing models and methods of research, discussing the results obtained, and preparing joint publications and presentations for international conferences and workshops.

Advanced methods and means of aerodynamic experiments, including panoramic measurement methods, will be used to implement the tasks of the project.

Expected Results

The following basic results are expected to be obtained:

– database of experimental results on the flow structure, local characteristics of the flow, and distributions of the heat-transfer coefficient in regions of interference of an oblique shock wave and a streamwise vortex with the body surface;

– dependence of the maximum heat-transfer coefficient in the region of shock-wave incidence on the degree of bluntness of the leading edge of a flat plate for a turbulent state of an undisturbed boundary layer;

– conclusion concerning the hypothesis on the existence of a threshold value of bluntness in the case of interference of an oblique shock wave with a turbulent boundary layer on a blunted plate;

– laws of propagation of the vortex wake and its dissipation at hypersonic velocities;

– unsteady characteristics of the process and regimes of interaction of the vortex wake with the bow shock wave generated by a cylindrical obstacle;

– unsteady characteristics of the process and regimes of interaction of the vortex wake behind the wing with an oblique shock wave generated by an inclined flat plate;

– validated codes for numerical simulations of interference flows of the types considered.

As a result of project fulfillment:

• better understanding of specific features of interference of an oblique shock wave and a streamwise vortex with the body surface will be achieved;

• vast experimental data will be used for verification of numerical codes and models designed for calculating complicated interference flows accompanied by generation of separation regions and streamwise vortices.

Project Number:	**#G- 060**
Full and Short Title:	Variable Geometry Propeller and its Control Aids **Variable Geometry Propeller**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$30,000 (US)
Commencement date:	(starting date) March 1, 1998
Duration:	6 months, extended by 3 months
Leading Institute:	Georgian Technical University, Tbilisi, Georgia
Contact Information:	Phone: +995 (32) 940052; 332329; 943716, fax: +995 (32) 942033; 9437I6, e-mail: inform@gtu.edu.ge
Supporting Institutes:	**No**
Collaborators:	Boeing Defense & Space Group, Philadelphia, PA, USA (Taylor R B)
Project Manager:	KHUTSISHVILI Shota
Contact Information:	Phone: +995 (32) 940052; 332329; 943716, fax: +995 (32) 942033; 9437I6, e-mail: inform@gtu.edu.ge
ISTC Senior Project Manager:	TYURIN Igor
Contact Information:	Phone: +7 (495) 9823196, fax: +7 (499) 9783603, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

Propeller driven aviation (helicopters, turbo-prop airplanes, compound helicopters) is still essential for transportation needs.

A rotor, having changeable diameter or geometry of blades during operation, is determined as the variable-geometry rotor (VGR). Development of rotors with variable diameter and blade twist during flight is a promising research direction.

A rotor with fixed geometry is a result of compromise between requirements of regimes of take-off and high speed in cruise flight. Take-off is optimal at the large diameter and small twist and cruise flight is optimal at the small diameter and large twist. The optimality is in large payload capacity at take-off and high maximum speed of cruise flight, which can be provided by VGR. The VGR is effective both for helicopters and airplanes. However, the VGR is especially effective for the airplanes with vertical take-off and landing (VTOL) in the both regimes (take-off and cruise flight).

The idea of VGR application is not a new one. There are patents with various schemes of rotor diameter changing, but they suggest very complex technical solutions not applicable nowadays. Thus, the problem of VGR has not been solved yet. In the USA, the Boeing Company concentrated on the problem of rotor blade twist, whereas the Sikorsky Company investigated the variable diameter rotor concept.

Project Objectives

The objective of this project was to develop and create a prototype of a variable-geometry propeller for vertical and fast take-off airplanes.

Description of the Work

This is a feasibility stage of an initial full project aimed at creation of a prototype of a variable-geometry propeller for vertical and fast take-off airplanes.

Obtained Results

Scientific and experimental approaches suggested for the accomplishment of Project objectives have been substantiated. A Georgian patent was filed: GE P I844B of May 8, I999 for invention of “Control Device of the Variable Geometry Rotor,” authored by S.Khutsishvili.

Number:	**#G-060-2**
Full and Short Title:	Variable Geometry Propeller (VGP) and Actuating Means (Actuating Components) **Variable Geometry Propeller**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$289,529 (US)
Commencement date:	(starting date) April 1, 2000
Duration:	30 months
Leading Institute:	Georgian Technical University, Tbilisi, Georgia
Contact Information:	Phone: +995 (32) 940052; 332329, 943716, fax: +995 (32) 942033; 9437I6, e-mail: inform@gtu.edu.ge
Supporting Institutes:	**No**
Collaborators:	Boeing Defense & Space Group, Philadelphia, PA, USA (Dadone L)
Project Manager:	TURMANIDZE Raul
Contact Information:	Phone: +995 (32) 940052; 332329; 943716, fax: +995 (32) 942033, 9437I6, e-mail: inform@gtu.edu.ge
ISTC Senior Project Manager:	TYURIN Igor
Contact Information:	Phone: +7 (495) 9823196, fax: +7 (499) 9783603, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

Propeller driven aviation (helicopters, turbo-prop airplanes, compound helicopters) is still essential for transportation needs.

A rotor, having changeable diameter or geometry of blades during operation, is determined as the variable-geometry rotor (VGR). Development of rotors with variable diameter and blade twist during flight is a promising research direction.

Project Objectives

The objectives of the Project were to investigate and develop a rotor with variable diameter, pitch, blade twist, and actuators.

Description of the Work

The work on designing and fabrication of the VGR and a test stand were performed. The rotor was developed step by step. Initially, a model of the VGR was designed and

fabricated. Thereafter, a model of the variable blade-twist rotor was designed and fabricated. Then the bench tests of principal units of the fabricated models were carried out. On the basis of the obtained results, a rotor with variable diameter and blade twist as well as an experimental stand for its testing were created. The operability conditions of rotor units and the test stand were determined. Preliminary thrust measurements and its dependence on various governing parameters have been conducted.

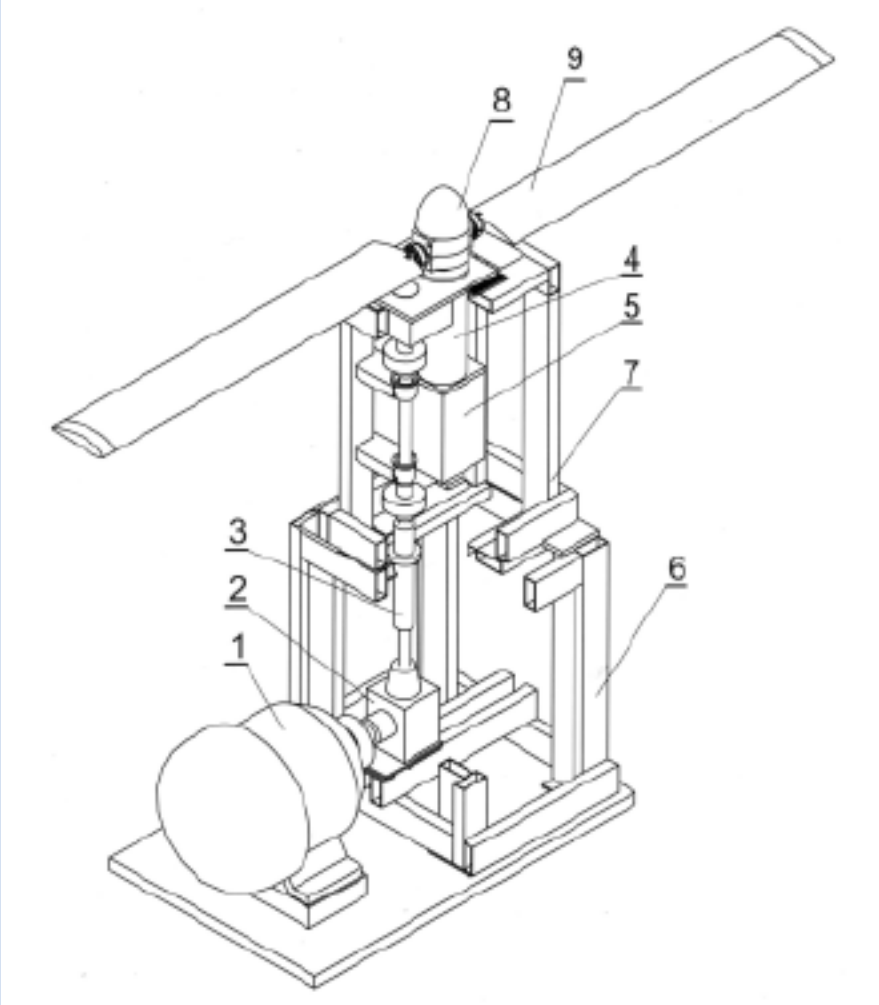


Fig. 48: Stand for testing a variable-geometry rotor:
1 – electric engine; 2 – reducing gear; 3 – transmission; 4 – hub;
5 – reducer; 6 – lower frame; 7 – upper frame; 8 – hub; and 9 – blade

The aerodynamic analysis of the developed VGR was carried out. In addition, the following tasks were solved:

– specification of aerodynamic calculations of the VGR;

– checking VGR geometrical parameters;

– definition of rotor thrust by tensometric and dynamometric methods;

– specification of calculations of forces and moments of important units in the kinematics chain;

– estimation of operability of twist and blade extension mechanisms;

– measurement and analysis of vibrations during the VGR operation, development of measures on their elimination; and

– development of measures on VGR design perfection and estimation of proposed versions.

Obtained Results

An original VGR with combinations of variable diameter and twist during flight has been created. The mechanisms and units controlling rotor diameter and twist variation have been developed. The versatile program of VGR tests on the specially designed test stand has been implemented. Tensometric and dynamometric measurements of rotor thrust at simulation of take-off have been conducted.

The VGR stand tests showed that at high rotational frequencies, significant centrifugal forces arise which affect the blade movable part. They appeared to be the most loaded elements of the VGR design with the jackscrew being its weakest unit. Therefore, the reduction of harmful influence of these forces is the problem to be attacked. The solution to this problem will open the ways of practical application of the VGR in flying vehicles.

As a result of project implementation, the following patents were filed:

1. Patent of Georgia No. GE P 2322B of September 10, 2000 for invention “Flying vehicle,” authored by S.Khutsishvili and R. Turmanidze.

2. Patent of Georgia No. GE P 2264B of October 25, 2000 for invention “Variable Geometry Rotor,” authored by S.Khutsishvlli and R. Turmanidze.

Number:	**#G-0916**
Full and Short Title:	Controlled Variable Geometry Rotor with Centrifugal Force Compensation **Variable Geometry Rotor with Compensation of Centrifugal Forces**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	234,380 € (EU)
Commencement date:	(starting date) June 1, 2005
Duration:	24 months
Leading Institute:	Georgian Technical University, Tbilisi, Georgia
Contact Information:	Phone: +995 (32) 940052; 332329; 943716, fax: +995 (32) 942033; 9437I6, e-mail: inform@gtu.edu.ge
Supporting Institutes:	**No**
Collaborators:	Boeing Defense & Space Group, Philadelphia, PA, USA (Dadone L); Boeing Operations International, Inc., Moscow, Russia (Kravchenko S V, Dadunashvili S); ONERA, Chatillon, France (Philippe J J)
Project Manager:	TURMANIDZE Raul
Contact Information:	Phone: +995 (32) 940052; 332329; 943716, fax: +995 (32) 942033; 9437I6, e-mail: inform@gtu.edu.ge
ISTC Senior Project Manager:	GOZAL Albert
Contact Information:	Phone: +7 (495) 9823281, fax: +7 (499) 9784637, e-mail: gozal@istc.ru
ISTC Website:	http://www.istc.ru

Background

The Project is the direct continuation of the ISTC Project #G-060-2. Within the frame of Project #G-060-2, an original variable geometry rotor (VGR) was created with dynamic changes in rotor diameter, setting angle, and twist of the rotor blade. However, the synchronism of rotor operation was violated by the influence of centrifugal forces on the mechanism responsible for changing the rotor-blade diameter.

Project Objectives

The objective of the Project was to investigate and develop a rotor with controlled diameter and blade twist during flight with compensation of harmful influence of centrifugal forces.

Description of the Work

A VGR equipped with the hydroaccumulation system compensating the effect of centrifugal forces has been developed and tested. Several

versions were considered and the most optimal one was used for creating a modified test facility (stand) on the basis of the test stand developed and manufactured earlier within the previous project (Fig. 49). The new test stand allowed simulation of take-off and cruise flight, and what is of particular importance, the simulation of transition regimes from take-off to cruise flight. The new test stand can be also used for aerodynamic investigations.

The scope of work was divided into 8 Tasks, including both theoretical (computer simulations) and experimental studies. In dynamic experimental tests, the stand imitated the engine and the VGR model simulating a propeller. Measurements were made at various rotation modes, including fan mode of thrust with changing the rotor rotational speed and diameter. This imitated the conditions of the aircraft hover mode. Based on the performed analysis, hydraulic compensation was chosen as the most flexible in control.

Experimental proof of at least partial discharge of the mechanism of rotor diameter variation from the influence of centrifugal forces was a primary issue. Accumulation of the acting energy of centrifugal forces in the hydropneumoaccumulator was used in the system of the centrifugal force compensation in tests with blade extension with its subsequent use for the partial discharge of the mechanism of rotor diameter variation during retraction of blades. Several versions of the system have been developed and analyzed and, as a result, the optimal one was selected and manufactured.

Fig. 49: Test stand with the variable geometry rotor

The safety of VGR dynamic tests was ensured by reliability of VGR units with the compensation system. The stand for static tests was also designed and manufactured for evaluating VGR reliability. At this stand, the loads acting at various rotor rotational speeds were imitated. The lines of elasticity of the blade depending on simulated rotation frequencies have been defined at the shifted and moved apart blade; also, the dependence of forces acting on a control lever on the simulated rotation frequencies has been obtained.

Experiments at the dynamic test stand were performed using a method of gauging an air flow speed with the revolving vane analyzer. The dependence of VGR thrust on the rotation speed at rotor minimum and maximum diameters was determined (Fig. 50). The distribution of induced speeds of the air flow along the rotor blade span has been investigated. It was found that increase of rotor diameter by a factor of 1.4 and change in blade twist in the range of up to 16 degrees, the thrust could increase by a factor of 1.6.

Obtained Results

The system for compensating the effect of centrifugal forces on the synchronism of rotor operation has been developed. The effectiveness of the system was proved by continuous retraction-extension of the rotor blade in the entire range of rotation speeds. Synchronic and reliable operation of the VGR mechanisms in various loading conditions has been demonstrated.

Fig. 50: Rotor blade prepared for the thrust test

Number:	**#G-1600**
Full and Short Title:	Updating of the Variable Geometry Rotor (VGR) Blade Diameter Change Mechanism Combined with the System of the Centrifugal Force Compensation and Extension of the Range of the Blade Twist Change **Variable Geometry Rotor**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project underway
Technology Development Phase:	Technology demonstration
Allocated Funding:	186,716 € (EU)
Commencement date:	(starting date) 1 September 2008
Duration:	24 months
Leading Institute:	Georgian Technical University, Tbilisi, Georgia
Contact Information:	Phone: +995 (32) 940052; 332329; 943716, fax: +995 (32) 942033; 9437I6, e-mail: inform@gtu.edu.ge
Supporting Institutes:	**No**
Collaborators:	AgustaWestland, Samarate, Italy (Pagnano G); The Boeing Company, Philadelphia, PA, USA (Dadone L)
Project Manager:	TURMANIDZE Raul
Contact Information:	Phone: +995 (32) 940052; 332329; 943716, fax: +995 (32) 942033; 9437I6, e-mail: inform@gtu.edu.ge
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

The Project G-1600 is the direct continuation of previous ISTC Projects G-060, G-060.2 and G-916.

Project Objectives

The objective of the Project was to update the mechanism of VGR blade diameter variation combined with the system compensating centrifugal forces at extended twist range.

Description of the Work

The goal to increase the twist change range and develop a mechanism of its provision was discussed with the Project Collaborators and stated for the Project team, that is, to increase the range of twist change to 5°–35°. This means that during take-off (at the maximum diameter), the twist of blades will be within 5°–6° and at the cruise flight, when the rotor diameter is minimal, the twist value increases to 35°.

Expected Results

The VGR demonstration model equipped with the advanced mechanism of diameter variation combined with the system compensating centrifugal forces and operating at the extended range of twist change will be created and tested. The model will provide a considerable increase in VGR efficiency and can be considered for such areas of application as aircraft industry, shipbuilding, wind power engineering, etc. Commercial potential of VGR will be considered and the Technology Implementation Plan will be developed.

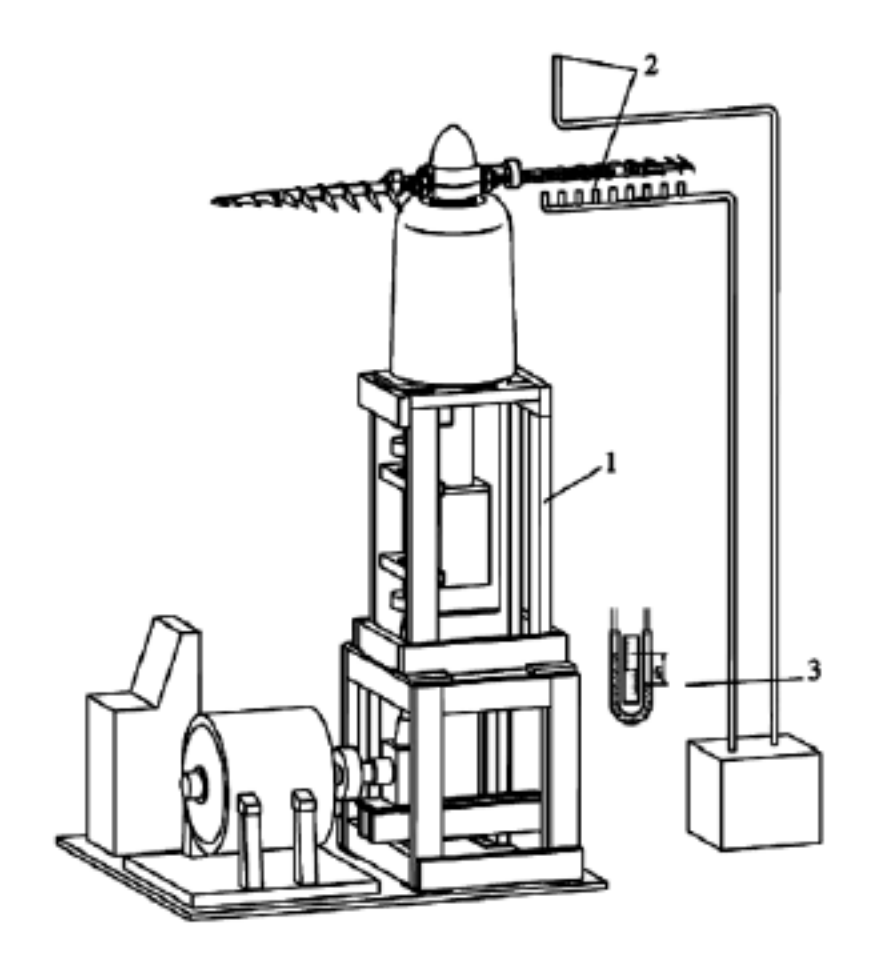


Fig. 51: Modified test stand: 1 – stand of VGR; 2 – pressure integrator; and 3 – manometer

Improvement of Safety and Operational Capacity

Project Number:	**#0138**
Full and Short Title:	Low-cost hemispherical resonator for small, commercial navigation systems. **Resonator Gyroscope**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology demonstration
Allocated Funding:	$491,000 (US)
Commencement date:	(starting date) December 1, 1994
Duration:	36 months, extended by 3 months
Leading Institute:	MEDICON, Miass, Chelyabinsk reg., Russia
Contact Information:	Phone: +7 (3513) 531575; 288982; 535920; 535424, fax: +7 (3513) 531575; 535920, e-mail: mdcn@medicon-miass.ru, e-mail: sales@medicon-miass.ru, website: http://www.medicon-miass.ru
Supporting Institutes:	No
Collaborators:	Litton Guidance & Control System, Space Operations, Goleta, CA, USA (Lynch D D)
Project Manager:	BODUNOV Bogdan
Contact Information:	Phone: +7 (35135) 28793, fax: +7 (35135) 21575, e-mail: mdcn@medicon.miass.chel.su
ISTC Senior Project Manager:	Tyurin Igor A.
Contact Information:	Phone: +7 (495) 9823196, fax: +7 (499) 9783603, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

A Hemispherical Resonator Gyroscope (HRG) is a new type of gyroscopes developed in USA by Delco Systems Operations and in Russia by Medicon Ltd. in Miass for using in ballistic missiles. The major advantages of HRG in comparison with other gyroscopes are: longer lifetime; lighter weight; higher reliability; lower power requirement; and smaller size. The HRG can be used for different applications. The HRG advantages stem from its operation principle based on the Bryan effect. This effect is the sensitivity of a thin vibrating shell to rotation. Although this phenomenon was discovered at the end of the 19th century, the first gyroscopes based on this effect were developed only in the 1970s.

The only HRG disadvantage is its relatively high cost. For military applications, the equipment cost is usually not too significant but it is very important for commercial applications. Due to its relatively high cost, today the HRG is mainly used for space systems, although one can successfully use it for aircraft, drilling oil wells, etc. Therefore, the reduction of HRG cost is an important problem. The development a low-cost hemispherical HRG resonator (the most expensive HRG part) allows this problem to be solved for the most part.

Project Objectives

The objective of the Project was to develop a low-cost hemispherical resonator for a commercial HRG.

Description of the Work

This project has been implemented by Medicon Ltd. with the support of Litton Guidance and Control Systems, Space Operations that has over 40 years experience in manufacturing inertial systems. The development was structured to achieve the results which would contribute toward a new HRG to be used by both Medicon Ltd. and Litton Guidance and Control Systems.

The project was based on two technical approaches aimed at:

– changing/simplifying the resonator design; and

– developing a new balancing technology.

The new resonator has no balancing tines, has only one support stem and a small size. Ion-milling was used to balance the developed resonator; ion-milling balancing technology allows one both to balance tineless resonators and to achieve high accuracy as ion-milling treatment is controlled much more simply than evaporation of fused quartz by laser or mechanical removing of the material from the hemispherical surface. One can remove unbalanced mass according to any law; as a result, the balancing algorithm is simpler and the total amount of material removed is smaller than under a point mass removal. Such a balancing process can be readily automated. As a whole, the ion-milling balancing technology results in a reduction of the resonator cost.

