

Research in Aeroelasticity and Application in Aircraft Design

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ABSTRACT

An overview of methods in aeroelasticity and structural dynamics research at the Central Aerohydrodynamic Institute (TsAGI) is presented.

Aeroelasticity Division of TsAGI supports the creation of high performance modern civil and military aircraft and the investigation of new design concepts. Analytical methods are developed and validated to solve the aeroelastic problems of aircraft. Main researches in aeroelasticity include development of flying vehicle computational models, multidisciplinary analysis, design and fabrication of dynamically scaled models, ground vibration and wind tunnel testing, analysis of flight tests and certification. During the preliminary design of an aircraft structure the problem is to define structural sizes that will ensure minimum weight while satisfying the numerous multidisciplinary constraints. The multidisciplinary optimization (MDO) processes have been implemented at ARGON software. For example, numerical optimization methods for design of aeroelastic wind tunnel models are presented below.

The problems of flutter and limit cycle oscillations connected with the All Movable Vertical Tail concept are considered in this paper. In the case of transonic flow using Godunov finite-difference method of Euler equation integration solved the problem of unsteady aerodynamics for deformed wings. The equations of motion of elastic aircraft with controls are obtained taking into account nonlinear unsteady aerodynamic loads. Calculations of loads are based on the principle of harmonic linearization. The iterative method for transonic flutter calculation was used in frequency domain.

1.0 INTRODUCTION

TsAGI was officially founded in 1918. During the following decades the structure of the institute changed several times to optimally fit the needs of the national economy and solve various scientific problems. Nowadays a reasonable combination of practical work, fundamental and experimental research provided the foundation for aircraft design. The complex of wing tunnels (WT), gas dynamic rigs comprises more than 60 test facilities providing flight simulation at a flow velocity from $v=10\text{m/s}$ up to $M=25$. Transonic variable density WT are intended for testing models to improve aeroelasticity parameters. Along with enhancing efficiency of traditional aircraft designs TsAGI researches new ways to further aircraft technology. For example, the Institute has conducted a research of the flying wing concept for a passenger aircraft, proving that the concept could reduce operational costs. Conceptual study has been carried out, one of advanced structure was selected and its model was tested in WT.

As the costs of model production and wind tunnel testing have been grown too much lately, such an approach becomes unacceptable today. This requires increasing the share of multidisciplinary optimization (MDO) analysis and testing special test models for typical configurations.

2.0 MULTIDISCIPLINARY OPTIMIZATION

Design of an aircraft requires consideration of extensive parametric investigations for obtaining successful configuration. Nowadays, aircraft design process consists of set of sequential developments by specialists of different groups: aerodynamics, structures, aeroelasticity, weights, etc. Such organization of the design process allows carrying out multidisciplinary analysis of possible solutions, but due to the complexity of the information exchange between specialists of the different groups it requires large time expenses and restricts number of considering variants. It is practically impossible to determine the tendency of change of different aircraft characteristics by varying of design parameters with relatively small step. Besides, the interaction of design parameters must be investigated for obtaining of near-optimal design solutions. Often simultaneous contribution of two or more different parameters to objective function of the system gives the effect, which is opposite to their separate contributions. Therefore the optimal solution can't be always found from the principles based on analysis results and by means of traditional sequential optimization. Important aspects for modern approach to design are reasonable choice of interrelated disciplines and composition of the system of the nested iterative cycles, which allows obtaining practical result in multidisciplinary optimization.

The main method for structural analysis in the design software is finite element method. Very refined meshes that are necessary for linear static analysis of stresses and panel buckling often can be impossible in the optimal design with aeroelasticity requirements. To overcome this drawback the ARGON multidisciplinary system for aircraft design that is based on agreed models of two levels was developed in TsAGI [1]. The problem of aeroelasticity is solved using the discrete-continual model of prescribed forms (PF); and finite element model (FEM) is used for detailed evaluation of structural strains and stresses (Fig.1). The main advantages of the software are operability in parametric analysis of aeroelasticity characteristics and feasibility of structural optimization of aircraft and its components with requirements on strength, buckling, stiffness and aeroelasticity by using two-level approach.