The Work Plan of the Project included four subtasks. Brief descriptions of each subtask and corresponding results are given below.

1. Development of the new resonator design

Medicon and Litton experience was used in developing the resonator design. Besides, the results of mathematical simulation and tests of resonator samples were used. Both Medicon and Litton manufactured new resonators. The manufactured resonators were used to develop the balancing process.

2. Balancing equipment and process

The balancing equipment was developed and manufactured by Medicon according to the Technical Schedule of the Project. The balancing equipment was located in a special clean room together with instruments, control computer, and power supplies.

Experiments led to a balancing technology that allowed the frequency splitting of the resonators and the magnitudes of the first three harmonics of the mass defect to be effectively reduced. Test results confirmed the developed method. A set of engineering specifications for the balancing equipment and process was developed.

3. Identifying the balancing algorithm

The balancing algorithm was identified and verified on the basis of calculations and experiments. It is a sequence of treatment and test operations to effectively reduce the 1st to 4th harmonics of the resonator mass defect.

4. Test resonators

To testing the resonators, special test equipment and test procedures were developed and manufactured. The values of the first four

harmonics of the mass defect and the *Q*-factor were among the measurement parameters.

More than 50 resonators were manufactured and tested. The results of tests were used to correct the balancing technology and engineering specifications.

Obtained Results

Design and manufacturing technologies of tineless, hemispherical HRG resonator 30 mm in diameter were developed. Engineering specifications for the resonator and technology were completed.

An ion-milling balancing method for tineless resonators allowing the removal of the 1st to 4th harmonics of the mass defect was developed and a set of engineering specifications was generated.

Medicon and Litton test results agreed within experimental error and indicated the suitability of these resonators for small, low-cost commercial navigation systems.

Conclusions

1. The ion-milling balancing technology developed reduced the frequency splitting down to 0.01 Hz.

2. The magnitudes of the 1st–3rd harmonics of the mass defect were reduced to 30 μg and less.

3. Balancing leads to the increase of the *Q*-factor of most resonators and to the reduction of *Q*-splitting.

Litton resonator test

After Medicon tests, Litton resonators were passed back to Litton for tests. Litton measured the frequency splitting. Litton measurements agreed with Medicon results within experimental error.

Number:	**#0138-2**
Full and Short Title:	Optimization of Characteristics of Low-cost Hemispherical Resonator for small, Commercial Navigation Systems **Resonator Gyroscope**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$125,000 (US)
Commencement date:	(starting date) May 1, 1998
Duration:	18 months
Leading Institute:	MEDICON, Miass, Chelyabinsk reg., Russia
Contact Information:	Phone: +7 (3513) 531575; 288982; 535920; 535424, fax: +7 (3513) 531575; 535920, e-mail: mdcn@medicon-miass.ru, sales@medicon-miass.ru, website: http://www.medicon-miass.ru
Supporting Institutes:	No
Collaborators:	Litton Guidance & Control System, Space Operations, Goleta, CA, USA (Lynch D D)
Project Manager:	BODUNOV Bogdan
Contact Information:	Phone: +7 (35135) 28793, fax: +7 (35135) 21575, e-mail: mdcn@medicon.miass.chel.su
ISTC Senior Project Manager:	TYURIN Igor
Contact Information:	Phone: (+7 495) 982 31 96, fax: (+7 499) 978 36 03, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

A Hemispherical Resonator Gyroscope (HRG) is a new type of gyroscope. By its potential, the HRG can replace most types of gyroscopes, which are currently used. The only significant disadvantage of the HRG is its relatively high cost. This factor is very important for commercial applications. The development of methods of manufacturing of a low-cost HRG resonator, which is the most expensive part of the device, makes it possible to solve the cost problem and to expand the fields of commercial application of the HRG.

Since 1994, Medicon Ltd. (Russia) and Litton Guidance and Control Systems, Space Operations (USA) have been carrying out research to develop a low-cost hemispherical resonator for commercial navigation systems within the framework of the ISTC project. The cost of high-quality silica glass and the cost of metallization process are essential components in the total cost of the resonator. Though the price of silica glass can vary within the range of 100–2000 $ per kilogram (depending on its optical parameters), its acoustic parameters, which are particularly

important for the HRG, are not measured during glass manufacture and they are not directly related to its optical quality. Therefore, the use of silica glass with the best optical parameters for resonator manufacturing can be too expensive, but the final characteristics of the resonator would be mediocre. The procedure of control of acoustic quality of silica glass billets will make it possible, on the one hand, to increase a yield ratio, and, on the other hand, to use low-cost, but acoustically good grades of silica glass.

After manufacturing and balancing, the HRG resonator is metallized. The characteristics of metal coating influence the performance of the whole HRG heavily enough. The influence of the metal coating strongly depends both on the coating material and the method of metallization. The nature of internal friction in a thin metal coating is little-studied. Therefore, it is possible to develop the methods of metallization only on the basis of research of coating acoustic properties.

The Project is the direct continuation of the technologies developed within the ISTC Project #0138.

Project Objectives

The main objective of the Project was to develop a method of metallization of a low-cost hemispherical HRG resonator and a procedure of quality control of silica glass billets used for manufacturing of such resonators.

Description of the Works

The Work Plan of the Project included 2 tasks. Each task and the results obtained are described below.

1. Research of acoustic losses in different kinds of silica glass

The equipment for investigating acoustic characteristics of cylindrical and hemispherical resonators in the temperature range from -100 to +300 °C at frequencies up to 100 kHz, as well as the set of model cylindrical resonators made of 7 different grades of silica glass were manufactured.

In the specified temperature range, the acoustic characteristics of these resonators were measured for different frequencies. The selected procedure made it possible to determine the internal friction both in silica glass and in the surface layer, and also in the metal coating, as well as to calculate elastic moduli of these glasses. Besides, the optical characteristics of these silica glasses were measured. All these experimental data formed the basis of a procedure of quality control of silica-glass resonator billets. The obtained values of elastic moduli permit the estimation of change of frequency of the resonator in the specified temperature range.

2. Metallization of fused quartz hemispherical resonators

On the basis of experimental testing of different metallization methods of resonator, a method providing uniform coating of the hemispherical resonator surface was developed. For the selected method of metallization, special equipment was designed and manufactured.

The metallized resonators were controlled and tested: the coating quality and acoustic parameters of resonators were checked. The metallization method was adjusted successively on the basis of the test results. Finally, the manufacturing process and the instructions on coating were developed.

The developed metallization process was included in the general manufacturing process; thus, the development of the technology of the low-cost hemispherical resonator was completed.

Obtained Results

The equipment, which was used for investigating and selecting silica glasses suitable for production of fused quartz resonators, was developed and manufactured.

The tested grades of silica glasses, taking into account their acoustic characteristics, were divided into 3 groups:

Group A: ***Anhydrous silica glasses with a low impurity content***. This group included expensive high-quality optical silica glasses. Most grades of these glasses were suitable for manufacture of resonators.

Group B: ***Silica glasses with an average impurity content***. The manufacturing process of these glasses did not provide a quality cleaning from impurities. These glasses had low optical transmission in the ultraviolet spectrum and were not suitable for manufacturing high *Q* resonators.

Group C: ***Silica glasses with a high OH concentration***. The glasses of this group occupy an intermediate position but under certain conditions they can provide high acoustic characteristics. It is possible to determine a potential level of this silica glass on the basis of complex acoustic and optical investigations. The glasses of this group have a rather low price and they are attractive due to optimum combination of price and quality. Taking into account the instability of acoustic characteristics, this silica glass can be recommended for the serial production of hemispherical resonators only after complex tests of each batch of material.

During investigations, the valuable results, which have a fundamental value for understanding of processes of internal and external friction in silica glasses, were obtained. The application value of these results consists in adjustment of processes of manufacture of high-quality fused quartz resonators.

A method of metallization of hemispherical resonator was developed and tested experimentally. An equipment, devices and production accessories for the selected method were designed, manufactured, and tested successfully.

The tests of the metallized resonators with the quality control of metal coating and the control of acoustic parameters of the resonators were carried out.

The sets of appropriate engineering specifications for the designed equipment and the metallization process were developed.

The developed procedure of material control and the metallization process were included in the resonator manufacturing process, thus the development of the technology of a low-cost fused quartz resonator for the HRG was completed.

Project Number:	**#0201**
Full and Short Title:	Problems of Investigation of Aircraft Vortex Wake Evolution and Flight Safety. **Aircraft Wake Safety Problem**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	$328,790 (EU: $109,596.67, JP: $109,596.66, US: $109,596.67)
Commencement date:	(starting date) April 1, 1995
Duration:	24 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	AIRBUS Industrie, Blagnac, France (Hinsinger R); Boeing Technical Research Center, Moscow, Russia; Japan Aircraft Development Corporation, Tokyo, Japan (Amano K); National Aerospace Laboratory NLR, Amsterdam, The Netherlands ONERA, Clamart, France (Duc J M)
Project Manager:	VYSHINSKY Victor
Contact Information:	Phone: +7 (495) 5568421, e-mail: vyshinsky@falt.ru, vyshinsky@rambler.ru
ISTC Senior Project Manager:	TOCHENY Lev
Contact Information:	Phone: +7 (495) 9823113, fax: +7 (499) 9783603, e-mail: tocheny@istc.ru
ISTC Website:	http://www.istc.ru

Background

Air transport continues to be the preferred mode of travel for a vast majority of citizens. However, many of world's airports have been overloaded since the early 1980s, and traffic would keep increasing over the next 20 years while very few new runways are brought into service. These trends would at least double the number of take-offs and landings at the world's largest airports, even if a full transition to wide-bodied aircraft like A-3XX and Boeing 747 is realized. Therefore, the determination and possible reduction of the minimum safe separation distance between airplanes during take-off and landing is a critical operational problem.

The emergence of jumbo aircraft (capable of carrying approximately 1000 passengers) is expected to partially alleviate the traffic congestion, but also magnifies the importance of reduction of the hazard caused by strong vortex wakes. These powerful vortices, caused by the combination of longitudinal and span-wise flows, are shed from aircraft wings in sheets. They can persist in the vicinity of runways for 2 to 3 min (during this time, a passenger aircraft can travel 25 km). The danger associated with another aircraft entering these vortices is real and potentially severe because the resultant radical lift change can cause wing stall, structural damage or engine failure due to compressor stall.

The Project is a continuation and extension of Project #201-95 "Investigation of vortex wake evolution and flight safety problems." The present project was focused on the analysis of specific technical solutions and measures intended to increase operational capacities of a contemporary busy airport.

Project Objectives

The objective of the Project was to study the vortex wake dynamics behind an aircraft and to search for specific measures and technical solutions aimed at enhancing the operational capacity of busy airports.

Description of the Work

The Project was aimed at the investigation of the stability of a far-field vortex wake behind an aircraft as well as at the development of specific recommendations on artificial vortex aging and decay acceleration.

The following aspects of the problem were investigated:

- the impact of aircraft configuration (cruise, take-off, landing) and flight regime (including power setting) on generation of a near-field vortex system and on its subsequent rolling up into two strong vortices;
- stability of a far-field vortex wake depending on initial conditions (determined by the core structure of the vortices and their relative disposition) and conditions of its existence with due regard for atmospheric factors (including atmospheric turbulence, wind situation, and atmospheric stratification) and earth proximity, vortex wake life and decay mechanisms;
- safe separation distances and procedures to prevent in-flight accidents arising when the following aircraft enters the wake of the lead aircraft during take-off and landing. This can cause a sudden radical lift change, aircraft departure, engine failure, structural damage, etc.

Theoretical and experimental investigations in the framework of the Project were underway in the following five directions: aerohydrodynamics, physics of atmosphere, strength and aeroelasticity, applied aeromechanics, and flight dynamics and control.

Aerohydromechanics investigations

Wake-vortex models were created; they include the **ZONWAKE** code, an asymptotically rigorous model, and the block engineering model (**BEM**). The last one is the pivotal model, which is used in flight-dynamics and strength and aeroelasticity models, and combines them in a single structure.

Zonal approach: four zones are considered with proper equations and boundary conditions in each zone:

(1) aircraft near-field where the panel method with vortex sheet deformation module is used;

(2) two-dimensional (2D) unsteady analogy for far-wake simulation including sinuous instability effects based on Crow's solution with empirical correction;

(3) Euler equations for a narrow zone along the wake axis;

(4) Reynolds-averaged equations for the Eulerian internal subzone where the anisotropic algebraic turbulence model was used.

Numerical matching at the zone boundaries were used to close the problem. Comparison of zonal approach calculations (for B-747 aircraft wake in the cruise regime) and experimental results demonstrated a good agreement both in vortex core growth and in flow field simulation.

Some preliminary results of comparison of the A-3XX and B-747 layouts in terms of their vortex-wake generation were obtained. Although the A-3XX aircraft generated 60% more intense total wake circulation as compared to B-747, its turbulent core radius and circulation were only 20% greater, which can be explained by similar tip-chord lengths. Thus, both aircraft pose approximately the same wake hazard for the follower, at least in the near field. The wake vortex lifetime for A3-XX was somewhat longer than that for the B-747 aircraft. The pictures of wake in horizontal and cross-sectional planes offer the possibility of safe separation-distance estimation using the vortex-wake model and cross-link time as its criteria.

The **block engineering wake model (BEM)** was an asymptotically nonrigorous combination of experimental results, analytical investigations, and CFD modeling. This model included the basic physical phenomena inherent in the wake flow:

- aircraft geometry effect (including take-off, cruise, and landing regimes);
- turbulent vortex core growth and circulation loss due to atmospheric turbulence;
- atmospheric stratification effect;
- vortex lifetime evaluation according to Crow's theory and empirical correlation.

Engineering model permitted one to calculate such characteristics as the circumferential velocity profile at each instant of time and wake height including the effect of atmospheric stratification.

The results of investigation of engine-jet and high-lift-devices influence on the wing-vortex formation in the near field were obtained in the water tunnel (GT-400). The strong jet influence on the multiple vortex-structure formation was observed. Not only vortices do affect the jet, as is well known, but the jet influences vortices rather heavily, too. The same problem was studied in a low-turbulence wind tunnel T-124. The investigation was aimed at the creation of a jet-vortex engineering model in the cold-jet approximation, finding means for artificial vortex-wake aging, and ascertaining optimal layouts from the wake danger standpoint.

Applied aeromechanics investigations

Differential deflections of aerodynamic wing surfaces (spoilers, flaps) were studied as a possible means of increasing the aircraft survivability in vortex-wake turbulence environment (mathematical modeling and experimental investigations in low-speed wind tunnel with a cascade of airfoils, T-103).

The obtained results are:

- an effective method was developed for simulating the impact of the vortex wake in the wind tunnel;
- for the model aircraft in cruise, take-off, and landing regimes, variations of the rolling and yawing moments as functions of the distance between aircrafts were close to the linear ones; the disturbing rolling moment on the model was virtually independent of flap deflection angles, while the disturbing yawing moment tended to increase with flap deflection angles;
- for reduction of the safe-separation distances, it was necessary to significantly enhance the available roll and yaw control powers of the following aircraft; preliminary investigations of the effectiveness of wing control surfaces have shown that the available rolling moment can significantly be increased at the cost of little variations in lifting capacity and longitudinal aerodynamic characteristics.

Vortex-wake visualization investigations

Light scattering on the water droplets arising during water vapor condensation, droplet coagulation and reverse processes (recondensation and recoagulation) have been considered. The picture observed depends

on the wave length of sounding radiation, phase state, mass spectrum of particulates, and angle of observation. Intensity of the scattered electromagnetic radiation, its ellipticity, polarization, and rotation of the electric field vector (components of the so-called Stokes optical vector) can be used to identify an aircraft wake in the ambient atmosphere.

Numerical results were obtained on gas-dynamic, optical, and chemical properties of the aerosol-containing wakes of the Boeing-747-type aircraft and on the advanced second-generation supersonic civil transport.

The onboard and ground-based wake-vortex monitoring facility should be developed using a jet-vortex wake model, flight dynamics, and strength and aeroelasticity models. The first model helps one to understand the picture observed, the other two furnish criteria for searching – what vortices are dangerous in along-track and cross-track penetrations. Dangerous vortices must be visible.

Flight-dynamic investigations

The main goal of investigations is the evaluation of safe distances between two aircraft landing on the same runway. Two kinds of control regimes, automatic and manual, were considered.

A probabilistic approach was used to create an adequate model of a vortex wake generated by the leading aircraft and an aerodynamic and dynamic model of impact on the following aircraft.

The models take into account movement of the vortices near the ground, circulation distribution and dissipation, as well as unstable oscillations of the vortices. The wind model includes two components: a steady wind and turbulent gusts. The methodology of statistical modeling for assessing the probability of large deviations of the kinematic aircraft trajectory parameters has been developed.

The allowable distances were determined both with and without vortex deformation.

Investigations pertaining to manual control were more expensive and exhaustive due to the necessity of using modern flight simulators and participation of experienced pilots, but some versions of vortex wake diagnostics and elimination can be checked only with this control mode.

The results showed that aircraft deviation by approximately 15–20 m from a vortex core suffices to safely execute the landing or take-off operation. Thus, one of the ways for increasing the airport capacity is timely vortex-wake detection using onboard roll-rate sensors.

For the proper decision on aircraft control under vortex wake conditions to be made, the following information will suffice:

- the aircraft approaches the wake vortex;
- vortex is positioned to the right or to the left of the aircraft.

The results showed that:

- the use of a wake detection and avoidance system allows one to evade dangerous effects of a vortex wake on the aircraft;
- the proposed lateral vortex avoidance maneuver gains a positive appraisal of pilots and can be easily performed;
- a visual contact with the ground surface on completing the lateral maneuver provides sufficient time for the pilot to eliminate the lateral deviation of the aircraft from the runway center line.

Strength and Aeroelasticity investigations

The main goal was to develop the criteria of safe separation distances between aircraft from structure and aeroelasticity standpoint. The critical situation in this case is the cross-track wake encounters (symmetrical mode of oscillation is determining).

Experimental simulation in a low-speed wind tunnel with the gust simulator and fixed and free flying Froude-similar models were used for testing the mathematical model developed.

The time history (for a time interval between a B-747 passage and an IL-103 aircraft cross wake penetration) of the maximum wing root bending moment ΔM on the follower was obtained. The safe time interval was found as the time of reaching the limit load. At the standard turbulence level, it equals 45 s, whereas at very weak turbulence, it reaches 165 s. That is, for an IL-103 flight speed of 78 m/s, safe distances are 3510 and 12,870 m, respectively. For comparison, the USA regulations demand it be 11,100 m.

By taking into account the random character of atmospheric turbulence by means of statistical modeling with defined distribution density, the probabilities of safely executing vortex-wake crossing were assessed. The worst case of vortex core encounter was considered. In the framework of this model, the new regulations do not guarantee that wake intersection is safe from the structural strength standpoint.

Thus, a safety zone diagram around a particular wake-generating aircraft can be plotted for particular atmospheric conditions (with account for an effect of atmospheric turbulence on a vortex wake decay) and following aircraft.

Plotting of the safety-zone diagram is the first step. The next steps are:

- finding the means of artificial vortex-wake aging and optimal layouts from a wake danger standpoint,
- vortex wake visualization and monitoring system creation,
- vortex avoidance maneuver,
- increasing the second aircraft controllability and survivability (gust attenuation) in turbulence environment.

Obtained Results

On the basis of experimental results and theoretical investigations, a probabilistic mathematical model of the vortex wake produced by an aircraft during landing was constructed. Accounted for in this model are the effects of ground proximity and atmospheric disturbances on moving and spatially curving vortex plaits. A methodology was developed for approximate calculations of velocity fields induced by curved vortices and a technique for calculating the aerodynamic loads and moments acting on an aircraft both in a quasi-steady flow regime and with taking into account unsteady effects. Estimates were obtained for the probability of in-flight reaching large values of the *f*-factor, which is the measure of hazard strength of a possible aircraft accident. On the basis of these estimates, a preliminary assessment of the soundness of existing safe-separation regulations for aircrafts of various types was performed and indicator diagram was plotted which showed that for small intersection angles close to the parallel flight, the safe distances were specified by stability and controllability of an aircraft encountering the vortex wake, whereas at large encounter angles, the safety zone was limited by the aircraft strength.

Project Number:	**#1018**
Full and Short Title:	Flight Safety, Aircraft Vortex Wake and Airport Operation Capacity **Aircraft Vortex Wake**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$250,000 (EU)
Commencement date:	(starting date) 1 May 1998
Duration:	24 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	AIRBUS Industrie, Blagnac, France (Hinsinger R); DaimlerChrysler Aerospace Airbus, Bremen, Germany (Hueneske K); Deutsches Zentrum fur Luft- und Raumfahrt e.V./Institut fur Physik der Atmosphare, Wessling, Germany (Gerz T); National Aerospace Laboratory NLR, Amsterdam, The Netherlands
Project Manager:	VYSHINSKY Victor
Contact Information:	Phone: +7 (495) 5568421, e-mail: vyshinsky@falt.ru, vyshinsky@rambler.ru
ISTC Senior Project Manager:	TOCHENY Lev
Contact Information:	Phone: +7 (495) 9823113, fax: +7 (499) 9783603, e-mail: tocheny@istc.ru
ISTC Website:	http://www.istc.ru

Background

According to ICAO forecasts, for some years to come the world annual growth of air traffic required will amount to 6.5% for freight traffic and 5% for passenger transportation. For the Asia-Pacific region countries, these figures will be twice as high. The impossibility of realizing the required freight and passenger traffic leads to economic losses (today's annual losses of USA economy makes up 2 billion USD and, according to the European Strategic Research Institute, annual total losses of European economies will reach 10 billion USD by 2000). By the year 2010, 13 European airports, even modernized, will have entered a period of crisis and will not be able to satisfy growing demands in air traffic. Still more severe crisis is in store for the Asia-Pacific countries.

ISTC Project #1018-98 "Flight safety, aircraft vortex wake and airport operation capacity" is a continuation and extension of Project # 201-95 "Investigation of vortex wake evolution and flight safety problems." The present project was focused on the analysis of specific technical solutions and measures intended for increasing operating capacities of a contemporary busy airport.

Project Objectives

The objective of the Project was to study the vortex wake dynamics behind an aircraft and to search for particular measures and technical solutions aimed at enhancing the operational capacity of today's busy airports.

Description of the Work

In accordance with the objective specified, the following measures have been considered in the framework of the Project:

1. **Alleviation of the vortex wake** behind a wake-generating aircraft. For this purpose:

– comparative investigations of various layouts of heavy and medium aircraft have been performed and the configurations most hazardous from the standpoint of their wakes strength have been revealed;

– an extendable data base on vortex wakes has been formed, requiring a minimum of information about aircraft; and

– a variety of specific measures have been considered to alleviate the strength of vortices and shorten the wake lifetime.

2. **Vortex wake visualization** behind a wake-generating aircraft. The following directions have been considered:

– existing methods;

– new developments of visualization methods (in particular, the use of molecular clusters forming in a jet-vortex wake as tracer particles); and

– concept of self-visualization of the wake behind ultra-high capacity aircraft carrying a required visualization equipment.

3. **Control augmentation** on a following aircraft in a wake turbulence environment. Apart from mathematical simulation, an experimental investigation has been performed in a wind tunnel fitted with a flow angularity generator. In particular, the following means were considered to counteract the induced rolling moment:

– differential deflection of the spoilers;

– additional aerodynamic control surfaces; and

– high-lift blowing systems.

4. The creation of a **flight simulator** to serve as a research tool and equipment for flight crew training in a simulated wake turbulence environment. The developed software included the following mathematical models:

– near and far wake models with allowance made for atmosphere stratification, ground proximity, atmospheric turbulence, and cross wind;

– a model of the aerodynamics of a following aircraft and its control surfaces in nonpotential vortical flow; and

– a flight dynamics model for a wake turbulence environment.

5. Based on the developed mathematical models, the creation of an **onboard system for detecting** and displaying **vortex wake encounters** using standard onboard sensors of angular velocities and *g*-loads. Such a system may be used for:

– an avoidance maneuver performance; and

– automatic deflection of additional control surfaces.

6. Possible **changes in air traffic control procedures** (problems of airports with several runways and mountain airfields), refinement of the safe-separation distance matrix (taking into account meteorological conditions).

Theoretical and experimental investigations in the framework of the Project have been carried in the following five basic directions: aerohydrodynamics, physics of atmosphere, strength and aeroelasticity, applied aeromechanics, flight dynamics, and control.

Aerohydromechanics investigations

The case of an aircraft in a landing configuration with high-lift devices deflected was considered with a series of features that complicate the problem. In the near wake field, the vortex sheet rolls up into several vortices of complex structure. At a distance of 6-10 wingspans, a multicore vortex structure is transformed into a coherent vortex pair. In the far wake zone (100 wingspans and over) the two-core structure breaks down due to vortex diffusion and sinuous instability development in the turbulent atmosphere.

The aerodynamic vortex wake model was created on the following basis:

1. Numerical methods (basic tool for wake evolution research):

• discrete vortex method and approximate engineering techniques (engineering approach and numerical experiment are combined in the code ENGWAKE; a nonlinear far vortex wake model in the turbulent atmosphere was constructed which did not require that the disturbance amplitude be smaller than the vortex wake span);

• zonal approach (asymptotic analysis with dividing the region studied into a set of zones where the equations of their own were solved numerically followed by matching the solutions on the zone interfaces); and

• boundary-value CFD problems for studying separate fragments of the phenomenon where modified algebraic and differential two parameter k-ε and q-ω turbulence models were considered aimed at adequately accounting for the flow swirl and the small-scale turbulence effect on the vortex diffusion and dissipation.

2. Analytical approaches which allow revealing some fundamental flow features in the wake, for example, the topology of the multicore vortex structure, mechanism of circulation loss in the wake or the possibility of appearing a local maximum in the radial circulation distribution.

3. Experimental investigations and validation of the model. TsAGI T-124 low-turbulence and T-105 vertical-wind tunnels (Fig. 52) allowed detailed wake characteristics to be obtained at distances of 0-6 wingspans behind an aircraft. The qualitative characteristics of the wake behavior were also studied in the GT-400 water tunnel. Used for the verification were also the experimental data obtained in tests on a flying model in ONERA catapult setup.

Vortex-wake visualization investigations

To visualize vortex wakes in the atmosphere, the following phenomena can be used:

• Doppler shift due to rotational motion of air masses (this approach is widely employed presently);

• significant difference in the concentration levels of water vapor, carbon oxide and dioxide, nitrogen oxides against the average atmospheric background;

• elevated concentration of molecules and molecular clusters with exited internal energy levels due to temperature differences between “hot” exhaust jets, “cold” vortex cores and the average atmospheric background;

• the presence in engine exhaust jets of foreign impurities (for instance, hydroxyl, soot particles) or tracer particles intentionally introduced into the wake; and

• entrainment and prolonged persistence of elevated concentrations of impurities in vortex cores.

The best natural tracers are condensable water droplets and molecular clusters preceding their formation. In the Project, careful consideration was given to formation of such tracers.

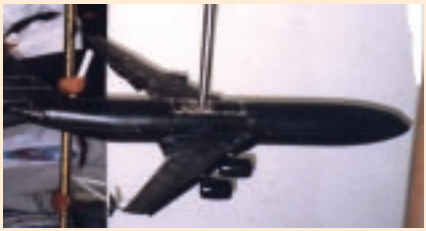


Fig. 52: Experiment in TsAGI wind tunnel T-105

In recent years, remote sounding of the earth atmosphere in the millimeter radio wave band has become widely used with the purpose of determining spatial distributions of its minor components. Millimeter and submillimeter wave bands meet the need for reliable, timely and continuous monitoring of processes taking place in the atmosphere, which is not always possible in the optical range. In the wave-number range $1 < \nu < 20$ cm^{-1}, the radiation absorption coefficient for water vapor dimers is comparable to or even in excess of the absorption coefficient for monomers. The range $7 < \nu < 8$ cm^{-1} appears to be especially promising, since the dimeric absorption mechanism is in this case in the atmospheric transparency window. The radio-frequency radiation absorption coefficient for water vapor dimers in millimeter and submillimeter bands is directly proportional to the square of concentration of monomers, whose content in engine exhaust jets is considerably greater than in the ambient atmosphere. Entrainment of combustion products by vortices results in a noticeable increase in the water vapor concentration in them. With increasing water vapor concentration, the absorption coefficient of monomers grows linearly, but this growth is little noticeable in the center of absorption lines against the background of its initially high level. In the atmospheric transparency windows, where the dimeric absorption mechanism dominates, a noticeable growth of the absorption coefficient is observed with increasing humidity. Thus, entrainment of humid combustion products by aircraft vortices makes them observable against the background of the ambient atmosphere due to formation of water vapor dimers in the vortices.

In the course of Project implementation, an algorithm was developed for computing the number density of the simplest clusters of water vapor (dimers, trimers, tetramers, etc.) in atmospheric air. In developing this algorithm, quantum-mechanical computations of the simplest cluster structure were used. The number density of clusters is very sensitive to temperature and pressure of the ambient gas, which places stringent requirements on gasdynamic simulation. It was found that the clasterization process takes place in mixing layers and near the axes of vortices, which is consistent with the results obtained in the framework of heterogeneous condensation studies.

For additional formation of clusters, *corona discharge* can be employed. This method necessitates a study of formation of clusters and microparticles being condensed on ions generated in the flow by corona discharge. In practice, such a discharge can be realized in locations of vortex shedding (in the neighborhood of the wingtips and flap edges). It is supposed that such a system can be created to simplify vortex visualization behind a heavy aircraft.

A further step forward has been made in developing the theory of droplets collision speed, the linkage has been taken into account between the characteristic time of turbulent fluctuations and the Stokes relaxation of the gas speed.

A simplified quasi-one-dimensional algorithm (Q1D) was verified, which was able to take into account a variety of chemical reactions between impurities and to determine their concentration at a distance from the engine nozzle.

A complex numerical algorithm was also developed which allowed taking into consideration the growth of micron-size droplets during their condensation and coagulation.

Strength & Aeroelasticity investigations

The problem of statistically mean displacements of an aircraft under the action of atmospheric turbulence has been addressed. These studies arose from the necessity to assess the initial amplitude of oscillations of the vortices forming behind a wing, and for this purpose, amplitudes of oscillations of an aircraft center

of gravity and the tips of its flexible wing were determined for various atmospheric conditions and flight regimes, including the use of an autopilot. In solving that problem, a methodology was used, which was widely employed in strength analysis to determine dynamic loads (*g*-forces) experienced by an aircraft flying in turbulent atmosphere. To verify the theoretical model, experiments were carried out with a Froude-similar free-flying aircraft model with a flexible wing in the TsAGI T-103 wind tunnel. In these tests, a gust simulator was used – a cascade of deflectable airfoils installed at the beginning of the tunnel test section.

The performed measurements showed good agreement between the theoretical and experimental assessments of the model displacements. The developed methodology was used in computing the displacements of an IL-96 aircraft in a turbulent atmosphere. These studies showed that the main effect on the development of the vortex wake sinuous instability in turbulent atmosphere comes directly from the action of turbulent gusts on the wake coherent structure rather than from the vortices initial amplitude. The results obtained will be used later on in studying the influence of atmospheric turbulence on the vortices initial structure through the action of gusts on oscillations of the wing sharp, vortex-generating edges.

To assess the probability of a structural failure of an aircraft encountering vortex wake, the airspace of a generalized airport was considered with an aircraft flying in a low-altitude holding regime. It is in such a situation that wake encounters are most probable. The probability of a structural failure due to the encounter is compared with that due to flying in a turbulent atmosphere. It was shown that in a number of cases vortex wakes are more dangerous (sometimes by an order of magnitude) than are rough-air gusts, but it is such gusts that airframes are frequently designed for. These data are the first results of research where both the vortex wake and structural strength are considered from a probabilistic standpoint. In so doing, to obtain a closed-form solution, a lot of simplifying approximations and assumptions were made. The methodology developed can be applied to a specific busy airport whose capacity limit is being approached or has already reached. Analogously, assessments of the risk of structural failures can be made for cases of wake encounters at airports with crossing runways.

Applied aeromechanics investigations

An aircraft which encounters a vortex wake can experience significant changes in the pitching, rolling and yawing moments as well as in lift. The most dangerous is the upsetting rolling moment occurring due to a considerable difference in the left and right wing lifts.

Investigations directed to increasing the available maximum rolling moment are very prospective from the standpoint of flight safety in trailing wake turbulence. To effectively counteract the wake-induced rolling moment, it is necessary to have an exceeding control of the rolling moment and an effective flight control system. The carried-out experimental investigations have shown the possibility of a twofold increase in the available rolling moments while maintaining a satisfactory level of the remaining aerodynamic characteristics of an aircraft. The differential deflection of the flaps in this case can be replaced later on by the deflection of only the outboard sections of the flaps in combination with the ailerons or by use of special methods for increasing the available rolling moments. Particular proposals are presently being analyzed for implementing this approach, including the use of a radio controlled aircraft model.

In solving the problem of increasing the passenger throughput of airports, an initial stage of investigation is required to collect experimental data associated with the effects of vortex gusts on aircraft aerodynamic characteristics. In addition to direct vortex wake simulation in a wind tunnel with the use of a wake-generating aircraft model installed

at a distance of 10-20 wingspans upstream of a following aircraft model, it is desirable to simulate vortex gust effects, using a special setups able to create in the tunnel test section a flow structure equivalent to a vortex wake with respect to the action on a following aircraft. For this purpose, in Project #201 an airfoil cascade was used with differentially deflectable airfoil sections, which was mounted at the exit of the tunnel nozzle. Further development of this approach has led to a modification of this setup to simulate flow angularity: the airfoil cascade was replaced by a single two-section tapered airfoil whose sections were able to be deflected differentially. Computational and experimental investigations have shown that the modified setup generates in the test section a flow structure which is closer to the flow in a vortex wake.

A great variety of aerodynamic layouts of aircraft (conventional configuration, canard, three-surface layout) and their geometrical parameters preclude experimental investigations into effects of wake-induced turbulence for every conceivable configuration. Computational methods are of a great help in this case (Figs. 53 and 54). Because of the complexity of numerical simulation, the problem of determining aerodynamic loads on an aircraft can be solved to a first approximation without taking into consideration the influence of the aircraft on the vortex structure ("frozen-flow" hypothesis). Such an assumption, as shown by investigations, does not result in significant errors in aerodynamic characteristics of aircraft whose trajectories are close to the vortex axis.

In solving problems of flight dynamics in a quasi-steady approximation (automatic landing modes, piloted flight simulator operating regimes), it is necessary to compute repeatedly aircraft aerodynamic characteristics in simultaneously integrating the equations of aerodynamics and flight dynamics, which requires highly effective numerical methods. They must take into consideration specific features of the configurations and flows under study. These requirements are met by numerical methods based on the vortex lattice theory, which, to allow for vortex-wake effects, introduces corrections in local

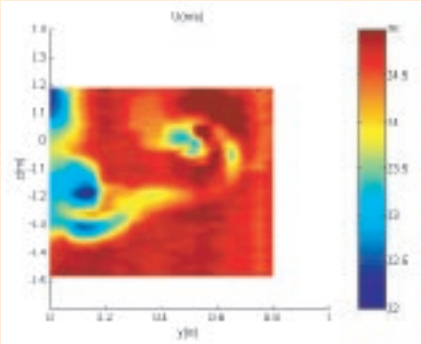


Fig. 53: Setting up of wind tunnel experiment

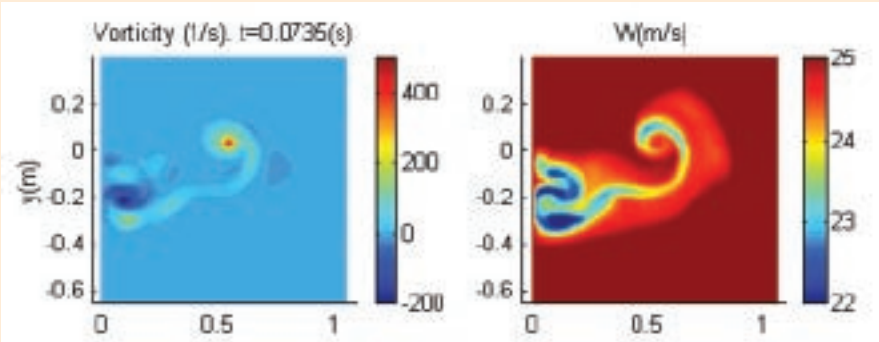


Fig. 54: Validating of mathematical models against experimental results

angles of attack of the configuration cross sections in compliance with flow angularity caused by the vortex wake. These methods take into account viscosity in the boundary-layer approximation and in the framework of engineering approaches, they allow simulation of flows with separation on one of the wings and of the associated change of the rolling moment sign.

The computed flow field around an aircraft model in the wake of the flow angularity simulator in the TsAGI T-103 wind tunnel and the computed flow in the wake behind an aircraft model in the DNW large-scale wind tunnel were compared with the appropriate experimental data obtained in these wind tunnels. A satisfactory agreement between the computed and experimental data was observed. Further development of the numerical methods is associated with determining distributed aerodynamic characteristics of aircraft components in a vortex-wake environment. In particular, the modification of the panel method previously used allowed sufficiently accurate computation of integrated and distributed aerodynamic characteristics in the linear range of the wing lifting qualities variation.

Flight-dynamic investigations

Studies into vortex wake problems are ultimately directed to enhancement of flight safety and their results must be reflected in instructions for pilots. The pilot opinion is determining and final. The central point uniting all directions of research is a flight dynamics model based, on the one hand, on a model of vortex wake and atmospheric turbulence and, on the other, on models of aircraft aerodynamics in a wake turbulence environment. All of this will result in the fact that only slow, gradual changes in the air traffic control and piloting procedures can find practical implementation and application.

Studies into flight dynamics in turbulent atmospheric conditions in the presence of the trailing wake vortical structure are aimed at a practical solution to the problem of increasing passenger throughput of busy airports.

Piloted flight simulators adequately representing trailing-wake turbulence will be useful in training pilots and working out emergency recovery procedures associated with vortex-wake encounters. Such simulators can also be helpful in comparative investigations of wake-generating aircraft and versions of an aerodynamic configuration under study to find measures for wake alleviation, assess and select criteria for safe-separation distances between aircraft on approach to landing, and preliminary analyze proposals concerning changes in air traffic control.

An airborne system for detecting vortex-wake encountering situations must help the pilot to execute an optimum avoidance maneuver or timely make a decision about go-around.

A proposed automatic landing mode is not intended to be practically used, at least in the near future, but it is needed for theoretical investigations in the framework of simplified approaches without the pilot in the control loop.

The created models render an invaluable service in solving specific practical problems for real airports. In particular, in the context of stochastic simulation one can prove that the considered changes in air traffic control do not increase the probability of aviation accidents compared to the current regulations.

Obtained Results

Based on available experimental data and theoretical studies, the engineering (ENGWAKE), asymptotic (ZONWAKE), and stochastic (FARWAKE) models of the aircraft vortex wake were constructed. Accounted for in the models are the details of aircraft aerodynamic configuration, effects of ground proximity and atmospheric disturbances on the motion and curvature variation of the wake vortices; vortex diffusion and circulation loss are also taken into consideration. A replenishable data base on the vortex wakes behind particular aircraft was created.

Engineering (VORTSEC) and simplified (VORTRAN and VORTLAT) mathematical models of aircraft and control surface aerodynamics for the trailing turbulence environment were developed.

To validate the mathematical models, tests were carried out in TsAGI T-103 (with flow angularity and gust simulators), T-105, T-124 wind tunnels and GT-400 water tunnel. The models were also verified against the results obtained in ONERA IMEL catapult setup, as well as in small and large DNW wind tunnels (the Netherlands).

Specific measures aimed at enhancing the airport throughput were considered, such as alleviation of heavy aircraft vortex wake, vortex wake visualization, aircraft controllability improvement under trailing turbulence conditions, onboard system for identification and displaying of the vortex wake encounter situations in combination with the vortex avoidance algorithm and automatically bringing into action additional control surfaces, and use of flight simulators for studying and pilot training in the trailing turbulence conditions.

Project Number:	**#0990**
Full and Short Title:	Study of Airframe and Cargo Mechanical Response at Accident Impact Transport Aircraft to Take-off and Landing Runway **Transport Aircraft Impact**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$150,000 (US)
Commencement date:	(starting date) April 1, 1999
Duration:	24 months, extended by 5 months
Leading Institute:	VNIIEF, Sarov, N. Novgorod reg., Russia
Contact Information:	Phone: +7 (83130) 44802, fax: +7 (83130) 29494, e-mail: staff@vniief.ru, website: http://www.vniief.ru
Supporting Institutes:	**No**
Collaborators:	Sandia National Laboratories, Albuquerque, NM, USA (Smith R E)
Project Manager:	SINITSIN Vladimir
Contact Information:	Phone: +7 (83130) 45097, fax: +7 (83130) 45958, e-mail: root@gdd.vniief.ru
ISTC Senior Project Manager:	KULIKOV Gennady
Contact Information:	Phone: +7 (495) 9823154, fax: +7 (499) 9784637, e-mail: kulikov@istc.ru
ISTC Website:	http://www.istc.ru

Background

Worldwide aircraft practice indicates that a significant part of accidents (about 50%) occurs at landing of airplanes. Emergency landing takes place in airports or nearby (in inhabited areas); therefore, the consequences of such accidents can be dramatic. Accidents of airplanes with dangerous cargo onboard (containing explosive, radioactive, poisoning, or other harmful and hazardous materials) are of particular danger. Detailed information on the response of airframe and cargo to airplane accidental impact against take-off and landing runway (TOLR) is important for increasing safety of cargo in such accidents and for mitigating impact consequences.

Direct testing of accidental landing of a radio-controlled airplane is very costly and requires the development of telemetry equipment monitoring basic parameters of airplane and cargo describing their response to accidental impact in the course of crash, and a system of aircraft remote control. A simpler and more reliable way of obtaining necessary information is inverse impact testing. In experiments of

this type, a sample (aircraft) is at rest prior to impact, and the striker-imitator of TOLR moves at a preset velocity. Inverse impact tests require no TOLR, decommissioned aircraft can be tested, and usual cable communication circuits can be used for receiving data from the gauges installed on the sample.

The tests by inverse impact method were suggested to be carried out on a gasdynamic shock stand including the following components:

– gasdynamically accelerated device with an accelerating compartment (tube) and explosive pressure generat ors (EPG);

– the striker-simulator of TOLR;

– the device for test object (TO) suspension that allows TO (fragment of the airplane) to be released from fastening prior to impact with the TOLR simulator, the brake device allowing TO to be stopped and caught after loading; and

– the computer-metering complex (CMC) for data acquisition and processing.

The stand was mounted in an open test site in VNIIEF used for explosion experiments. To facilitate the work on stand designing and manufacturing, some elements of available VM1EF gasdynamic stand were used. As a TO, AN-26 transport airplane widely spread in transport aviation was considered; its purchasing has been arranged preliminary. As this airplane was not too large, it was possible to test fragments of wings and fuselage at the stand.

The important virtue of the bench tests, apart from those indicated above, was a possibility to perform testing of individual aircraft fragments (for example, fragment of a cargo compartment with a cargo). Such experiments allowed monitoring signals from gauges mounted on frame elements and furnishing reliable information on expected parameters in tests with entire aircraft.

The gasdynamic test-bench and testing methodology developed within this project could be used in future for testing the response of protective containers for transportation of hazardous and dangerous cargoes to accidental impacts.

RFNC-VNIIEF possesses modern experimental facilities and high skilled scientists and technicians with rich experience in conducting complex gasdynamic experiments. This guaranteed successful implementation of project tasks.

In 1994, RFNC-VNIIEF has developed a conceptual plan of aircraft crash and fire testing under the contract with Sandia National Laboratories (SNL). SNL were interested in continuation of the work and were ready to collaborate in the project in implementing technical tasks and experiments, as well as in discussions on the results.

Activity on this project was also of interest for *Transnucleaire*: its products could be in future tested at RFNC-VNIIEF for resistance to accidental impacts.

Project Objectives

The objective of the Project was to substantiate a possibility to determine mechanical response of airplane and cargo at accidental impact against TOLR based on the results of testing the models of fuselage fragments and cargo at gasdynamic test bench by the method of inverse impact.