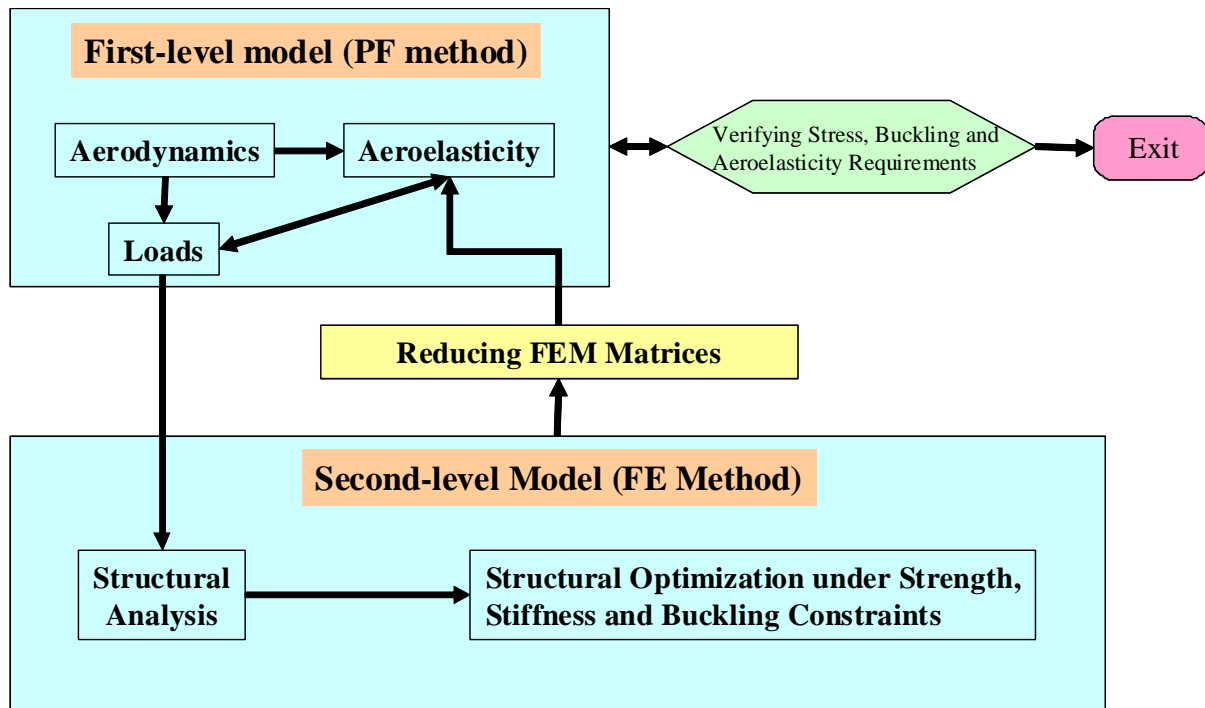


Fig. 1 Diagram of aero-strength design cycle in the ARGON package

The ARGON software package is intended for airframe optimization, prediction of stiffness/stress/mass distributions, aerodynamic characteristics, loads and aeroelastic characteristics of the aircraft. It is based on the common initial data for structural model of two levels and integrates the following disciplines:

- linear aerodynamic analysis;
- analysis of maneuver loads on elastic structure;
- structural analysis and optimization using plate/beam theory and finite element models;
- calculation of eigen frequencies and modes;
- aircraft static aeroelasticity and flutter analysis;
- aeroservoelasticity analysis.

Structural analysis in ARGON can be carried by means of two models: PF and FE. With the first one the structure is modeled as a set of aircraft parts joined with springs. Deformations of each part are sum of polynomial functions. Each part of an aircraft consists of structural elements of the following types: isotropic, orthotropic and laminated panels (plates), and one-dimensional beams that have bending and torsion stiffness. The Ritz method is employed to form the linear equation system. The Ritz solution procedure is used to determine the numerical values of the set of unknown coefficients that minimize total energy. The PF model results are used to form initial data for detailed structural design by the finite element method's model. Examples of finite element meshes of different aircraft types generated in ARGON system are represented on Figure 2. Based on the finite element method the stresses and strains can be evaluated more accurately. Optimization of design parameters under strength, stiffness and buckling constraints can also be performed using this model. The finite element stiffness matrix for the optimal thickness can be transformed into the stiffness matrix of the PF model. This makes it possible to verify aeroelastic characteristics of the aircraft. The design cycle is completed if strength, buckling and aeroelasticity constraints are satisfied.

Structural analysis program by FEM contains a wide variety of isoparametric one- and two-dimensional finite elements. The aerodynamic and inertial loads that are obtained by using the PF model can be automatically transferred to nodes of the finite element mesh. Isotropic and orthotropic materials can be treated. The latter can be employed to form composite laminates.

The aeroelasticity/strength design cycle starts with calculation of loads for various maneuver parameters of aircraft. Optimization under both strength constraints for obtained loads and aeroelasticity constraints is performed. Loads for the optimized elastic structure are calculated again, and new optimization is carried out for loads on elastic aircraft. Optimization results for the first level model give: the extreme load cases for structural parts with their corresponding load distribution, preliminary structural sizes, stiffness requirements as constraints on generalized displacements, etc.

Two approaches are used to analyze unsteady load cases. The first approach is based on integration of differential equations describing rigid-body motion and control system operation; elastic deformations are taken into account in quasi-steady approximation. In the second approach the dynamic equations of elastic aircraft motion are integrated in generalized modal coordinates.

For solving the dynamic aeroelasticity problems the equations are reduced to generalized coordinates corresponding to the natural modes without flow. Flutter speed can be used as objective functions or can be included in constraints at the structural optimization. Analysis and experimental research on aeroservoelasticity are performed in frequency and time domains. The most effective methods are the integrated ones in which validity of results is provided by direct experimental measurements of Frequency Response Functions of control system paths, while broadness of information is provided by parametric

numerical studies based on experimental results.

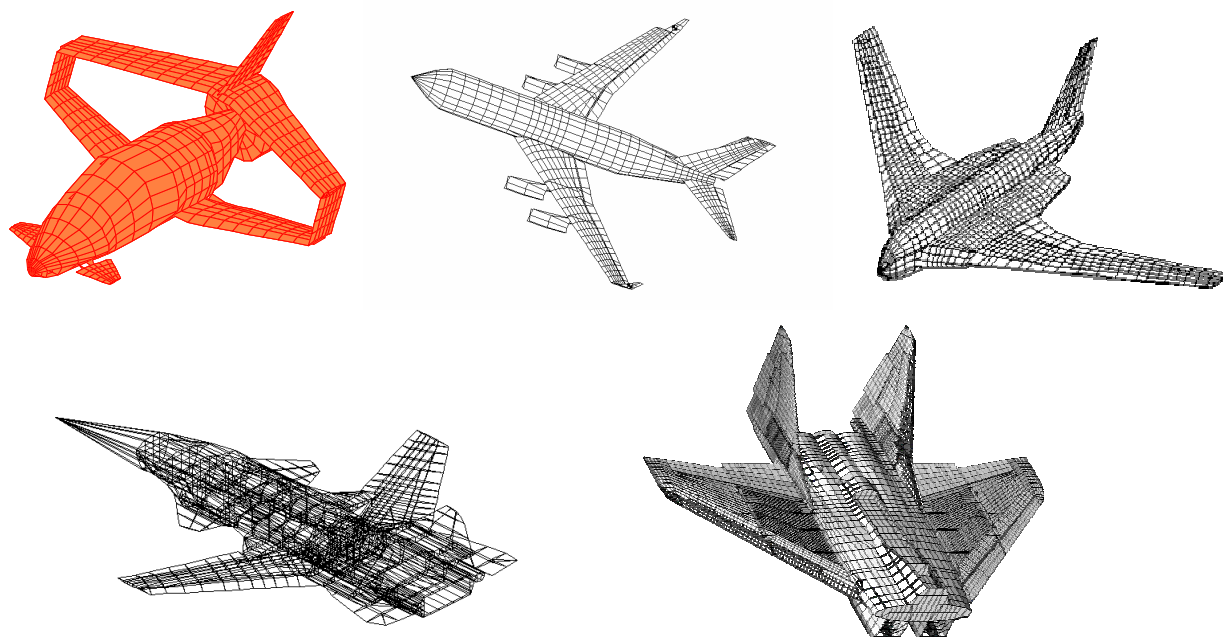


Fig. 2 Examples of finite element meshes of different aircraft types generated in ARGON system

The optimization problem in ARGON is to determine the values of design variables, which would minimize the objective function (mainly the mass of the structure) for the number of structural response constraints. The functions of constraints are analyzed with the developed structural models. On the PF model the constraints on stresses, natural frequencies, aeroelastic lift effectiveness, aileron effectiveness, and critical flutter velocity can be taken into consideration. On the FEM model the optimization of design variables is carried out for only the constraints on stresses, displacements, and buckling of panels. Optimization module including algorithms based on methods of nonlinear programming such as Pshenichy method and sequential quadratic programming has been implemented in ARGON system.