Description of the Work

The tests by the method of inverse impact were performed at the gasdynamic test bench including the following basic components:

– two gasdynamic accelerating devices of the gun type with accelerating compartments – tubes 0.357 m (small device) and 0.792 m (large device) in diameter, and EPG;

– impactors-simulators of TOLR 55–57 kg and 370–390 kg mass – pistons of the small and large accelerating devices, respectively, accelerated to the required velocity by the pressure of explosion products of high explosive charges; and

– CMC for conducting measurements and data processing.

The metal impactor had the surface clad with concrete. It was impacted against a TO – a simplified model of transport-airplane fuselage fragment of reduced scale (1:10 and 1:5) with a cargo weight model fastened in it. In the experiments, the emergency landing of airplane with cargo with retracted chassis was imitated. The characteristics of accidental impact of airplane against TOLR (the value and direction of airplane velocity vector, landing angle, etc.) were specified by the collaborator.

The technique of calculating the airplane response to impact against TOLR was validated in the experiments at the gasdynamic test bench with a simplified model of fuselage. The numerical method was used for selecting and justifying the basic geometrical parameters of the representative model of fuselage (the ratio between the longitudinal and cross sizes of a fuselage fragment), for determining the influence of wing on fuselage fragment behavior at impact, and for determining a time-dependent load on the fastened cargo.

Simplified and reduced (with scales 1:10 and 1:5) models of a cargo compartment fragment from AN-26 transport-airplane fuselage with a weight model of cargo fastened in it has been chosen as the TO. The TO scaled 1:10 was a thin-walled (wall 1 mm thick) cylinder made of aluminum alloy D16T (density 2.8 g/cm^3, Young modulus 72 GPa, yield strength 300 MPa). The cylinder was supported by five ribs from inside which simulated the airframe. Also, it contained a floor simulator in the form of an aluminum plate 1 mm thick. This plate was fastened to the cylinder by screws and supported by aluminum partitions from the side of TO bottom, which, in turn, were rested on the airframe. The weight model of the transported cargo was a rectangular steel plate of 1 kg mass (the mass of typical cargo was assumed to be 1 t) which was fastened to the floor simulator by screws. The TO was 200 mm in diameter and 400 mm long.

The TO scaled 1:5 was a bit different in design and was manufactured from aluminum alloy Amg-6 with strength characteristics slightly different from D16 alloy. The basic difference between the TOs of various scales was in the way of weight model fastening. In the TO of larger scale, the weight model was fastened to one end of the plate-dynamometer rather than to the floor. The other end of this plate was fastened to the floor by screws. Besides, the cargo model was placed inside frames fastened to the floor. The frames allowed cargo to move along the TO axis but prevented cargo displacement from the floor in the normal direction. The cargo mass was 8 kg.

A response of AN-26 transport-airplane fuselage cargo model and the weight model of cargo fastened in it to the impact against TOLR was determined experimentally. The impact conditions (characteristics of emergency landing) were as follows: landing velocity 100 m/s, velocity vector direction 30° to TOLR, landing angle 0°, chassis not extended, and landing on concrete TOLR.

The experiments with the TO scaled 1:10 were performed with simpler models and in simpler experimental setup as compared to the experiments with the TO scaled 1:5. The experiments were performed at the small test bench. In these experiments, TOLR was modeled by a piece of steel tube (219 mm in diameter, 534 mm long) with steel plugs welded to its end faces (disks 20 mm thick and 356 mm in diameter). It was accelerated at the gasdynamic test bench up to velocity of 50 m/s and was impacted against the TO placed on its path. The TOLR simulator mass was 43 kg. The impactor velocity vector was directed normally to the longitudinal axis of the TO: its value was equal to the value of the vertical component of the airplane landing velocity. The experiments with the TO model scaled 1:10 were performed with the purpose to adapt DRAKON-3D/S software code for numerical simulation of TO-TOLR impact. Besides, in these tests, the experimental procedure was verified in detail.

The experiments with the TO model scaled 1:5 were performed at the large test bench. In these experiments, emergency airplane landing with impact against TOLR was also

simulated. The impactor-simulator of TOLR was manufactured from a piece of steel tube (738 mm in diameter, 1200 mm long) with plugs welded to its end faces (disks 8 mm thick and 787 mm in diameter). At one side, the tube with a part of plug was cut at an angle of 30° to the axis in such a way that a segment 10 cm high was left after plug cut. The tube cavity was filled with pieces of wooden boards up to the cut place and concreted by a concrete layer of about 4 cm thick on the cut plane. The concreted surface was carefully leveled. The impactor mass in this case was varied within 370–390 kg. Before testing, the TO was mounted at a special wooden support on a path of TOLR simulator motion at a distance of about 2 m from the exit cross section of the accelerating compartment. To obtain the required impact parameters in the experiment, the TO was placed in such a way that the angle between the TO axis and the axis of the accelerating compartment was equal to 30°. Then, the generatrix of the cylinder was parallel to the plane of oblique cut of the TOLR simulator (landing angle 0°), and the angle between the TO axis and the direction of TOLR simulator velocity vector was 30°. The bottom end of the TO was placed 2–3 cm above the lower point of the plane of the TOLR model cut that allowed simulating not only TO-TOLR impact but also subsequent sliding of the TO along TOLR.

For determining the TO response to the impact against TOLR in the experiments with the TO scaled 1:10, electrocontact gauges were used to measure mutual displacement of the cargo weight model and TO bottom during the impact, as well as piezoaccelerometers to measure the cargo weight model acceleration in the impact direction. In the experiments with the TO scaled 1:5, the above-listed measurements were supplemented with measurements of dynamometer deformation by foil strain gauges, whereas cargo acceleration was measured in two directions: along the longitudinal axis of the TO and normally to the floor plane.

The dependencies “dinamometer deformation vs. time,” “cargo displacement relative to TO bottom vs. time,” and “impact induced cargo acceleration vs. time” were obtained experimentally. Visual examination of the TO after impact experiments revealed that their deformation was qualitatively similar for both models scaled 1:5 and 1:10 but there were also significant differences associated with loading directions (normal impact in the first case and oblique in the second). In particular, deformation from the normal impact was appreciably larger from the impact side compared with that at the opposite side of the TO. This was explained by the effect of inertial forces during TO-TOLR impact and further deceleration in the course of TO sliding along the concrete surface of TOLR.

Numerical simulation of TO response to impact was carried out using DRAKON-3D/S software package intended for solving problems of transient deformation of three-dimensional constructions consisting of branching shell elements and nondeformable solids at contact interaction. The calculations were performed with account for friction at a contact of aluminum and concrete. The friction coefficient was assumed to be 0.3. The results of calculations were compared with experimental data for the TO scaled 1:10. Excellent agreement was obtained for cargo displacement and for time history of cargo acceleration. This comparison substantiated the possibility of using numerical simulation for adequate modeling of normal TO-TOLR impact of given configuration with a nondeformable cargo weight model. Comparison of numerical simulations with experimental data for the TO scaled 1:5 also showed satisfactory agreement. The time history of dynamometer deformation was close to that obtained in the calculations. Satisfactory agreement between predicted and measured cargo accelerations in the normal direction to the impactor surface was also obtained.

Obtained Results

Extensive experimental and computational studies of response of small-scale models of transport-airplane fuselage fragments with cargo to accidental impact against TOLR have been carried out using the inverse impact method. The method of inverse impact proved to be very efficient in determining the mechanical response of scaled TO models to accidental impact against TOLR. Despite it is too early to extend the results of these studies to full-scale impact conditions, one can claim with confidence that such studies provide comparative efficiencies of different design solutions towards improving airplane resistance to the impact and, in particular, increasing the resistance of transported cargos to the effects of accidental loading. The testing approach requires further improvements. To reduce the influence of scaling on TO behavior, it is worth to increase the scale of models. To incorporate the influence of realistic features of airplane design (which were absent in the simplified TOs) on mechanical response of both airplane and cargo to accidental impact against TOLR, it is worth to continue the studies towards testing fragments of a real airplane fuselage.

Decrease of Environmental Impact

Project Number:	**#0200**
Full and Short Title:	Ecological Aspects of the Impact of a Supersonic Civil Aircraft (SST) of the Second Generation of Environment. Methods of Reducing Sonic Boom, Community Noise and the Supersonic Civil Aircraft Impact on the Ozone Layer **Sonic Boom for Supersonic Aircraft**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	$800,000 (EU: $400,000, US: $400,000)
Commencement date:	(starting date) October 1, 1995
Duration:	36 months, extended by 2 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	**No**
Collaborators:	AIRBUS Industrie, Blagnac, France (Hinsinger R); Boeing Technical Research Center, Moscow, Russia; DaimlerChrysler Aerospace (Satellites), Friedrichshafen, Germany (Fischer B); National Aerospace Laboratory NLR, Amsterdam, The Netherlands; Snecma Moteurs/Direction de Production-LAY, Evry, France (Karadimas G)
Project Manager:	PAVLYUKOV Yevgeny
Contact Information:	Phone: +7 (495) 5564000, fax: +7 (495) 7776332
ISTC Senior Project Manager:	KULIKOV Gennady
Contact Information:	Phone: +7 (495) 9823154, fax: +7 (499) 9784637, e-mail: kulikov@istc.ru
ISTC Website:	http://www.istc.ru

Background

Future of supersonic transport (SST) is closely connected with solving relevant ecological problems such as the impact of aircraft on the Earth's ozone layer, community noise, and the sonic boom problem. In particular, SST take-off and landing generates high level of community noise, which significantly exceeds the level of noise produced by subsonic passenger aircraft. According to the current regulations of International Civil Aviation Organization (ICAO) specifying

the allowable impact of civil aviation on the environment, SST community noise level cannot exceed noise requirements for modern subsonic aircraft (ICAO, Annex 16, Ch. 3). The intent of the Project was to investigate methods of achieving SST community noise compliance with ICAO reference requirements for subsonic civil aircraft. Another goal was to elaborate recommendations regarding powerplant noise suppressing systems which reduce jet noise with relatively low thrust loss. Recommendations on application of other SST community noise reduction methods were also a subject of the Project.

Project Objectives

The objective of the project was to develop theoretical grounds and experimental verification of different methods worked out for mitigating deleterious environmental effects of prospective supersonic transport of second generation (SST-2), namely, for reducing the community noise and sonic boom, and preserving the Earth's ozone layer.

Description of the Work

The work started with the formulation of the basic concept of SST-2 configuration, its powerplant, characteristics, and conditions of cruise flight. The main parameters of the SST-2 basic version were chosen as the initial data for the analysis of environmental impact of SST-2 fleet operation.

On the one hand, SST-2 must feature better seat capacity, longer range of flight, and higher lift-to-drag ratio as compared to aircraft of first generation (Tu-144, Concorde). On the other hand, it must meet FAR-36-3 standards in terms of the community noise, ozone layer impact, and sonic boom minimization.

Community noise reduction

Two mechanisms of noise radiation caused by generation of instability waves in supersonic jets were studied. Main mechanisms of noise generation in axisymmetric supersonic jets, namely, mixing noise responsible for discrete components of noise spectrum and a broadband shock noise component, were analyzed experimentally by the Project team earlier. In this Project, interaction of the shock and discrete noise with the flow structure and influence of external disturbances on supersonic jet noise generation were considered. Flow-driven large-scale vortices were shown to be a significant source of noise in supersonic jets. Concurrent flow influence on the noise generated by a supersonic jet was discussed as well.

Acoustic characteristics of jets issuing from a multicomponent rectangular ejector nozzle were studied, including analysis of the effect different components exert on radiated sound. A combination of the multicomponent nozzle with an ejector changed the spectrum of radiated sound. A four-lobed nozzle reduced low-frequency noise (so-called mixing noise generated at the ejector exit) by 10–11 dB whereas a nozzle with three lobes reduced the noise by 11–12 dB in the direction of the most intense sound radiation.

The Project Work Plan also included studies of thrust characteristics and flow field relevant to and axisymmetric noise suppressor nozzle. The data obtained made it possible to modify the nozzle. Both numerical analysis and experiments (Figs. 55–59) showed that the modified nozzle had thrust losses less than in Tu-144 aircraft within the studied range of flight Mach number M = 0–0.95.

Detailed investigations of sound-absorbing ejector coatings resulted in determining the optimal impedance value and parameters for one-layer (homogeneous) resonant structures ensuring maximum noise suppression at a tuned frequency. It was shown that the attenuation frequency band could be extended by means of two-layer, three-layer, and combined coatings covering the same area.

Numerical simulation of the flow field inside the noise-suppressing nozzle was based on the explicit Godunov–Kolgan–Rodionov method for convective fluxes, explicit central difference method for diffusion fluxes, and locally implicit approximation of source terms in the equations governing turbulence parameters. This was a second-order approximation method for all variables. A corresponding software module was developed. Test calculations of known flows with free and near-wall turbulence verified the software code and showed its high performance.

The analysis of flow fields in the noise-suppressing nozzle allowed the acoustic nozzle properties to be evaluated. A numerical method developed for this purpose was based on the analytical solution to the Lighthill wave equation as well as on the sound quantum tracing approach in geometrical acoustics. With the known detailed flow field inside the nozzle, this method was very helpful in assessing the noise radiation intensity for "natural" and "shear" jet noise in all directions as well as the radiation frequency spectrum.

Sonic boom

In the course of Project implementation, techniques for calculating pressure distribution in a sonic boom wave produced by a flying supersonic aircraft have been developed. The problem was solved for different aircraft configurations, flight speeds, and altitudes for the conditions of standard atmosphere.

The minimum possible levels of sonic boom (within the concept of equivalent body of revolution) were determined for wide ranges of flight regimes in terms of Mach numbers and flight altitudes, as well as for different aircraft dimensions and weight (light business aircraft, medium and heavy vehicles). These data were further used when solving the problem of minimization of the sonic boom produced by aircraft of arbitrary configuration.

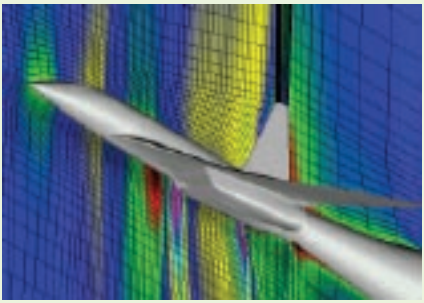


Fig. 55: Calculations of SST-2 flow field

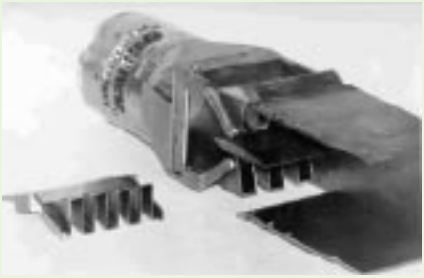
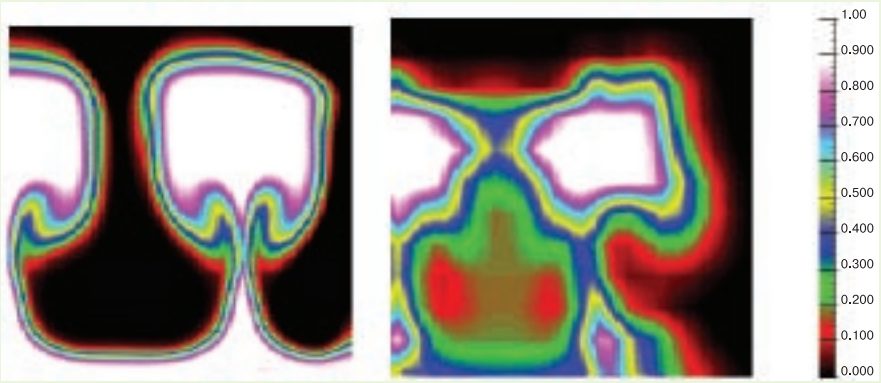


Fig. 56: Three-dimensional rectangular mixer-ejector nozzle for SST-2 noise suppressing



(a) *(b)*

Fig. 57: Computational fluid dynamics (a) and experimental (b) study of 3D rectangular mixer-ejector nozzle flow for SST-2

Parametric numerical analysis of the effect produced by the shape and dimensions of different aircraft components on sonic boom intensity was conducted. The analysis was supplemented by calculations aimed at revealing the effect of aircraft shape variation on its aerodynamic characteristics and possible reduction of sonic boom.

As a result, several means aimed at reduction of sonic boom intensity proved to be effective, namely, backward shift of the dihedral wing combined with a modified form of the wing (longer extension of the wing leading edge), higher sweep angle of outer wings, canards, changed nose, and total redistribution of loading along the aircraft body.

A software code developed for calculating characteristic ray trajectories allowed the primary and secondary sonic boom audibility zones to be determined. As a demonstration example, the code was successfully applied for calculations of audibility zones for aircraft landing in the United Kingdom. The areas exposed to both primary and secondary sonic booms were determined. The direction of landing approach was shown to be of crucial importance for shaping a secondary boom carpet, which could be completely avoided under certain conditions including meteorological conditions.

The effect of aircraft acceleration on the geometry of the sonic boom carpet was also studied. A particular attention was paid to characteristic ray focalization (locations where the sonic boom exhibits maximum intensity). Stringent constraints on aircraft maneuvering were shown to help in avoiding focalization.

Propagation of sound signals with randomly varying amplitude and phase through turbulent atmosphere was analyzed theoretically. Signal amplitude and phase fluctuations in heterogeneous turbulent atmosphere can make the sound level higher as compared with its nominal volume in still air when received by a stationary sonic detector. For analyzing this phenomenon with respect to SST-2 sonic boom problem, a special algorithm was developed.

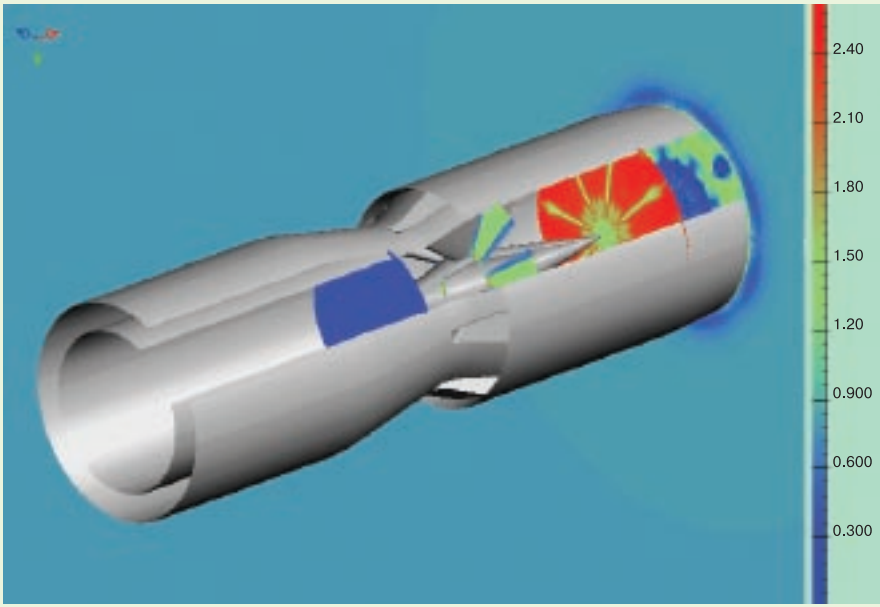


Fig. 58: Axial mixer-ejector nozzle for SST-2

Ozone layer impact

Combustion products penetrating the troposphere and stratosphere can affect environmental photochemistry, thermal balance, and eventually, the Earth's climate. Before the chemical species arrive in the air, they have undergone numerous transformations in aircraft jets and vortices, e. g., water vapor and sulfur oxides SO_2 and SO_3 change into the sulfur acid vapor H_2SO_4. H_2SO_4-based aerosol has a pronounced effect on the atmosphere radiation affecting thereby the air temperature.

The gasdynamic parameters of two-dimensional (2D) plane and axisymmetric flows were numerically analyzed with regard for elementary clusters. Spatial configurations and vibrational mode frequencies of the clusters were estimated on the grounds of statistical and quantum chemistry. Formulae for calculating cluster formation and dissociation rates were suggested. A numerical algorithm for calculating nonequilibrium concentrations of elementary Van der Waals clusters inside a nozzle, emanating jet, and near wake of the SST-2 vehicle was suggested. The combustion process in air was modeled for several flight regimes at various altitudes and for different values of the equivalence ratio.

The studies performed allow a set of recommendations on the flight conditions favorable from the ecological point of view to be suggested. The following conclusions were drawn:

- intensification of jet mixing entails a sharp temperature drop and subsequent "freezing" of chemical reactions, which inevitably reduces damage to ozone in turbulent mixing layers;
- increase in hydroxyl concentration at the nozzle exit by 2–3 orders of magnitude makes the engine jets producing ozone, at least compensating thereby for its absorption by aircraft engines;
- SST-2 engine jets can generate species (that are absent at the nozzle exit) in concentrations much higher than their natural air concentrations. These are sulfur containing (SO_3, HSO_3, H_2SO_4) and nitrogen containing (N_2O_5, HNO_3) chemicals, whose further evolution should be considered in global atmosphere chemistry as they can play an important role in terms of environmental impact.

An engineering methodology for calculating engine emission parameters has been developed. Emission indices of carbon oxides, unburned hydrocarbons, and nitrogen oxides in the cruise flight conditions were determined. Two types of SST-2 vehicle cruise flight conditions were analyzed, namely, subsonic and supersonic, to estimate the required engine thrust. Engine power and parameters for SST-2 cruise flight were determined assuming equality between the required and available thrust for these flight paths. The calculations were performed with regard for loss of the air intake total pressure and nozzle thrust loss, as well as air bleed for powering various aircraft systems.

New criteria for estimating SST-2 ecological soundness were suggested and analyzed. The study resulted in the elaboration of three main criteria for:

- loss of ozone as determined from numerical modeling of aircraft operation scenarios;

Fig. 59: Wind tunnel tests of axial mixer-ejector nozzle for SST-2

• effective specific emission coefficient for discharged gas components (to be determined for every gaseous species in combustion products);

• mass of the gas component introduced in air above the tropopause (to be determined for every gaseous species in combustion products).

The calculations showed that a fleet of 500 SST-2 vehicles should have no significant effect on the Earth ozone layer when flying at a subsonic speed (subsonic cruise flight). However, the altitude gain in supersonic cruise flight would result in higher loss of ozone and elevated values of the specific emission coefficient for NOx, which could become much higher than at subsonic cruise flight. The mass of nitrogen oxides discharged into air above the tropopause was shown to follow a similar trend. The results obtained should be further specified. This is particularly important for 2D and three-dimensional (3D) models of atmospheric circulation.