The structural design of a passenger aircraft wing is a complex multidisciplinary problem, which includes many multidisciplinary criteria such as stress, fatigue, buckling, effectiveness of control surfaces, flutter, etc. The traditional approach to multidisciplinary optimization is entirely improper for the problems where different configurations of wings must be considered. Usually such problems include design variables defining the shape of wing, and aerodynamic performance constraints or lift-to-drag objective function must be taken into account. All drawbacks of the traditional approach can be overcome by using multidisciplinary design optimization process at design of aircraft wing. The MDO and multidisciplinary analysis processes have been implemented at ARGON software [2]. As example, numerical optimization methods for design of aeroelastic wind tunnel models are presented below.

3.0 OPTIMIZATION APPROACH TO DESIGN OF AEROELASTIC DYNAMICALLY SCALED MODELS OF AIRCRAFT

Aeroelastic dynamically scaled models (DSM) play important role at designing of modern aircraft. They are used in wind tunnel tests for investigations of the flutter and other aeroelastic problems. DSM is the model, which is geometrically similar to the full-scale airplane and has the similar distribution of masses and stiffness. The main problem in the design of DSM is to define correctly the stiffness and mass

properties of separate components of the model that simulates the airplane [3]. The numerical optimization methods have been used for design procedures of DSM. Modular multipurpose elastic model were studied in Ref. 4, where different objective functions for design of DSM were considered.

Two different approaches to design of elastic components of an airplane aeroelastic model are proposed in present paper. Usually the beam scheme is used for the high-aspect-ratio wing or long fuselage. In this case the distribution of bending stiffness in two planes (EI1, EI2) and torsion stiffness (GJ) are specified in structural model. The plate-beam scheme is used for modeling a small aspect ratio wing and wide fuselage of airplane. In this case the stiffness characteristics are specified by set of panels, plates, beams.

The formulation of the problem of determination of model stiffness parameters is based on the following:

- A mathematical model of a full-scale structure has been studied, its structural elasticity and mass-inertia characteristics have been calculated and aeroelasticity problems have been researched.
- Model similarity scales (K_L – length scale, K_V – velocity scale or K_q – dynamic pressure scale, K_D – mass density scale) have been selected.
- A simpler model primary structure, which is different from primary structure of a full-scale object, has been selected; materials for usage also have been selected.

It is necessary to determine the structural parameters, under which the elastic similarity of a model and a full-scale structure is obtained with the specified precision. Simultaneously, these parameters should satisfy the technological and geometrical constraints (the minimum thickness is determined by the thickness of composite plies, the maximum thickness is determined by the heights of aerodynamic airfoil). In addition, the structure of elastically scaled model should satisfy the strength requirements. The described above objectives for determination of the design variables can be considered in the problem of minimization of nonlinear function with linear and nonlinear constraints. An optimization problem based on desired criterion is formulated as:

Minimize $f(x)$

Subject to
$$\begin{aligned} g(x) &\leq 0 \\ x^l &\leq x \leq x^u \end{aligned}$$

where x is the vector of structural design variables, x^l and x^u are vectors of lower and upper bounds for design variables, $f(x)$ is the objective function. The other criteria can be included in nonlinear constraints $g(x)$. Also requirements on strength characteristics for chosen design cases can also be included in the nonlinear constraint. Implemented algorithm allows including constraints with any linear combinations of design variables. Optimization procedure employs an algorithm based on the method of sequential quadratic programming for searching design variables. The advantage of the implemented algorithm is that it provides feasible design variables at the iteration. In the case of composite materials the round-off procedure is used to obtain integer number of composite layers.

Optimization procedure for design of dynamically scaled models is demonstrated on example of low-aspect-ratio horizontal tail (HT) of maneuverable aircraft. Preliminary computational researches of full-scale structure show availability of flutter in transonic range of speeds, and a decision for performing of flutter tests in high-speed wind tunnel was taken. The computational model of full-scale HT is shown in Figure 3. Structural model consists of beams and panels, and mass distribution is described by concentrated masses. The chosen wind tunnel dictates the following similarity scales: $K_L=0.5$, $K_q=0.7$, $K_D \approx 1.5-2.0$.