A new technique of laser monitoring of air contamination has been developed. It is based on diagnostics of trace molecular species in multicomponent mixtures by infrared spectroscopy of double resonance at saturated absorption. The technique suggests preliminary excitation of a selected vibrational level of molecules being detected and differential absorption at the adjacent hot transition. Systematic study into the possibility of spectral diagnostics of SST-2 engine emissions within different bands of contaminant molecule radiation spectrum has been carried out based on available calculated data on concentrations of electronically excited molecules and the developed software complex for analysis of radiation intensity of molecular band systems.

Thus, the calculation techniques developed during the Project and validated against experiments enable

• determining the achievable noise reduction in the ejector noise-suppressing nozzles at a minimum nozzle thrust loss; working out recommendations on the noise-suppressing nozzle design and air route parameters as well as engine control procedures for the aircraft take-off and landing;

• evaluating the sonic boom intensity and ascertaining measures aimed at reducing it by finding an optimal configuration of SST-2 vehicle and its elements; determining the sonic boom carpet and focalization depending on the state of the atmosphere and flight regime along the route;

• applying particular mathematical models for better understanding of physical processes in SST-2 wakes;

• predicting the impact of SST-2 flight on the ozone layer and elaborating the remote sounding methods for monitoring SST-2 discharge compositions.

Obtained Results

The results obtained during the work on the Project allow one

• to determine the achievable jet noise reduction level in ejector noise-suppressing nozzles at minimum loss of nozzle thrust and to advise on the noise-suppressing nozzle design, flight path parameters, and engine control during take-off and landing;

• to estimate the sonic boom level and suggest ways of its reduction by optimizing aircraft configuration and to determine the geometry of audibility and sonic-boom focusing zones depending on the stratified air conditions, SST-2 air route, and flight regime;

• to specify mathematical models of physical processes taking place in SST-2 wake and on the anticipated effect of SST-2 flight on the Earth's ozone layer; to advise on the minimization of SST-2 deleterious impact; and to propose methods for the remote analysis of aircraft discharges; and

• to outline further investigations required for the development of ecologically sound SST-2.

Number:	**#0497**
Full and Short Title:	The Fundamental Investigation and Experimental Working out of the Methods for the Creation of the Ecological Pure, High Temperature, Annular Combustion Chamber for Turbojets **Combustion Chamber for Turbojets**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$167,000 (EU)
Commencement date:	(starting date) March 3, 2005
Duration:	36 months, extended by 2 months
Leading Institute:	MAI (Moscow Aircraft Institute), Moscow, Russia
Contact Information:	Phone: +7 (499) 1584264; 1511373, fax: +7 (499) 1582927, e-mail: AET@mai.ru, website: http://www.mai.ru
Supporting Institutes:	**No**
Collaborators:	SNECMA, Moissy Cramayel, France (Kervistin R, Rollin G)
Project Manager:	RUTOVSKY Vladimir
Contact Information:	Phone: +7 (495) 6126010, e-mail: irina_kravch@mail.ru
ISTC Senior Project Manager:	TEMEEV Sergey, RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

Development of a high-temperature combustion chamber is one of the most important problems as the increase of gas temperature in air-breathing engine improves engine performances. A high-temperature annular combustion chamber with minimum emission can be designed based on principles which are quite different from conventional. If the air-fuel ratio in the combustion chamber with standard operation process decreases to the level of $\alpha < 1.8...1.5$, the combustion efficiency decreases abruptly whereas the value of harmful emissions in the exhaust increases (primarily NOx).

At present, considerable progress in theoretical and experimental investigations of complex flows in combustion chambers has been achieved. The research team of this Project has also got a rich experience in such investigations, in particular those related to the operation process of combustion chamber components. Team's previous works were aimed at providing stable operation of combustion chambers and other elements in the flow path such as frontal devices ensuring air-fuel mixture preparation.

Project Objectives

The primary objective of this Project was to develop recommendations towards a design of pollutant-free high-temperature combustion chamber for gas turbine engine.

Description of the Work

The Work Plan included:

- literature review on low-emission combustion chambers with particular attention to design of swirl vanes and their experimental and theoretical investigations, as swirl vanes determine mixing quality and flame holding;
- experimental investigations of swirl burners;
- experimental investigations of the combustion chamber operation process; and
- recommendations on operation process organization in a low-emission combustion chamber.

At the Moscow State Aviation Institute, a scheme of an annular combustor with fuel supply through a large number of fuel injectors placed in the front section of the combustor is being considered as a possible solution for a low-emission combustor with reduced nitrogen oxide formation in combustion products of hydrocarbon fuels. The frontal device of such a combustor has two parts (Fig. 60):

– a row of combined flame devices (CFDs) in the combustor central part and two axial vane swirlers (AVS); and

– encircling of the row of CFDs from top and bottom.

Fuel is fed to the frontal device, both to the CFDs and AVS. In this scheme, the CFD is the snail fuel swirler, a tangential air swirler, and a cone branch duct with a reverse-flow zone inside. In an annular combustor, the number of such CFDs depends on the combustor diameter and in a first approximation can be selected as the number of injectors for common combustors. The role of the AVS in the annular combustor is played by AVS.

The main characteristics of such a combustor are listed below:

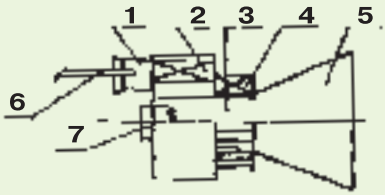


Fig. 60: Schematic of the CFD: 1 – input branch duct; 2 – fuel vortex generator; 3 – mixing chamber; 4 – air vortex generator; 5 – exit duct; 6 – spray nozzle; and 7 – swirl-type burner

• almost all the air and fuel (except for the air cooling the walls) is supplied to the combustor through the frontal device, which provides mixing and combustion of fuel-lean mixture at the optimal use of the combustor volume;

• for good mixing of air with fuel and producing a homogenous air-fuel mixture directed to the combustor, the fuel is fed to the combustor through a large number of injectors;

• the mixing in the main flows of fuel and air takes place in the AVS in small channels, which enables to burn the air-fuel mixture at low turbulence within a short distance;

• the air passing through the CFDs and AVS is swirled, so that all the flows from the combustor center to its periphery have reverse swirling. This provides generation of big tangential velocity gaps, an increased turbulent level in the flow, and accelerated mixing of air with fuel in the regions of flow interaction.

Obtained Results

Analysis of the literature on modern and advanced combustion chambers for aviation engines indicated that most perspective and widely spread are the frontal devices with so-called swirl burners with premixing and flame holding. Premixing followed by mixture burning in the conditions of elevated turbulence of swirled jets leads to smoke reduction in the combustion chamber below sight limits as well as to a considerable decrease of other noxious substances in the combustion products.

A universal experimental facility for investigating the operation process in combustion chambers of gas-turbine engines and their individual elements has been developed at the Moscow Aviation Institute.

A systematical study of the flow structure and temperature distribution in a wake of the frontal device had been performed. In this device, the opposite rotating flows were used to intensify mixing. It has been demonstrated that such a swirl burner generated zones with a high turbulence level. Along these zones, the axial component of the velocity vector decreased. As a result, the axial velocity changed the direction near the axis and the recirculation zone was generated. In the recirculation zone, a tangential component of flow velocity is produced and very intense mixing of combustion products with reactants takes place.

In the aviation combustion chambers, which are very short, to quickly eliminate swirling structures in flow and to ensure the uniformity of flow parameters at the combustor exit, the swirlers with opposite flow rotation should be used.

A model combustion chamber of novel configuration has been developed. The model chamber simulates the operation process in a two-zone low-emission combustor. At the design stage of the model combustor, computational and theoretical estimations of main characteristics of promising variants have been obtained using a suggested technique of three-dimensional (3D) calculations of temperature in a gas-turbine engine combustor. The calculations made it possible to reduce the number of iterations as well as the time needed to get the final variant of the model combustor. The calculations showed that fuel atomization and evaporation were the governing processes determining the temperature field in the combustor. It has been demonstrated that in the model combustor under study, the major amount of fuel should be supplied to the AVS. The amount of fuel supplied to the CFDs should provide engine operation in the idle mode and stable combustion at all operation modes.

The combustion process in the model combustor was investigated numerically and theoretically at different fuel distributions between the main and auxiliary combustion zones. Different schemes of the model combustor were assessed in terms of their NOx emission characteristics. The numerical and theoretical studies showed

that the developed model combustor exhibited reduced nitrogen oxide emissions. The mechanism of NOx reduction was explained by mixing acceleration which led to homogenous combustion.

A model combustion chamber of tubular configuration has been designed and manufactured (Figs. 61 and 62). Experimental investigations of lean blow-out characteristics of the model combustion chamber with a complex frontal device including a swirl burner and additional swirlers were performed. The proposed model chamber had a wide range of stable operation. The obtained experimental data fully confirmed adequacy of the developed mathematical model.

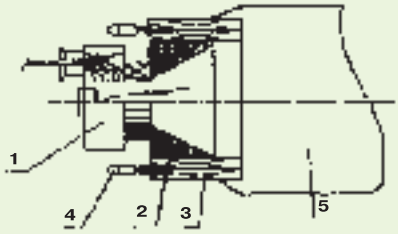


Fig. 61: Schematic of front device for a tubular combustion chamber: 1 – CFDs; 2 and 3 – AVS; 4 – injectors of fuel supply in AVS; and 5 – flame duct

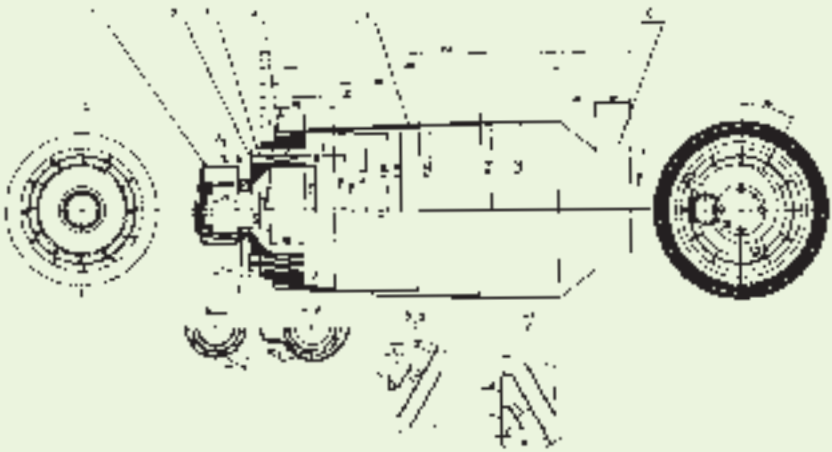


Fig. 62: Tubular combustion chamber: 1 – CFDs; 2 – funnel; 3 – AVS; 4 – ring-shaped flame holder; 5 – flame duct; and 6 – exhaust branch duct

Project Number:	**#0627**
Full and Short Title:	Complex Investigations of Possibilities of Reduction of Aviation Influence on Environment and its Utilization for Ecological Monitoring **Airborne Monitoring**
Tech Code/Area/Field:	SAT-SAF/Space, Aircraft and Surface Transportation/Space Safety
Status:	Project completed
Technology Development Phase:	Technology development
Allocated Funding:	$100,000 (EU)
Commencement date:	(starting date) August 1,1998
Duration:	12 months
Leading Institute:	Gromov Flight Research Institute, Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5565897; 5565607, fax: +7 (495) 5565334, e-mail: tsyplakov@liicom.ru, website: http://www.lii.ru
Supporting Institutes:	No
Collaborators:	Deutsche Forschungsanstalt fur Luft- und Raumfahrt e.V., DLR, Institut fur Optoelectronik, Oberpfaffenhofen, Germany (Volker Tank)
Project Manager:	DEDESH Victor
Contact Information:	Phone: +7 (495) 5565608; 5565627, fax: +7 (495) 5565586, e-mail: kd3@aha.ru
ISTC Senior Project Manager:	TYURIN Igor
Contact Information:	Phone: +7 (495) 9823196, fax: +7 (499) 9783603, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

The Project was aimed at developing recommendations on reducing the impact of civilian aircraft on the environment, including noise at take-off and landing, atmospheric pollution with engine exhaust, and systems for monitoring noise and emissions.

Project Objectives

The objective of the Project was to provide theoretical substantiation and practical recommendations for research methodology, mathematical modeling, experimental tools and facilities, as well as full-scale (in-flight and ground-based) investigations in support for further advance in lowering the influence of aviation on environment and using the aviation for ecological monitoring.

Description of the Works

The following three tasks were solved within the Project:

Task 1. Theoretical substantiation of approaches to decrease the community noise by means of optimizing the aircraft trajectory of climb (take-off) and descent (landing).

Task 2 Development of methods for airborne monitoring of troposphere contamination and investigation of the influence of aircraft engine emissions on atmosphere contamination in cruise flight conditions.

Task 3 Theoretical substantiation of methodologies for complex airborne monitoring of land, water, and atmosphere by sensors operating in the various bands of electromagnetic spectrum.

Obtained Results

• A method for determining an anticipated noise level at application of various piloting procedures has been developed. The method is based on acoustic data ("noise matrices") obtained experimentally and on the known variation of flight parameters. A good agreement of predicted and measured results was obtained.

• A model permitting the effectiveness of different low-noise piloting procedures to be evaluated has been developed. For final verification of the model in terms of noise reduction, flight tests are required.

• The type of landing approach trajectory as well as the hardware/software providing such a trajectory were recommended. The trajectory in the airport zone was shown to be represented by a particular three-dimensional (3D) curvilinear path. To perform airplane piloting along the recommended 3D low-noise trajectory, a provision for a suite of standard flight control complexes should be made.

• A method of control loop synthesis was suggested. The control loop formed by this method permits the mutual influence of lateral/directional and longitudinal motions, influence of variable speed of flight, and influence of high-lift devices extension on the control quality to be compensated. The efficiency of such a control loop was proved in flight tests on Tu-154 and An-22 airplanes.

• Recommendations on in-flight studies of the effect of aircraft emissions on atmospheric air contamination and on physical and chemical processes in the atmosphere for conditions of cruise flight in the upper troposphere have been developed.

• Methodological support was developed for in-flight studies of quantitative and qualitative changes in composition of gaseous and aerosol components of atmosphere contamination caused by aircraft engine emissions in various zones of aircraft wake and in air corridors of cruise flight. Depending on the set of measuring tools installed on board of a sounding airplane, the measurements of gaseous and aerosol components can be performed by direct or remote sounding in the exhaust jet and in the wake.

• The approaches to determine gaseous species concentrations at jet-engine nozzle exit in flight conditions were considered.

• Traffic intensity of civil aircraft in the airspace of the Russian Federation was analyzed. The most contaminated regions of air traffic and the busiest routes in those regions have been identified. These routes were recommended for further studies.

• A methodology of in-flight studies of the effect of civil aircraft emission on troposphere contamination in a chosen segment of air corridor has been developed.

• Recommendations on creating a system and methodology for complex in-flight monitoring of land, water, and atmosphere based on modern high technologies of data collection and processing were developed. The approaches for choosing the sites of airborne monitoring meeting the requirement of the maximum efficiency from the aviation aids were suggested.

• General and specific requirements were formulated for multizonal terrestrial surface images in terms of the effectiveness of integrated digital processing and visualization of spectrozonal image totality (total combinational). A set of criteria was developed as to the quality and optimality of the multizonal video information visualization for seeking the formation of local anomalies at terrain using brightness and spectral approaches.

• Demonstration software with the description of functional capabilities and user interface has been developed. The software provides the automated interpretation of video information with high completeness and validity and delivers the results in quasi-real time in the form of unified synthesized image for further applications in conventional technologies of ecological monitoring.

Number:	**#0627.2**
Full and Short Title:	Complex Investigations of Possible Reduction of Aviation Impact on the Environment and its Utilization for Ecological Monitoring **Airborne Monitoring**
Tech Code/Area/Field:	ENV-APC-MIN/Environment/Air Pollution and Control/Monitoring and Instrumentation
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	189,340 € (EU)
Commencement date:	(starting date) April 1,2000
Duration:	12 months
Leading Institute:	Gromov Flight Research Institute, Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5565897; 5565607, fax: +7 (495) 5565334, e-mail: tsyplakov@liicom.ru, website: http://www.lii.ru
Supporting Institutes:	No
Collaborators:	Deutsches Zentrum fur Luft- und Raumfahrt e.V./Institut fur Optoelectronik, Oberpfaffenhofen, Germany (Tank V, Dewes W); European Commission/Joint Research Center/Space Applications Institute, Ispra, Italy (Winter R); National Aerospace Laboratory NLR, Amsterdam, The Netherlands
Project Manager:	DEDESH Victor
Contact Information:	Phone: +7 (495) 5565608; 5565627, fax: +7 (495) 5565586, e-mail: kd3@aha.ru
ISTC Senior Project Manager:	TYURIN Igor
Contact Information:	Phone: +7 (495) 9823196, fax: +7 (499) 9783603, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

This Project is the direct continuation of the ISTC Project #0627 (feasibility stage).

Project Objectives

The objective of the Project was to develop a methodology (experimental facilities and methods) of in-flight studies of the environmental impact of aviation in terms of noise and atmosphere contamination and of using aviation for ecological monitoring.

Description of the Work

There were three Tasks in the Project.

Subject 1 Development and realization of civil-aircraft piloting procedures at the stages of

climbing and descending for landing with the constraint of minimum noise generated by the airplane on the terrain.

Subject 2 Development of tools for in-flight monitoring of troposphere contamination and for determining the impact of aircraft engine emissions on atmosphere contamination in cruise flight conditions.

Subject 3 Development of the system and methodology of complex airborne monitoring of ground, water, and atmosphere with sensors operating in various electromagnetic spectrum bands and with up-to-date technologies of data processing.

The following works were carried out:

Subject 1

A list of additional onboard equipment with compositions and functions permitting the low-noise path to be realized during aircraft landing with keeping a prescribed safety level has been developed. In the course of preparations to flight trials, the following tasks were solved:

- the schemes of landing approach were refined to provide the reduction of the community noise in flyby the protected area from the side (on an arc of set radius in continuous descent) or flyover (with flyover the protected zone on a more steep glide slope);
- the software/hardware were adjusted to provide the differential mode of operation of onboard SNS equipment;
- the equipment for community noise measurements was prepared and the measuring sites were identified;
- the software/hardware means were prepared for reference measurements of the aircraft trajectory and for determining relative coordinates of noise measurement points;
- the program of experiments was compiled.

The executed program of flight trials aimed at the development of low-noise piloting procedures in the zone of airfield confirmed the possibility of landing approach down to a height of H = 100–60 m along a complex-shape three-dimensional (3D) trajectory in a control-wheel mode. For a given zone of protection from the aircraft noise located under the standard glide path in the region of outer marker locator, the application of curvilinear landing approach with continuous descending brings to a noise lowering on terrain by 4–8 dB (5–8 TPNdB) depending on the location of measurement point, meteorological conditions, accuracy of keeping the preset path, and engine operating regime. At landing approach with a two-segment glide slope, similar measurements resulted in the noise level reduction by 4–10 dBA (4–8 TPNdB).

Subject 2

The methodology and experimental facilities for conducting in-flight studies of the influence of aircraft emission on atmosphere contamination in cruise flight conditions have been created and tested at Su-24 airplane used as a flying laboratory (Fig. 63). The information and measurement complex, installed in the flying laboratory permitted the coordinated maneuvers in a paired flight or in the zone of air corridors to be performed accompanied with measurements and data acquisition of aerodynamic characteristics as well as physical and chemical composition of atmospheric air.

The methods and means for sampling and accumulation of air samples in the airplane wake and in the air corridor of cruise flight of passenger and transport aircraft, as well as the methods and means for subsequent gas analysis in chemical laboratories aimed at determining the concentrations of nitrogen oxides, carbon monoxide, methane, unburned hydrocarbons, and products of their destruction have been developed and tested.

A Su-24 sounder equipped with the means for measuring airflow pressure-pulsation fields in cross sections of the aircraft wake and air humidity, and for determining the airplane position on the chart of terrain in the air corridor zone and the distance

to a gas-generator airplane in a paired flight have been manufactured and tested. The software for automated data processing during and after flight has been developed and tested as well.

Subject 3

The methodology of performing in-flight experiments with collecting and processing the results of ground surface sounding for ecological assessments has been developed. The procedure of airborne remote monitoring of environment in production sites, refining, and transportation of gas-and-oil products has been developed. The ways of improving the visual interpretation procedure based on automated image processing have been identified. Thermal models of different objects and backgrounds on the earth surface have been developed permitting the changes in temperature to be determined and the optimal time for ecological monitoring to be selected. The algorithms and software have been developed to realize the methodology of automated data processing.

The developed software has been realized in the form of experimental prototype of the program complex for automated processing of multizonal images, including the combination of modules for image processing integrated in a common graphical envelope msiproc.exe. The software possesses wide functional capabilities.

Obtained Results

Subject 1

- Analysis of community noise related statistics.
- Mathematical simulation of expected noise level across various nonstandard approach flight paths.
- First stage of in-flight experiments demonstrated noise abatement with regard to the multisegment steep and “curve” approach.

Subject 2

- Development of onboard means for air and gas sampling/storage and gas analysis technique.
- Su-24 based Flying Test Bed sounder equipped and put into operation.
- Recommendations for specific research flights (within heavy air traffic corridors and in chase flight).
- Initial stage of flight research carried out on Su-24 airplane.

Subject 3

- Recommendations for complex aerial monitoring of ground, water, and atmosphere based on diverse physical principles.

Fig. 63: SU-24 aircraft-sounder compartment (pod) for air and gas sampling and storage

Number:	**#1477**
Full and Short Title:	Investigation of Dynamics, Stability and Remote Sensing Methods of Vortex Multicomponent Flow in the Wake of Subsonic Civil Aircraft **Vortex Flow in the Aircraft Wake**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Technology demonstration
Allocated Funding:	$50,000 +50,000 € (EU: 50,000 €, US: $50,000)
Commencement date:	(starting date) June 1, 2002
Duration:	18 months, extended by 5 months
Leading Institute:	VNIIEF, Sarov, N. Novgorod reg., Russia
Contact Information:	Phone: +7 (83130) 44802, fax: +7 (83130) 29494, e-mail: staff@vniief.ru, website: http://www.vniief.ru
Supporting Institutes:	**No**
Collaborators:	Aerospatiale Airbus, Toulouse, France
Project Manager:	IL'IN Sergey
Contact Information:	Phone: +7 (83130) 44802, fax: +7 (83130) 29494, e-mail: staff@vniief.ru
ISTC Senior Project Manager:	PRADAS-POVEDA Jose-Ignacio, SAFRONOVA Olga
Contact Information:	Phone: +7 (495) 9823166, fax: +7 (499) 9784637, e-mail: safronova@istc.ru
ISTC Website:	http://www.istc.ru

Background

One of major ecological problems, associated with the development of new civil subsonic and supersonic airplanes, is the understanding of aircraft impact on the Earth atmosphere. The pollution effect of engine exhausts on the atmosphere depends on flight altitude, concentration and chemical composition of exhaust gases, and exhaust jet interaction with the aircraft trailing-vortex system. Condensation of water vapor contained in the engine jet and in the atmosphere leads to the onset of contrail and exerts a pronounced effect on cloud formation. Spreading of engine jets and their mixing with the surrounding medium depend on the velocity field in the far aircraft vortex wake and are governed by the dynamics and stability of the trailing vortex as well as by its breakdown. All the processes mentioned can significantly affect the chemical composition of the atmosphere, its optical characteristics as well as solar radiation and heat transfer through the atmosphere.

Project Objectives

The objective of the Project was to develop mathematical models of the aircraft vortex wake dynamics, particle formation in the wake, stability of the single-phase and two-phase trailing vortex flows, simulation of the breakup of the subsonic and supersonic aircraft jet/vortex wake, and novel methods of laser remote diagnostics in experiments for gas flow with chemical admixtures. The created models and methods could be used for obtaining reliable estimations of harmful effects produced by subsonic and supersonic civil aircraft on Earth atmosphere; for developing new approaches to reduce these effects in flight corridors with intense traffic. These studies open a clue to the solution of various problems associated with dangerous influence of trailing vortices on aircraft near operating airports.

Description of the Work

The following issues related to the impact of aircraft on the Earth atmosphere have been studied in the Project:

– numerical modeling of aircraft vortex wake;

– experimental modeling of engine jet near the nozzle; and

– development of new methods of remote laser control.

Experimental investigations of gasdynamic parameters and chemical composition of an exhaust jet downstream of the aircraft engine nozzle aimed at determining the initial distributions of gasdynamic parameters and concentrations of harmful species at the engine nozzle exit and at creating an experimental database incorporating spatial distributions of main species concentrations in aircraft engine exhaust jets had to be performed. Within the Project, it was planned to develop the experimental setup based on a combustion chamber fuelled with real aviation kerosene and to measure the concentrations of CO_2, H_2O, NO, and CO using the method of jet probing by the radiation of tunable CO_2-laser emitting within the range of 9–11 micron. The experimental data obtained were intended to be used as initial data for numerical simulations of jet/vortex wake flow behind the subsonic and supersonic aircraft.

Investigations of the vortex sheet roll-up process and specific features of vortex flow development, as well as modeling of near and far regions of the subsonic and supersonic aircraft vortex wakes were planned. It was intended to develop the appropriate models and to study numerically the roll-up process of the vortex sheet and trailing vortex formation in the near vortex wake region taking into account the influence of the exhaust engine jet and presence of water vapor in the wake. The features of both laminar and turbulent vortex flows in the vicinity of the trailing vortex viscous core, condensation of water vapor contained in the engine jets and in the surrounding air, formation of liquid and solid particles in the near field had to be studied as well. The influence of heat and mass exchange between the air and the condensing and freezing particles on the vortex dynamics, the evolution of small-amplitude disturbances in the single-phase and multiphase turbulent vortex flows, the influence of the growing disturbances of the unit trailing vortex on the Crow-type instability of the trailing vortices pair were also planned to studied. The initial stage of contrail formation behind the aircraft had to be simulated. Theoretical investigations included the development of physical models and formulation of the boundary-value problems for describing the processes under consideration. It was intended to develop the mathematical methods, numerical algorithms, and noncommercial computer codes for solving the formulated problems.

Novel methods of remote diagnostics of gaseous medium in the aircraft wake had to be developed. The following aspects were taken into consideration:

– infrared excitation of major components in engine jet by monochromatic, multifrequency and chirped-frequency laser action under conditions of different processes of collisional relaxation; and

– equilibrium and nonequilibrium vibration-rotational absorption of sounding infrared radiation in the nonhomogeneous aircraft jet.

It was intended to study a double-frequency variant of photoacoustic spectroscopy, as well as to determine a possibility of utilizing nonlinear interaction of two laser beams for the flow diagnostics. Novel methods based on the indicated phenomena of nonlinear spectroscopy will permit the composition of complex gas admixtures to be determined at various unfavorable for remote sensing conditions.

Obtained Results

1. Experimental module with a combustion chamber, automatic registration, and control system.

2. Methods of measuring jet physical characteristics.

3. Discrete tunable CO_2-laser operating within the wavelength range of 9–11 mm.

4. Database containing initial distribution of concentrations, velocities, and other parameters of engine jet at the nozzle exit.

5. Novel methods of remote sensing of civil airplane exhaust jets.

6. Mathematical models and computer codes for the calculating particle formation and growth in the wake.

7. Mathematical models and computer codes for calculating main parameters of dynamics and development of vortex flow, modeling near and far airplane vortex wake in concurrent subsonic and supersonic flows.

8. Mathematical models and computer codes for numerical simulation of the initial stage of contrail formation and influence of condensation/evaporation processes on the aircraft vortex wake dynamics.

9. Mathematical models and computer codes for investigating the evolution of small-amplitude disturbances in single-phase and two-phase viscous-core flows of the trailing vortex.

10. Mathematical models and computer codes for numerical simulation of Crow instability of the line trailing vortex pair with respect to intrinsic disturbances of the isolate viscous vortex core.

11. Mathematical models and computer codes for studying strong laser excitation of major components of airplane jets in the field of infrared radiation of various intensity, duration, and spectral composition.

12. Recommendations on the development of active methods of investigation of real airplane wakes.

13. Determination and description of mechanisms of contrail formation.

Project Number:	**#2249**
Full and Short Title:	Supersonic Civil Aircraft Impact on Environment **Supersonic Aircraft Impact on Environment**
Tech Code/Area/Field:	ENV-APC/MIN/Monitoring and Instrumentation Environment/ Air Pollution and Control SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research
Allocated Funding:	$120,000 +200,000 € (EU: 200,000 €, Other Funding Sources: $120,000)
Commencement date:	(starting date) 01.11.2003
Duration:	24 months, extended by 3 months
Leading Institute:	Central Aerohydrodynamic Institute (TsAGI) Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5564101, fax: +7 (495) 7776332; 5564337, website: http://www.tsagi.ru
Supporting Institutes:	No
Collaborators:	AIRBUS Industrie, Blagnac, France (Dr. E. Maury, Dr. A. Anger, Dr. R. Forster, Dr. J.-J. Mirat); ONERA, Chatillon sous Bagneux, France (Prof. G. Elias, Dr. R. Ramarason); DLR, Wessling, Germany (Dr. Volker Grewe)
Project Manager:	SHUSTOV Andrey
Contact Information:	Phone: +7 (495) 5564412; 5564072, fax: +7 (495) 556433; 9110019, e-mail: shustov@tsagi.ru
ISTC Senior Project Manager:	TYURIN Igor
Contact Information:	Phone: +7 (495) 9823196, fax: +7 (499) 9783603, e-mail: tyurin@istc.ru
ISTC Website:	http://www.istc.ru

Background

Further development of supersonic civil transports calls for solutions to a number of ecological problems, in particular, the problems of community noise, sonic boom (SB), and air pollution. This Project is a direct continuation of the ISTC Project #0200 “Ecological Aspects of the Impact of a Supersonic Civil Aircraft of the Second Generation (SST-2) of Environment. Methods of Reducing Sonic Boom, Community Noise, and the Supersonic Civil Aircraft Impact on the Ozone Layer.”

Project Objectives

The objective of the project was to obtain a more complete knowledge on fundamental aspects of acoustic and aerodynamic phenomena attending the appearance of aircraft community noise, SB, and impact on the atmosphere, as well as knowledge required for reducing the environmental impact of advanced air vehicles.

Description of the Work

Task A. Community noise reduction

Experiments with nozzles were carried out in TsAGI TPD wind tunnel. Weight studies comprised measurements of air flow in nozzle models, test section Mach number, available nozzle pressure ratio, nozzle ideal thrust, nozzle flow coefficient, and the longitudinal component of nozzle thrust. In addition to the listed thrust characteristics of the nozzle models, the analysis included the pressure fields in the jets.

The cold-jet acoustics experiments on the nozzle models were performed in the anechoic chamber AK-2, whereas the studies of acoustic characteristics of jets with temperature up to 900 K were performed in acoustic chamber C17-A4. Both chambers were equipped with necessary measuring tools and enabled determination of noise intensity and spectrum for the nozzle models under study.

Universal software codes were developed for the nozzles and for the complete-design models for noise generation in supersonic jets of complex geometry. The development of the complete-design models for noise generation in the complex-geometry nozzles implied profound studies of axisymmetric jets based on analytical and computational analysis and physical mechanisms of noise generation, thus enabling the development of innovative approaches to noise suppression.

The database aimed for validating the developed computational techniques for simulating model flows and establishing the mechanisms of aerodynamic noise suppression due to the complex geometry effects has been developed. Various technical solutions for SST-2 noise-suppressing nozzles as well as test models of the SST-2 ejector nozzles have been verified. A unique innovative technique of measuring turbulent jet noise based on the synchronous analysis of signals from the microphone grid has been developed and used for obtaining the azimuth structure of jets acoustics.

Task B. Studies of influence of atmosphere conditions on SB and possibilities of its reduction

Sonic boom signatures were analyzed for supersonic airplanes of different configurations flying at different meteorological conditions with the aim of obtaining information on the influence of the state of the atmosphere on the intensity and form of SB signature. One of Project objectives was to develop a data bank for evaluations of existing models accounting for the influence of turbulence on the characteristics of SB. The analysis based on the comparison of measured and predicted SB signatures was obtained with the use of an available code. The algorithm of this code did not account for the effect of turbulent atmosphere. The discrepancies between measured and predicted SB signatures reflected the effect of atmospheric turbulence. A new model was developed for evaluating the probabilities of SB intensity for supersonic aircraft accounting for the influence of atmospheric turbulence.

The methods of the theory of random processes and the hypothesis on locally homogeneous and isotropic turbulence, as well as the assumption of small integral scale of velocity correlations as compared with the thickness of the layer of turbulent fluctuations were used in the model.

Collecting and processing of the data on atmospheric turbulence permitted the relationships between the parameters of atmospheric turbulence and mean parameters, such as wind shears and temperature gradients to be identified.

In the frame of the previous ISTC Project #200, the code for calculating the trajectories of secondary SB propagation was developed.

In a new Project, this code was further developed to calculation the secondary SB intensity. For this purpose, reflection of disturbances from layers of thermally-inhomogeneous atmosphere in the presence of wind was analyzed. The analysis of solutions was conducted for a particular case, when the integrals determining attenuation coefficients had a nonintegrable singularity. The ways of analytical continuation of the solution behind the turnaround point of the ray were searched and the singularities of SB wave propagation in secondary fields of influence were investigated.

The surface design methods for supersonic aircraft with low level of SB and minimum losses in lift-to-drag ratio were based on both linear (panel method) and nonlinear (integrating Euler equations) aerodynamics.

The efficiency of using natural and artificial laminarization (of the boundary layer on the wing surface of supersonic aircraft) concepts was evaluated with an aim to increase the lift-to-drag ratio and reduce the level of SB on the basis of semiempirical method.

Task C. SST-2 atmospheric impact

The boundary-value problems were formulated and appropriate computer codes were developed for predicting the influence of various initial conditions on the processes of vortex sheet rolling-up and on the characteristics of two-phase turbulent flow taking into account interphase heat and mass transfer in the vortex wake behind a small aspect-ratio wing.

Experimental studies were conducted in the low-turbulence subsonic T-36 wind tunnel at TsAGI. The wing model and rigging allowing the replacement of tip vortex generator and performing pneumometric and thermoanemometric investigations of the effect of various lift-force distributions and boundary layer state on the near flow-field structure behind a wing were designed and manufactured. The spectrum of turbulent fluctuations in a jet vortex wake was rather complex. In particular, along with large-scale energy-carrying vortices (frequency range I), it can contain Kolmogorov (range II) and Heisenberg (range III) branches predicted theoretically. Besides, the spectrum can be anisotropic and time-and-space varying.

The forms of ice crystals produced in natural conditions in the atmosphere were very much different, namely, needles, rods, columns and their combinations, flat plates, e. g., hexagonal or consisting of separate flat sectors, stars or tree-like, and many others. In a number of cases, the crystal growth took place in some highlighted directions instead of spherically symmetric patterns. These facts allowed finding a number of particular cases permitting analytical consideration of kinetic equations for colliding, evaporating or growing due to condensation particles. Condensation, concentration or temperature interactions of aerosol particles in the wake occurred in the transitional regime of gas flow around a particle (from a free-molecule to continuum flow). The mathematical model for this flow was the Boltzman kinetic equation. As was shown in the previous investigations, Direct Simulation Monte-Carlo method (DSMC) was a suitable method for the numerical solution of the Boltzman equation in the weakly nonlinear problems under study.

All the problems under study were multi-parametric with the parameters specifying

– characteristics of the gas flow around a particle (full pressure characterizing the flow regime, partial pressures, and temperatures);

– geometrical characteristics (particle sizes, shapes, and spacing);

– inner particle structure (sizes of pores and their shapes, pore extent, and its distribution inside a particle);

– rate constants of heterogeneous reactions (coefficient of condensation/absorption of the components, etc.).

To reveal the characteristic properties of the processes under study, similarity criteria, and characteristic dependencies, a theoretical study based on asymptotic and/or approximate analysis of the phenomena was required. Therefore, the asymptotic analysis was conducted both

for the flow regime and for other parameters (geometrical, reaction rate constants, etc.). This analysis and numerical simulations with the DSS and Monte-Carlo methods resulted in the determination of force (condensation and temperature) interaction of aerosol particles. The asymptotic analysis in the continuum regime was supplemented with numerical simulation based on the Navier–Stokes equations or their generalizations for slow nonisothermal gas flows with suitable boundary conditions of slippery, condensation, etc. The characteristic features of both systems of equations were small pressure variations and the absence of mechanical energy dissipation. To study the influence of aerosol particles porosity on the effective particle surface (for various heterogeneous processes or reactions), asymptotic and approximate approaches and geometrical models developed earlier during the investigation of condensation processes were employed.

Due to the numerical analysis of new physical and chemical processes (reactions), the modification of numerical methods to study the flow in single pores and outside a particle was elaborated. The quantitative analysis of the flow of gas mixtures with catalytic reactions in the porous particles on the basis of macroscopic averaged definition of the flow in the porous particles was carried out.

Some traditional spectroscopic methods applicable for wake diagnostics were considered to be applied in the Project, namely,

– spontaneous Raman scattering;
– laser-induced fluorescence;
– long-path differential absorption;
– IR Fourier spectroscopy, etc.

When comparing these methods, the influence of line overlap in multicomponent mixture was evaluated quantitatively using the partial and cross sensitivity and selectivity criteria. Also, when developing an alternative method of spectroscopic detection of different gaseous species in the airplane wake, the possibility of using for this purpose laser excitation of a selected volume of medium was considered. The processes of rotational relaxation and laser excitation of molecular gas were simulated by means of rate equations for populations of vibration-rotational levels in the conditions of Maxwell equilibrium. The calculations were performed using the latest versions of HITRAN and GEISA spectroscopic databases.

Task D. Efficiency of methods developed for reducing of harmful impact of SST-2 on the environment

Calculations of engines characteristics, gas parameters in the nozzles of jet engines with the bypass ratio 0.5...2.5, and emission characteristics were performed. The preliminary conceptual design of SST-2 vehicle with take-off weight 20...200 t, rational trajectory of flight, and required levels of decreasing of community noise was suggested.

Characteristics of SST-2 power plant variants, mathematical models of power plants, their optimized parameters and control laws designed for noise reduction and high performance in cruise flight were obtained. The existing criteria of SST-2 impact on environment during the cruise (subsonic or supersonic) flight and flight in the vicinity of airport were analyzed and new criteria were proposed. The methods for calculating the impact of SST-2 exhaust products on the atmosphere were developed.

The effect of newly developed technologies (aimed at reduction of community noise, SB, and exhaust emission) on the characteristics of SST-2 vehicle variants has been analyzed their efficiency in terms of reducing the SST-2 impact on the environment was evaluated.

The rational aircraft parameters, as well as power plant and trajectory control during take-off and landing were estimated using the modified versions of computer codes for simulation and optimization of aircraft and engine parameters and for modeling the flight dynamics during take-off and landing regimes. The conceptual design and system analyses were performed with the aid of computer aided design tools available in TsAGI.

Obtained Results

The following main results were obtained:

– the experiments with sector noise-suppressing nozzle models showed that the sector nozzle is a promising configuration for noise suppression in SST-2;

– the integrated numerical methodology for investigating thrust and acoustic characteristics of nozzles with complex 3D geometry has been developed. Calculations of sound fields were performed for realistic nozzles and for different regimes of exhaust jet flows;

– the approach to actively influence the sound-radiating turbulence in supersonic jets using its section corrugation has been suggested and verified;

– it was shown that for efficient application of sound absorbing coatings in the ejector duct, artificial methods allowing localization of the most significant sources in a limited region of the ejector duct should be used. Such methods can be based on forced mixing between the main flow and coflow in the ejector duct. Application for the invention "Method of reducing the jet noise: Nozzles with noise suppression (the variants)" has been submitted;

– the results of measurements of SB signature generated by Tu-144 and Concorde airplanes were collected to form a data base. The analysis of the influence of atmospheric conditions showed that the distribution of probability of SB intensity for nominal meteorological conditions was close to the log-normal law. However, for the developed turbulence and cloudiness, there were essential deviations from the log-normal law at relatively large and small overpressures. The data obtained are of great practical importance for planning future supersonic flights;

– on the base of the model of isotropic atmospheric turbulence, the empirical method for evaluating probable deviations of SB parameters from the predicted values has been developed. The results of calculations by the suggested method agree qualitatively with experimental data trends. The next possible step in investigations of atmospheric turbulence effects could be the implementation of the new noncommercial code in a routine SB software code;

– the mathematical model of secondary SB propagation through singular points (turnaround points of rays) has been developed. Parametric investigations of SB intensity when passing through a turnaround point were conducted. Specific features of propagation of disturbance fronts were analyzed depending on the state of the atmosphere and various trajectories and flight regimes of an airplane. To analyze SB intensity, the wave passage through a caustic surface was considered;

– the method of designing of a mean camber wing surface for a supersonic passenger airplane was developed. The design principle was based on the construction of a mean camber line of wing profiles which would ensure minimum pressure drag induced by the lift and, simultaneously, fulfillment of restrictions on the level of SB on the ground;

– some versions of aerodynamic compositions of supersonic airplanes in different classes of take-off weight with low level of SB, high level of performances and weight efficiency have been proposed. The analysis of the results of wide-range parametric investigations has demonstrated that for supersonic airplanes of administrative class (mass 450 t, length 40–45 м), there are strong grounds to expect a possibility to reduce SB loudness below 65 dBA;

– recommendations to reduce SB were suggested, which encounter (*i*) the use of developed V-shaping of wing main and console parts; (*ii*) the use of a "minimizing" body of revolution as a nose part of the body and weal curving for the central axis of the body; and (*iii*) transferring engine nacelles on the upper wing surface.

Number:	**#3097**
Full and Short Title:	Development of Methods to Research Atmosphere Contaminations, Conditions of Formation and Composition of Airplanes' Condensation Trails **Airplanes' Condensation Trails**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics ENV-APC/Environment/Air Pollution and Control
Status:	Project completed
Technology Development Phase:	Basic and Applied research
Allocated Funding:	$60,000 +199,520 € (EU: 199,520 €, Other Funding Sources: $60,000)
Commencement date:	(starting date) September 1, 2006
Duration:	24 months, extended by 3 months
Leading Institute:	Gromov Flight Research Institute, Zhukovsky, Moscow reg., Russia
Contact Information:	Phone: +7 (495) 5565544; 5565607, fax: +7 (495) 5565334, website: http://www.lii.ru
Supporting Institutes:	**No**
Collaborators:	AIRBUS SAS, Blagnac, France (Forster R); Deutsches Zentrum fur Luft- und Raumfahrt e.V./Institut fur Physik der Atmosphare, Wessling, Germany (Junior A)
Project Manager:	DEDESH Victor
Contact Information:	Phone: +7 (495) 5565608, fax: +7 (495) 5565627, e-mail: kd3@aha.ru
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

Global climate change is a world-wide recognized issue. Global warming is a consequence of the industrial activity of the mankind, including transport system. Aviation, as a part of the global transport system, in addition to direct pollution of atmosphere by carbon and nitrogen oxides (CO_2 and NOx), leads to formation of condensation traces or contrails (Figs. 65 and 66). Contrails form as a result of condensation and freezing of water steam contained in exhaust jets and initiate formation of cirri which play a key role in radiation balance of heat exchange between the atmosphere and the earth surface. Formation of aircraft condensation traces is a complex physical and chemical process depending on many factors including particular aircraft and engine characteristics.

Project Objectives

The objectives of the Project were

- to study quantitatively the process of contrail formation, its key parameters and conditions with respect to airplane type, engine type, and flight regime; and
- to develop a comprehensive methodology of quantitative valuation and forecast of contrail formation using a specially equipped flying test bed based on Tu-154 sounder/generator airplane.

Description of the Work

The following scientific and technical tasks were solved:

- development of the methodology for calculations and forecast of contrail formation conditions, in particular, humidity supersaturation degree in the process of mixing exhaust jet with the ambience;
- development of the methodology for experimental studies of contrail formation conditions using flying test beds with contrail probing and generators; and
- development of the methodology for comparing computational results with experimental data and evaluating the influence of aircraft engine characteristics on contrail formation at specific ambient conditions.

Obtained Results

1. A quantitative predicting model of steady contrail formation in the near field of exhaust jets of airplanes with different engine types has been developed. As the criterion for contrail formation, the maximum humidity supersaturation index h_Σ was used. It consisted of two terms, $h_\Sigma = h_M + e_{amb}$, where h_M is the maximum supersaturation with respect to water or ice at mixing of the exhaust jet with dry atmosphere ($e_{amb} = 0$) depending on engine characteristics, ambient temperature, and ambient pressure (flight altitude), and e_{amb} is the atmospheric humidity at the flight altitude. According to the results of 2D numerical simulations of engine exhaust jet in the atmosphere, along with the stagnation temperature of the jet , its static temperature T_{4stat} has to be also considered, which was not the case in the earlier works.

2. As a result of calculations, the maximum humidity supersaturation index h_Σ has been estimated and compared with published experimental data and with the data of particular experiments held on the flying test bed Tu-154 sounder/generator (Figs. 67 and 68). It has been shown that:

- at flights of airplanes at various altitudes with T_{amb} changing according to the ISA and deviating from ISA by ±15...20 °C, two altitude

Fig. 64: Contrails in the atmosphere

Fig. 65 Contrails over the Central Europe (photo from satellite)

borders of steady contrail formation are possible for the same values of the maximum humidity supersaturation index h_{Σ} with respect to water. In the considered examples the borders took place at altitudes H = 7...8 km and H = 10...11 km;

• the predictive model allowed estimating the changes of border altitude for steady contrail formation during the flight of a particular airplane at atmospheric temperature and humidity changes and for different engine operation modes;

Fig. 66 Sensors on the Tu-154M-based flying laboratory:
1 – SKG sensor; 2 – BSIV sensor; 3 – IVOKS sensor; and 4 – periscope

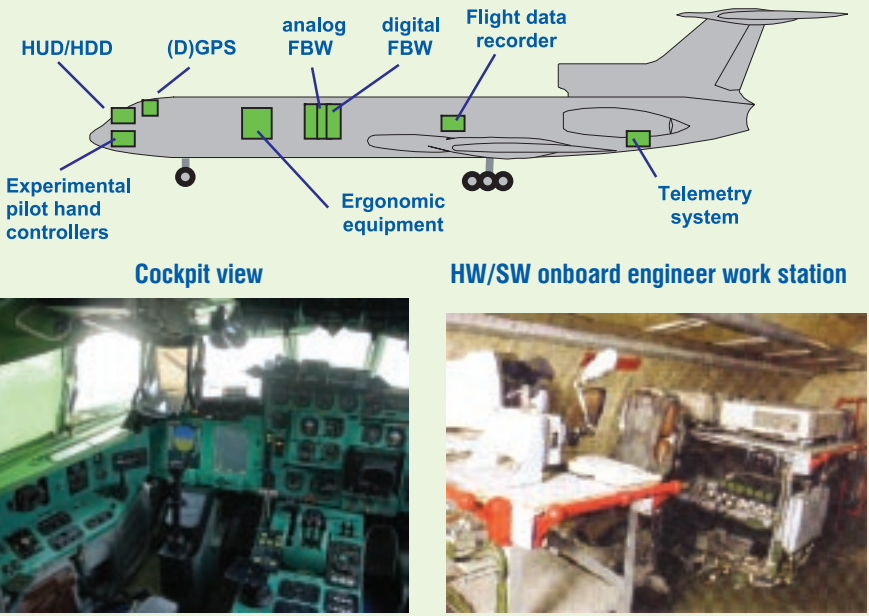


Fig. 67: Tu-154M in-flight simulator (instrumentation)

- for the flying test bed Tu-154 with D-30FU engine (bypass engine with mixing chamber), a decrease in ambient temperature T_{amb} led to the increase of the upper border of steady contrail formation by 1.5...2 km;
- in some cases, contrail formation was observed at $h_{\Sigma} < h_{\Sigma \text{water border}}$ (between saturation curves with respect to water and ice) that can be explained by the presence of crystallization centers (soot, etc.);
- there exists interaction of the condensation process with vortex trails of aircraft of different types; and
- the studies of steady contrail existence time in the far field with due regard for the ambient temperature and humidity are required, as well as the studies of aircraft flights in clear atmosphere and in cirrus clouds, studies of interaction of contrails with turbulent wakes of aircraft and atmospheric turbulence, studies of contrails thickness and the presence of trace pollutants in the contrails and in ambient air (including soot and other particles).

The main obtained result was the development of a unique quantitative model capable of predicting the contrail formation conditions and substantiating various approaches for the reduction of aviation impact on the global climate. The model was tested against the results of flight experiments performed in the flying laboratory based on Tu-154 airplane. A good agreement between predicted and measured results has been obtained.

Number:	**#3186**
Full and Short Title:	Theoretical Investigation and Experimental Development of Methods of Building up Nontoxic Combustion Chamber of Gas-Turbine Engine with Low Soot Formation in Combustion Liner **Nontoxic combustion chamber**
Tech Code/Area/Field:	SAT-AER/Space, Aircraft and Surface Transportation/Aeronautics
Status:	Project completed
Technology Development Phase:	Applied research, Technology development
Allocated Funding:	$174,000 (JP)
Commencement date:	(starting date) May 1, 2006
Duration:	36 months
Leading Institute:	MAI (Moscow Aviation Institute), Moscow, Russia
Contact Information:	Phone: +7 (499) 1584264; 1511373, fax: +7 (499) 1582927, e-mail: AET@mai.ru, website: http://www.mai.ru
Supporting Institutes:	**No**
Collaborators:	JAXA/Aeronautical Environment Technology Center, Tokyo, Japan (Hayashi S)
Project Manager:	RUTOVSKY Vladimir
Contact Information:	Phone: +7 (495) 6126010, e-mail: irina_kravch@mail.ru
ISTC Senior Project Manager:	RYZHOVA Tatiana
Contact Information:	Phone: +7 (495) 9823280, fax: +7 (499) 9784637, e-mail: ryzhova@istc.ru
ISTC Website:	http://www.istc.ru

Background

Development of gas-turbine engines is accompanied with the increase in their main thermodynamic parameters: air pressure behind a compressor and gas temperature ahead of the turbine.

The temperature increase in combustion chambers leads to increase in NOx emissions if the methods of controlling this emission remain unimproved. At the same time, the requirements to the emission level of gas-turbine engines, in particular NOx, become more and more stringent. Therefore, special methods of organizing the operation process in combustion chambers are required which would be efficient in terms of emission reduction under high-temperature conditions.

It is known that considerable reduction of NOx and soot emissions can be expected in combustion chambers operating on Lean Premixed Prevaporized fuel, so-called LPP schemes.

Recently, a number of papers on low-emission combustion chambers using an idea of preliminary homogenization of a fuel-air mixture have been presented at the International Symposia on Air-Breathing Engines (ISABE). These works demonstrated that the most promising scheme of a low-toxic combustion chamber for a gas-turbine engine satisfying all relevant requirements is a Multinozzle Combustion Chamber. Its design for cruise flight conditions will have a combustion scheme close to that of a lean homogeneous mixture. The improvements of this scheme seem possible on the basis of new data on mixing processes and nitrogen oxide and soot formation kinetics.

At the Moscow Aviation Institute, the experimental study of flow structure and temperature distribution in a wake behind single-swirl burners has been performed. For more intense mixing, the flows with opposite swirling were used in such burners. A model combustor with a complex frontal device including a swirl burner and additional swirlers has been created. Theoretical and experimental investigations of this combustor showed that the velocity field (or overpressure) influences considerably the rate of nitrogen oxide formation. When flow swirling in the burner was strong (which led to generation of developed circulation flows behind the burner exit section), a strong increase in nitrogen oxide emissions and respective reduction of CO emissions took place. Therefore, further research efforts should be focused at the direct-flow scheme, which has no large-sized recirculation zone, thus providing combustion stabilization. The direct-flow scheme requires the development of particular schemes of combustion stabilization and flame holding.

At present, a new frontal device (module) has been designed, which can be used in tubular and annular combustors. The new frontal device consists of a central swirler and a surrounding jet mixer. Liquid fuel is supplied both to the central swirler and the mixer. It is suggested that this scheme of fuel supply and the new frontal device scheme will solve the problems of combustion stabilization and enable a combustion process with low harmful gaseous and particulate (soot, smoke) emissions.

Project Objectives

The objective of the Project was to elaborate recommendations on a design of pollutant-free high-temperature combustors for gas-turbine engines.

Description of the Work

Modernization of combustors requires a large amount of experimental and computational data. Therefore, to achieve the Project objective, the computational, theoretical, and experimental methods were used for studies of the operation process in combustion chambers of the considered design.

The present work included:

- further development of a Computational Fluid Dynamics (CFD) model based on improved computational technologies for simulating critical flow regions in a combustor;
- calculations and development of a Frontal Device (FD) (Fig. 68) with an Advanced Jet Mixer (AJM) (Fig. 69) and pneumatic fuel atomization with improved characteristics to select a rational design of the FD for the test model;
- manufacturing of an AJM test model and updating the test facility for the purposes of the Project;
- experimental studies of AJM characteristics to determine parameters governing the characteristics of fuel–air mixture, the rate of turbulent combustion, and aerodynamic characteristics behind the model; and
- elaboration of recommendations on the design of a full-scale combustor based on computational and experimental investigations.

The use of up-to-date computational codes for chemically-reacting flows can help to reduce the development cost of combustion chambers owing to more accurate selection of configurations, which decreases the number of modifications needed for achieving required characteristics. Nevertheless, in spite of great effort spent on the development of CFD codes, experimental investigations of combustion chambers and their elements still

draw considerable attention. The experimental data are still used in the form of semiempirical correlations in mathematical models. In this work, the experimental study of the model combustor with a proposed frontal device was carried out at a modern test facility. On the basis of experimental investigations, the operation process in the proposed frontal device, recommendations on the geometry of its main elements and their main parameters have been elaborated (Fig. 70). Experimental investigations of the frontal device in the model combustor made it possible to estimate the accuracy of the mathematical model and computer code used for predicting the main flow parameters in such a combustor.

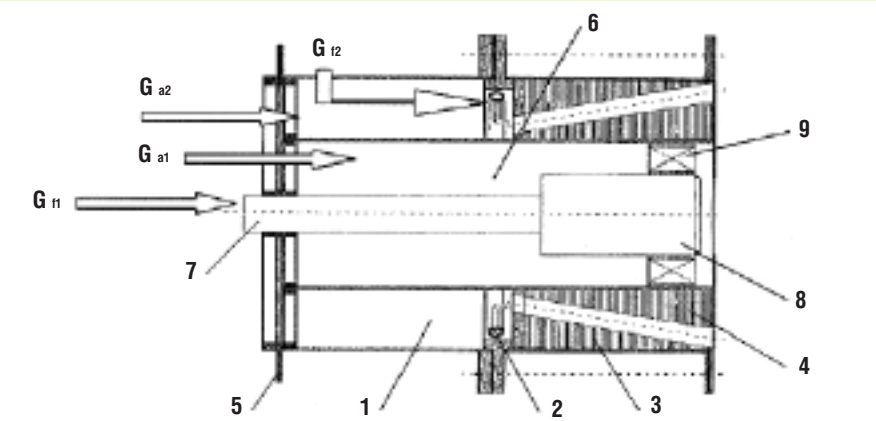


Fig. 68 Schematic of the model FD: 1 – air channel; 2 – jet nozzles; 3 – set of milled outer plates; 4 – set of milled inner plates; 5 – diaphragm; 6 – air channel; 7 – fuel manifold; 8 – axial centrifugal nozzle; and 9 – vane swirler

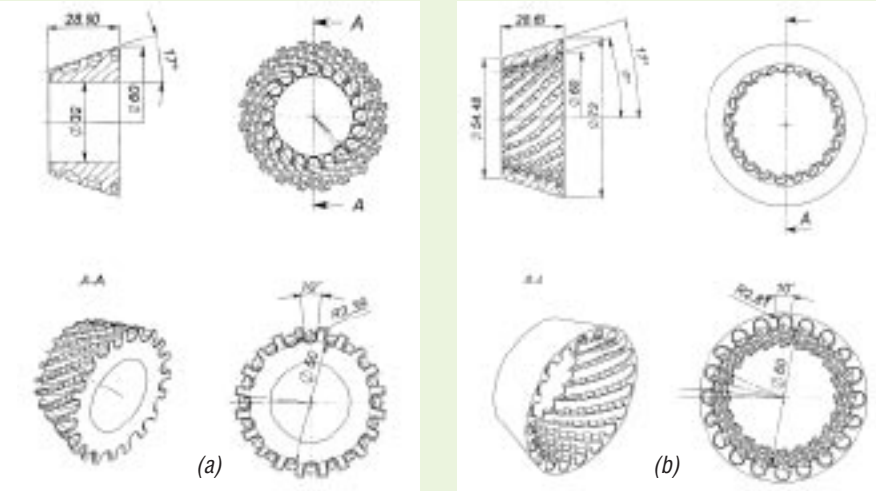


Fig. 69: Model jet mixing device: (a) inner contour; and (b) outer contour

Obtained Results

1. A model combustion chamber has been developed in the form of a tubular combustor with a complex frontal device consisting of a combined flame device and an advanced jet mixer.

2. A universal experimental facility for investigating the operation process in combustion chambers of gas-turbine engines and their individual elements has been developed at the Moscow Aviation Institute.

3. On the basis of the recommendations made, the main geometric parameters of the model FD have been calculated and an experimental model of FD has been manufactured.

4. The mathematical model of NOx and soot formation at combustion of aviation kerosene was refined. The computational model has been further modified to take into account interaction between swirled and weakly swirled flows. The experimental data confirmed the adequacy of the mathematical model.

5. The combustion process in the model combustor has been investigated numerically and theoretically at different fuel distribution between the main and auxiliary combustion zones. Different schemes of a model combustor have been evaluated on the basis of their emission characteristics. The numerical and theoretical study showed that the developed model combustor made it possible to reduce nitrogen oxide and soot emissions. The mechanism of such reduction was determined by mixing acceleration resulted in homogenous combustion.

6. The results of experimental investigations of the operational process in the FD were analyzed for the case when kerosene burned in air. Two combustion zones, a central one with diffusion combustion and the outer one with homogenous combustion, were found to exist in the FD. The FD under consideration allowed the reduction of NOx and soot emission due to

- some leaning of fuel-air mixture in the central part (including the recirculation zone);
- reduction of the central recirculation zone, which led to shortening of the residence time of combustion products in this zone; and
- partial homogenization of the fuel-air mixture in the jet mixer.

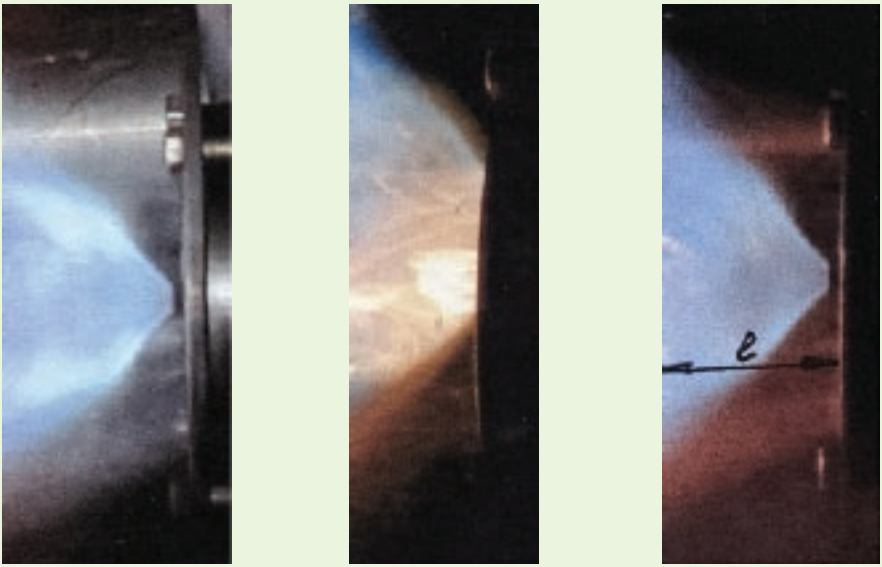


Fig. 70: Operation of the FD in different modes

Institutes – ISTC Recipients in Aeronautics

Russian State Research Center
"Central Aerohydrodynamic Institute named after professor N. E. Zhukovsky" (TsAGI)

Director

Sergey CHERNYSHEV

Address

1 Zhukovsky Street, Zhukovsky, Moscow reg. 140180, Russian Federation

Contact information

Phone: +7 (495) 5564101, fax: +7 (495) 7776332, e-mail: ved@tsagi.ru, www.tsagi.com

Main fields of activity

- Aerodynamics, flight dynamics, control systems and aircraft safety
- Strength, aeroelasticity, service life and damage tolerance, structural materials
- Aerothermodynamics and gasdynamics
- Aircraft concept design
- Aeroacoustics, engine emission, green solutions
- Seaplane and high-speed boats aerodynamics
- State expertise of aviation projects
- Complex applied tasks of industrial aerodynamics and strength
- Development of unique experimental facilities, measurement and data-processing systems
- Design and manufacture of aerodynamic models, dedicated test rigs, and nonstandard equipment
- Strategic planning, system research and generation of aviation development programs

Participation in significant domestic and international projects

Virtually all domestic aviation and space units were developed on the basis of scientific and experimental research performed in TsAGI.

- An-124, Il-96, Tu-204, Tu-334 aircraft series
- MiG-29, Su-27, MiG-31 fighters
- Mi-26, Mi-24, Ka-50, Ka-60 helicopters
- Buran air-space shuttle and Energia-Buran complex

TsAGI is involved in the research projects of EU Framework Programs as a partner.

FP6:

NACRE, FLYSAFE, FLIRET, SIMSAC, TELFONA, HISAC, ALCAS, NICETRIP, QUANTIFY

FP7:

SADE, DREAM, MAAXIMUS, ALICIA, OPENAIR, DESIREH, SUPRA, VALIANT.

TsAGI is a National Contact Point (NCP) in Aeronautics established in 2004.

Summary of the experimental base

TsAGI testing facility meets the highest world class standard.

TsAGI unique installations fit into or exceed world level analogues in many characteristics and efficiency in the following themes:

- complex of wind tunnels and gasdynamic research installations;
- static and dynamic strength laboratories;
- thermal strength and acoustic chambers;
- complex of hydrodynamic facilities;
- propulsion and compressor test benches;
- flight simulators; and
- air-power generating complexes

List of ISTC funded projects

Nos.0036, 0199, 0200, 0201, 0548, 0592, 0761, 0808, 1018, 1549, 1978, 2050, 2086p, 2249, 2633, 3077p, 3085, 3319, 3622, 3872

Central Institute for Aviation Motors development named after P. I. Baranov (CIAM)

Director

Vladimir SKIBIN

Address

2 Aviamotornaya street, Moscow 111116, Russian Federation

Contact information

Phone: +7 (499) 7635747, fax: +7 (499) 7636110, e-mail: avim@ciam.ru,
http://www.ciam.ru/index.php?SId=9&lang=ENG

Main fields of activity

The P. I. Baranov CIAM is a leading scientific center of the Russian aviation engine building industry. It possesses a unique test base for ground and altitude testing of aviation engines. CIAM is a head institute in the development of critical technologies and creation of a scientific and technical base for developing advanced engines for the new generation aircraft. The main lines if CIAM activities are:

- fundamental studies in the areas of gasdynamics, heat physics, strength;
- technology advance development;
- development of advance engines for various aircraft;
- development of standards;
- development of high efficient GTU for energy and gas pumping;
- testing engines for maneuverable aircraft;
- scramjet studies;
- exploration of basic icing problems;
- study of compressor acoustic performance; and
- certification tests.

Participation in significant domestic and international projects

Partners in RUSSIA

The main Russian partners are:

TsAGI, VIAM, LII, NIIAS, MIG, DB Sukhoi, Tupolev, Klimov, MMPP Salyut, Saturn, UMPO, Research Institute of Graphite, Composite, Keldysh Research Center, M.B.TSNIIMASH, IVTAN, ITAM SB RAS, ICP RAS, and others.

International Cooperation

The CIAM's Cooperation with the foreign countries started in the 1950s with the experimental facilities in Turayevo.

Since the second half of 1980s, the International Cooperation was rapidly developed in two directions:

(*i*) participation in the International aviation salons and exhibitions, symposia, scientific societies (ISABE, ICAS, ASME, AIAA, SAE, AIAA, etc.); and

(*ii*) participation in international projects.

During ten years, the CIAM scientists perform researches in the frames of major international programs on the impact of aviation on atmospheric processes and climate. In accordance with the Sixth Framework Program of European research in the field of aviation, CIAM is working to create a "clean" aircraft engine (Project VITAL) and supersonic passenger aircraft (Project HISAC).

Summary of the experimental base

CIAM test research center

There is a CIAM branch near Moscow, a unique complex of facilities with total installed electric power of 750 MWt designed for testing flight speed-altitude conditions in an altitude range of 0...27 km, Mach number range of 0...4 for air-breathing engines with thrust up to 25 tf and for large scramjet models of M = 7. The facilities allow testing, including certification, of aircraft articles of leading foreign manufacturers (General Electric, Eurocopter, SNECMA, and others). In 1998-2006, the rigs were built:

- for testing scramjets on hydrogen and hydrocarbon fuel;
- for engine testing in icing conditions, including certification;
- for experimental development of low-noise birotative propfans;
- for studies and development of compressor stages, heat stress of metal ceramic and other advance structure materials.

List of the ISTC funded projects

Nos.0672, 0672.2, 0935, 0936, 2740, K-035

Siberian Branch of the Russian Academy of Sciences/Khristianovich Institute of Theoretical and Applied Mechanics (ITPMech)

Director

Academician Vasily Mikhailovich FOMIN

Address

4/1 Institutskaya Str., Novosibirsk 630090, Russian Federation

Contact information:

Phone: +7 (383) 3304268, fax: +7 (383) 3307268, e-mail: admin@itam.nsc.ru, www.itam.nsc.ru

Main fields of activity – Mathematical modeling in mechanics

– Aerogasdynamics

– Physicochemical mechanics

– Mechanics of solids, deformations, and destructions

Participation in significant domestic and international projects

Partners: TsAGI, TsIAM, RSC "Energia," NPO "ALTAI," Scientific Production Enterprise AO "ISKRA," TsNIIMash, European Space Agency (ESA-ESTEC), DLR, company HTG, ETW, Aerodynamisches Institut Aachen, Universitat Stuttgart (Federal Republic of Germany), company Aerospatiale, airlines Dassault Aviation, INRIA, ONERA (France), PIAM, Beijing University, CARDC (People's Republic of China), Rutgers University, NASA Langley, Wright-Patterson Air Force Laboratory USA, airlines Boeing, Scientific Center Rockwell (USA), Westfield College, University of London (England), Universiteit Antwerpen, von Karman Institute for Fluid Dynamics (Belgium), Akita University (Japan), National Science Council (NSC), National Space Organization (Taiwan).

Summary of the experimental base

A unique aerodynamical experimental base has been created in the Institute. In wind tunnels developed by ITPMech, the following processes are being simulated: gas flows within the range of speeds from small subsonic to space (M = 0.1-25) and Reynolds numbers up to natural for hypersonic flying speeds. It enables to simulate the characteristics along the whole flight path of aerospace systems (type "Energiya-Buran").

List of the ISTC funded projects

Nos.0128, 0612-2, 1863p, 2172p, 3646, 0887, 1858, 2109, 3550, 3151, 3872

State Unitary Enterprise RUSSIAN FEDERAL NUCLEAR CENTER All-Russian Scientific Research Institute of Experimental Physics (FSUE RFNC – VNIIEF)

Director

Valentin KOSTYUKOV

Rady ILKAEV – Scientific Director

Address

37 Mira Ave, Sarov, Nizhny Novgorod reg. 607188, Russian Federation

Contact information

Teletype: 651203 Mimoza, telex: 151109 Arsa SU, tel: +7 (83130) 44802, fax: +7 (83130) 29494, e-mail: staff@vniief.ru, http://www.vniief.ru

Main fields of activity

The VNIIEF institutes, design bureaus and research centers are successfully working in the following main areas:

- stewardship of the nuclear stockpile of Russia and improved efficiency, safety and reliability of nuclear warheads;
- development of combined computer simulation methods for various physical phenomena using advanced high-performance computing systems;
- advanced design methods for complex engineering systems;
- hydrodynamics of transients, detonation physics, and technology;
- design of specific automatics equipment;
- nuclear physics and radiation physics;
- development and operation of research reactors for the purposes of science;
- development of unique accelerator technologies;
- high-temperature plasma physics;
- ultrahigh magnetic fields;
- inertial confinement fusion;
- lasers and laser-matter interaction physics;
- development and operation of state-of-the-art technologies for control and accountability of nuclear materials;
- science and technology support of the international arms limitation and nuclear nonproliferation treaties;
- new material technologies;
- environment protection and monitoring;
- nuclear power;
- nonnuclear weapons research and development; and
- defense conversion.

Participation in significant domestic and international projects

With its high scientific and technological capabilities, RFNC – VNIIEF has been able to expand its research and development programs and successfully explore new high-technology areas, obtain world-class scientific results and carry out unique fundamental and applied studies.

RFNC – VNIIEF is closely cooperating with the key Russian scientific and commercial organizations, research institutions, design bureaus, and industrial associations.

Since 1990, the Institute has been extensively involved in international cooperation. The international cooperation covers a wide range of topics from fundamental physics to social projects.

The highlights of creative interactions developing between the Institute and the international scientific community were joint Russian-US projects along research on the physics of superhigh-power explosive magnetic generators, high energy density, controlled fusion, and magnetized plasma.

The contacts of the Institute with the leading foreign scientific centers and companies (in USA, France, Germany, UK, China, Japan, and others) keep on growing. Its activities within international cooperation programs demonstrated the capabilities of RFNC – VNIIEF as one of the world's foremost scientific centers.

The international science and technology cooperation of RFNC – VNIIEF is associated with the efforts of world scientific community towards non-proliferation of nuclear weapons technologies.

The first international contacts of RFNC – VNIIEF date back to 1990. That was when memoranda and protocols were signed with the scientific establishments of the USA, France, China, Czechia, and Belgium.

Since 1992, RFNC – VNIIEF maintains contacts with **International Science and Technology Center (ISTC)** .

The main areas of RFNC – VNIIEF international cooperation are:

- high energy density physics;
- high-temperature plasma physics;
- nuclear physics;
- laser physics and high-power laser technology;
- gasdynamics and detonation physics;
- computation and simulation, information technologies;
- nuclear power safety;
- technological aspects of nuclear materials control, accountability, and storage;
- production of high-purity isotopes;
- tritium technologies;
- development of equipment for various research and production needs; and
- miscellaneous new technologies, biomedical included, and advanced materials.

The RFNC – VNIIEF international science and technology cooperation proceeds in accordance with intergovernmental and framework agreements supporting the international arms reduction, nuclear nonproliferation and test ban treaties, joint research programs in fundamental and applied science, and industrial partnership.

The RFNC – VNIIEF international partners are:

- National laboratories of the US DOE;
- Commissariat a l'Energie Atomique (France);
- international scientific organizations: IAEA and CERN;
- scientific organizations of USA, European Union, China, and Japan;
- the Chinese Academy of Engineering Physics; and
- industrial companies of USA and Europe.

RFNC – VNIIEF is the regular participant in important symposiums arranged by IAEA and International and European physical societies.

Summary of the experimental base

The research and test complex performs experimental testing of both military equipment from the Russian nuclear stockpile and commercial products for their strength and resistance to mechanical, thermal and climatic environments as may occur throughout their service life.

Scientifically and technologically, the complex is capable of testing the properties and behaviors of structures, such as stress-strain state, relative displacements of parts and assemblies, load levels, thermal fields, structural dynamics, etc., and also items can be tested there remotely that contain explosive, radioactive, and fissile materials.

The complex's test facilities are able to provide:

- static loads as high as hundreds of tons;
- shock-induced accelerations at thousands of *g*;
- various types of vibrational loads; and
- arctic cold and tropical heat, 100 percent humidity, and solar radiation.

The experimental checkout of products is based on a set of industry standards, norms of strength, and the applied procedures for vibrational, inertial, thermal, and climatic tests that adequately simulate the operation details and emergencies in a laboratory environment.

Vibration tests are conducted by the procedures that are based on extensive experimental evidence, so that they help conclude on the vibration resistance of various test items in diverse operation environments. The hardware and software capabilities serve well to determine lifetime and the most stressed points in the product optimize it mechanically and predict its service life and behavior under various vibrational loads during operation.

The complex's scientists are successfully working to study the effects of shock on test items, which may also include very sophisticated and large mechanical systems as heavy as several tons. There is a suite of test facilities built and test procedures developed at the complex to conduct in-laboratory shock load experiments.

A pneumatic hydraulic shock facility is used to imitate quasi-static loads and other shock loads when the item needs to be tested with a specific shape of shock impulse and appropriate loading time.

The shock loading data are obtained using an equipment package that measures accelerations, deformations, and displacements.

With drop test facilities, the test items varied in weight and size, including containers and packages, can be dropped from a specified height in terms of safety standards.

The centrifugal facility enables inertial tests for different weights of items using different orders of linear acceleration and it also provides loading at increased acceleration growth rates. The measurement package is to record deformations and displacements of the test samples.

The complex's static test facilities can provide the loading tests with recording of displacements, deformations, and forces.

There is a facility at the complex, which is used for strength and leak tests of gas systems under high pressures and evacuation, static and shock loads included, for the effects of linear accelerations and angular velocities, or high pressure at a time with linear vibration, or shock accelerations.

The temperature and climate chambers, with their equipment and techniques, computer-assisted control, measurement and checkout procedures, is sufficient to perform:

- temperature tests of large-size items in the range of –70 to +300 °C, and element-by-element studies in –70 to +300 °C range;
- severe thermal cycling and alternating temperature cycling tests;
- simulation of nonstandard heating by large heat flows;
- testing of items as applied to various fire accident scenarios; and
- long-term climatic tests under specified temperature and humidity conditions in the range from –70 to +180 °C and 20%–98%, respectively.

Various structures are tested for abnormal environments (drop, fire, and flooding), for which purpose there is quite a variety of test facilities operating at the complex per se and on other sites within the Institute.

ISTC funded projects

Total: 443 ISTC projects, including 2 projects in Aeronautics

Electrohydraulic vibration machine

Pneumatic hydraulic shock facilityb PU-1600

Centrifugal facility

Press

Static test facility

Moscow Aviation Institute, MAI (State University of Aerospace Technologies)

Rector

Anatoly GERASCHENKO

Vyacheslav SHEVTSOV, Pro-rector for Science

Address

4 Volokolamskoe Shosse, GSP-3, Moscow 125993, Russian Federation

Contact information:

Phone: +7 (499) 1581373; 1580465; 1584264, fax: +7 (499) 1582977, 1582927,
e-mail: AET@mai.ru, intdep@mai.ru, http://www.mai.ru

Main fields of activity

University organizes and conducts basic, applied research and experimental development activities aimed at providing training, scientific and pedagogical staff at the world's qualification requirements, as well as effective use of scientific and technological capabilities of the University for economic development and solving social problems of the country.

The main scientific directions of the University are:

- aeronautics;
- aerospace heat;
- armament and military equipment;
- humanities and social sciences;
- engine-power plants;
- cybernetics, informatics, automation and computer technology;
- control and quality management;
- space technology and rocket science;
- mathematics and applied mathematics;
- engineering and mechanical engineering;
- medical equipment;
- mechanics;
- scientific and scientific-methodological support of the development of science and education;
- instrumentation;
- physical and chemical basis of applied research;
- ecology and environmental management;
- economics and management;
- electronics, radio engineering, communications; and
- energy, electrical engineering.

Participation in significant domestic and international projects

Five fundamental scientific discoveries for dynamic systems have been patented; the optoelectronic device "Photon" designed here is now operating in outer space; innovative power sources based on new principles invented and constructed here are currently used in aircraft and aerospace system units, etc.

All University staff and students can join in this work in the creation or in the design of new devices, and even new flying vehicles; 14 types of them are world-wide known for 6 records in aviation sports.

Recently, the new superlight small-size aircraft "Aviatica" was designed and constructed in MAI by staff and students. This aircraft is now indispensable for certain conditions and thus is in very great demand in this country and abroad. Now, there are about 200 pieces of "Aviatica" aircraft in the sky all over the world, and this vehicle was completely created and produced in MAI.

Summary of the experimental base

MAI has a unique technical base for carrying out scientific experiments, including 8 of concern, and 38 specialized research laboratories, 80 academic departments and laboratories in the departments. These are unique laboratory aircraft and helicopters to real samples and flight simulators, aircraft own developments, unique facilities for studying the processes in rocket and hypersonic jet engines, wind tunnels, benches for studies of superconductivity, unique motors; academic and scientific displays of radar systems and active phased array antenna arrays, advanced systems for signal processing and image; laboratory space and rocket technologies with field samples, modern weapon systems, laboratory information and CALS-systems, advanced computing centers.

The Institute has created unique laboratory facilities, where some items of the equipment have no analogues in the world.

Training for the aerospace and defense industries is held in full-scale models of equipment, including aircraft, helicopters, missiles, weapons systems, avionics and radar.

MAI is the only university in the world, with its own airport, which provides flight practice for future design engineers with a degree in Aerospace.

The uniqueness of MAI is that the institution has historically been created with the aim of training specialists for virtually all divisions and brigades, and factories of aviation industry (ranging from structural design of the wing, fuselage, landing gear, propulsion systems to technology and economy of production). Based on orders from enterprises of the military-industrial complex, since more than 50 years ago MAI has started and further develops training in the field of rocketry, space exploration, weapons systems and precision weapons, programs for aerospace systems. MAI is the only University in the world which scientifically accompanies aircraft production.

Currently, MAI prepares planners and designers for a broad profile of aviation, missile and space, and defense industries. For many years, in MAI successfully work:

- the student pilot aircraft design bureau-design and production of light airplanes and sport aircraft (SKBS);
- the student design bureau of aviation simulation (SDB AM);
- the student helicopter design bureau (SKBV) – developer of remote-piloted small aircraft taking off vertically apparatus.

List of the ISTC funded projects

Nos.0374, 0497, 0501, 0804, 0804.2, 1154, 2598, 3186, 3871

Gromov Flight Research Institute (LII)

Director

Evgeny GORBUNOV, Chief

Vyacheslav TSYPLAKOV, Principal Deputy Chief, Scientific Director

Address

Zhukovsky-2, Moscow Region 140182, Russian Federation

Contact information

Phone: +7 (495) 5565544; 5565607, fax: +7 (495) 5565334, http://www.lii.ru

Main fields of activity

Development, flight research and tests, validation and certification of advanced aeronautic and related technology products.

Fundamental research: aerodynamics, flight dynamics, flight control, stress and fatigue, hermodynamics, human factor, flight safety, etc.

Applied research: propulsion, avionics, aircrew/passengers life support and emergency escape systems, human factor, flight safety, ecological aspects of aviation (community noise, engine emission).

Prioritized research – experimental flight research and test using: Flying Test Beds, In-Flight Simulators, Experimental Aircraft, and Flying Models.

Scientific Research Center (Divisions)

- Flight Mechanics
- Propulsion & Related Systems
- Avionics & Systems Integration
- Electromagnetic Compatibility & Lightning Protection
- Flight Safety & Aircraft Operability
- Hypersonic Flight
- Ground/Flight Test Instrumentation
- Flight Data Processing &Telemetry System

Participation in significant domestic and international projects

The Institute was virtually involved in the development and testing of all domestic aviation and space units, including Buran airspace shuttle.

Search of optimum modes of flight at re-fuelling of various planes is carried out at GFRI.

For this and other problems, a number of flying laboratories have been created on the basis of Su-7B, Su-15, An-12, Tu-22, MiG-22, and Il-76 airplanes.

The Institute was involved in work with “Buran” with the group of test pilots. The school of test pilots has been created. Graduates became leading pilots in the country. For 40 years, the school has prepared more than 400 pilots.

Since 1992, International Aerospace salon MAKS is carrying out in GFRI and attract many participants from Russian aviation and defense companies as well as foreign participants. The Institute has continued direct cooperation with the main aerospace players in Europe, USA, China, and India.

GFRI is involved in several research projects of EU Framework Programs and also in networking EU Project AERONET.

Summary of the experimental base

Current operated flying facilities:

- Tupolev-154M In-Flight Simulator
- Sukhoi-24 Flying Test Bed for emission research
- Ilyshin-76 Flying Test Bed for engine test
- Flying Test Bed for hypersonic flight test

List of the ISTC funded projects

Nos.0627, 0627.2, 0935, 3097

Tupolev-154M In-Flight Simulatorfor research

Sukhoi-24 Flying Test Bed for emission

Ilyshin-76 Flying Test Bed for engine test

Research & Production Venture Medicon Ltd.

Director

Bogdan BODUNOV

Sergei BODUNOV – Chairman, Board of directors

Address

31 Mendeleev Str., Miass, Chelyabinsk reg. 456320, Russian Federation

Contact information

Phone: +7 (3513) 531575, fax: +7 (3513) 535920; 535424; 288982,
e-mail: mdcn@medicon-miass.ru, www.medicon-miass.ru

Main fields of activity

- Gyroscope technologies.
- Medicine technologies.

Participation in significant domestic and international projects

Recent partnership:

2007 – SPT-Geo Ltd. (Ufa, well trajectory measurement)

2008 – Sichuan Institute of piezoelectric and acoustooptical technologies (China)

2009 – Doosan Dst Co. Ltd, Korea Republic

27.12.2008 – a diploma and a gold medal for Hemispherical Resonator Gyroscope (HRG) development at 9th particularized exhibition 'Dual-use products and technologies. Defense industry diversification' which took place in Moscow on October 21–24, 2008.

Summary of the experimental base

Since 1998, Medicon has been developing a reasonably priced small HRG for civil application, and also unique processing equipment for:

- high-precision chemical treatment of quartz glass components;
- precision balancing of quartz glass resonator; and
- HRG assembly and testing.

ISTC funded projects

Nos.138; 138A

List of the Project Proposals (open for funding)

- **#1237** "Development of Fuelling Systems for Transport" (**Liquid Gas Fuel System)**

Keldysh Research Center

Project Manager: A. Gubertov

E-mail: kerc@elnet.msk.ru

- **#1551** "Development of Airliners' Automation and Aircrew Information Principles to Enhance Flight Safety" (**Enhance Flight Safety)**

Central Aerohydrodynamic Institute (TsAGI)

Project Manager: Yu. Shelyukhin

E-mail: ved@tsagi.ru

- **#0233** "Investigation and Ellaboration of Control Principles of High-Performance Electronic Scan Radars for Air Traffic Control (ATC) Systems Based on Artificial Intelligence Technology and Facilities" (**Electronic Scanning Radars)**

GNPO Altair

Project manager: Shcherbakov

E-mail: mail@altair-navy.ru

- **#0320** "Development of Automatic Control System for Freight Accurate Landing (Water Landing) Gliding Parachute (ACSFLP)" (**Parachute Landing Control System)**

Design Bureau of Instrument-Making

Project Manager: Komissarenko

E-mail: kbkedr@tula.net

- **#0449** "Research of Problems in the Creation of Convertible Passenger and Transport Aircraft with Tilt-Rotor System" (**VTOL Aircraft with Tilt-Rotor Systems)**

MAI (Moscow Aviation Institute)

Project Manager: Tishchenko

E-mail: AET@mai.ru

- **#0469** "Development of a New Technology for the Reduction of Vehicle Drag" (**Flying Vehicle Drag Reduction)**

Central Research Institute of Machine Building (TsNIIMash)

Project Manager: A. Krasilnikov

E-mail: corp@tsniimash.ru.ru

- **#0848** "Development of Methods for Calculating Shapes of Ice Formations and Their Impact on Aerodynamic Characteristics, Stability, Control, and Flight Safety of Civil Aircraft" (**Impact of Ice Formations on Flight Safety)**

Central Aerohydrodynamic Institute (TsAGI)

Project Manager: G. Andreev

E-mail: ved@tsagi.ru

- **#0852 "**Development of a Satellite System for the Precise Location of Aircaft Crashes" (**Satellite Location on Aircraft Crashes)**

Federal State Unitary Enterprise V.S.Semenikhin Sceintific Research Institute for Automatic Facilities

Project Manager: Ainbinder

Phone: +7 (495) 3307166

Fax: +7 (495) 3305133

- **#0871** "Investigation of Aerodynamic, Structural and Technological Aspects of New Configurations of Airplane Elements and their Conversion Application" (**New Configurations of Airplane Elements)**

Moscow Institute of Physics and Technology

Project Manager: Arutyunov

E-mail: vyshinsky@falt.ru

- **#1017** "Aerodynamics of Super and Hypersonic Vehicles"
  (**Aerodynamics of Hypersonic Vehicles)**

Siberian Branch of RAS/Institute of Theoretical and Applied Mechanics (ITPMech)

Project Manager: A. Kharitonov

E-mail: admin@itam.nsc.ru

- **#1170** "Optimization of Three-Dimensional Components
  and Integrated Configurations of Supersonic Aircraft"
  (**Optimization of SST Aircraft Configurations)**

Central Aerohydrodynamic Institute (TsAGI)

Project Manager: V. Golubkin

E-mail: ved@tsagi.ru

- **#1553** "Research and Development of Mathematics Models,
  Hardware and Software for Dynamic Safety of Aviation"
  (**Concept of Dynamic Safety of Aviation (CoDySa)**

Russian Academy of Sciences/Institute of Control Problems

Project Manager: I. Chagaev

E-mail: pavlov@ipu.rssi.ru

- **#1676** "Development of a Method for Easing of a Shock Wave at Passage of a Sound Barrier"
  (**Sound Barrier Overcoming)**

Hypersonic System Research Institute, LENINETZ, Holding Company

Project Manager: T. Yanchenko

Phone: +7 (812) 3737178

Fax: +7 (812) 3799041

- **#1895** "Synthesizing 4D Flight Paths of Civil Aircraft in the Framework of "Free Flight" Concept"
  (**Aircraft Flight Routes Optimization)**

Federal State Unitary Enterprise Russian State Scientific Center State Research Institute of Aviation Systems (GosNIIAS)

Project Manager: Yu. Buryak

E-mail: info@gosniias.ru

- **#2498** "Complex researches of an opportunity to increase flight safety of civil airplanes with the help of an expert crew emergency decision support system" (**Expert system of flight safety increase)**

Gromov Flight Research Institute

Project Manager: E. Kharin

E-mail: tsyplakov@liicom.ru

- **#2833** "New Approaches to Predictive Joints Design Based on Detailed Description of Local Elasto-Plastic Strain History by Combining the Holographic Interferometry Data and Numerical Simulation" (**Predictive Joints Design)**

Central Aerohydrodynamic Institute (TsAGI)

Project Manager: S. Pisarev

E-mail: ved@tsagi.ru

- **#3013 "**Study of Wind-Tunnel Turbulence Influence on the Structure and Characteristics of Shear, Separated and Swirling Flows" (**Turbulence Influence on Shear, Separated and Swirling Flows)**

Central Aerohydrodynamic Institute (TsAGI)

Project Manager: M. Ustinov

E-mail: ved@tsagi.ru

- **#3557** "Development of Physical and Mathematical Bases and Computer Programs for Simulation and Calculation of Aviation Engines Noise Generation, Propagation and Attenuation and Decrease of its Influence on Passengers, the Population and an Environment" (**Aviation Engines Noise)**

Central Institute of Aviation Motors (CIAM)

Project Manager: A. Osipov

E-mail: ved@ciam.ru

- **#G-784** "Aerodynamic Disk-Shaped Aircraft with Vertical Takeoff and Landing" (**Disk-Shaped Aircraft with Vertical Takeoff)**

Georgian Technical University

Project manager: G. Kvaratskhelia

E-mail: gtu@nilk.org.ge

Acknowledgement and Disclaimer

The ISTC Secretariat would like to cordially thank all the institutes, individual scientists and other key persons for providing assistance in obtaining photographs and information of funded projects and any other material that appears in this book. The book aims to provide an overview of the work of the ISTC in the aerospace and aviation sector, although in no way claims the intention of covering all aspects of ISTC work or to offer a full scientific account of the work itself. Many more institutes, scientists, engineers and other persons not represented in this book have been involved in the ISTC and have played an important role in the work of the Center. Only for reasons of space they have not been included in this edition. Although the ISTC has sought to include as broad a representation as possible of those connected with the Center through its 15 Years of operation, the ISTC unreservedly apologizes for any omissions.



International Science
and Technology Center (ISTC)
32-34 Krasnoproletarskaya Str.
Moscow 127473
Russian Federation
www.istc.ru