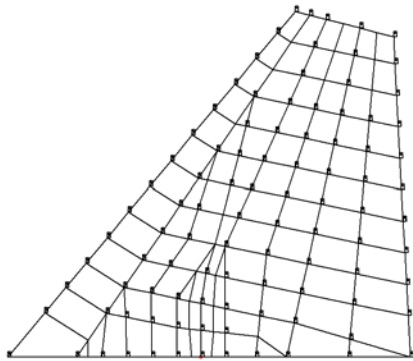


Fig. 3 Computational model of full-scale HT

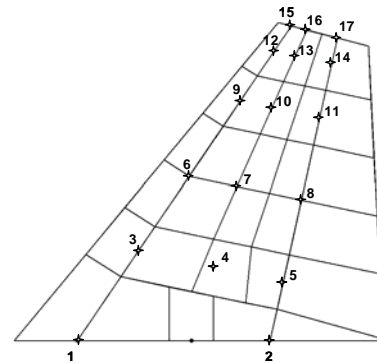


Fig. 4 Location of points for control of structural stiffness

For convenience of analytical researches at DSM design the ideal model was created. In this model the structural layout consists of the same elements as in full-scale model but its all parameters are recalculated with similarity scales. Specifying the similarity scales can automatically generate such ideal model. Structural layout of DSM was chosen by using experience of design of analogous structures. The experience of DSM design is integrated to special library of technological decisions in the “Manual for designers of DSM”. In our case the structural layout includes plywood core, which coincides in plan form with structural primary box. Control of structural stiffness is accomplished in chosen 17 points (Fig. 4). The structural model was fixed in the central part of the root section. Eighteen quadrilateral panels model composite layers which thickness must be determined from the condition of the proximity of matrices of elastic influence coefficients for ideal and designing models. The optimisation procedure described above was used to determine thickness of composite layers. Therefore, vector of design variables includes 18 panel’s thicknesses. Comparison of the vibration frequencies of the designed model with the frequencies of the ideal model is shown in Table below. The first vibration mode shapes for the designed model and ideal model are in satisfactory agreement.

Mode	Frequencies of ideal model, Hz	DSM	
		Frequencies, Hz	Difference, %
1 st Bending	69.7	70.1	0.5
Torsion	180.8	189.5	4.8
2 nd Bending	230.3	224.4	-2.6

4.0 AEROELASTIC EQUATIONS OF MOTION

Aeroelastic equations of motion are derived on the base of methods, which are developed in ARGON computer code. The Ritz method is used; the deformations of the aircraft structure are represented as polynomial functions of the spatial coordinates. The whole structure is represented by a set of thin, originally flat elastic surfaces, which can be arbitrarily located in the space. For each elastic surface the distribution of mass and stiffness is specified. All elastic surfaces are jointed in unified structure by the elastic connections, which allow simulating various fastening conditions in the attachment points between them with required accuracy.

For each elastic surface the polynomial can be chosen separately. The aerodynamic loads, which may be found by some aerodynamic theory or taken from experimental data, are acted on the elastic surfaces in the flow. For solution of problems of dynamic aeroelasticity (dynamic response, aeroservoelasticity) the equations are reduced to generalized coordinates corresponding to shapes of natural vibration modes

without airflow. In frequency domain they can be written in matrix form:

$$\begin{aligned} (-\omega^2 C + j\omega D_0 + G)q &= Q^a + R \delta_r \\ y &= (H_0 q + j\omega H_1 - \omega^2 H_2)q \end{aligned}$$

where $q = \text{col}(q_r, q_e, \delta)$ is a vector of generalized coordinates describing motion of airplane as rigid body q_r , its elastic displacements q_e , deflections of controls δ ;

C, D_0, G are matrices of inertia, structural damping and structural stiffness, correspondingly,

Q^a is vector of generalized aerodynamic forces;

δ_r is a vector of deflections of control actuator rods;

R is a matrix of effectiveness of control actuators;

y is a vector of output parameters which are displacements, twist angles, accelerations and angular speeds in transducer locations and forces and moments in chosen sections;

H_0, H_1, H_2 are transformation matrices between generalized coordinates and physical parameters.

Aerodynamic forces in frequency domain (for harmonic motion) are determined by doublet lattice method. After transformation to modal coordinates they can be represented in the following form:

$$Q^a = -(j\omega \rho V D + \rho V^2 B)q + \rho V D^w w,$$

where D, B are matrices of aerodynamic damping and aerodynamic stiffness calculated for specified reduced frequency; ρ is mass density of air; V is flight speed; D^w is vector of gust effectiveness (for specified reduced frequency); w is gust speed.

The generalized forces Q^a in time domain can be determined by aid of the rational approximation in Laplace domain or inverse Fourier transformation. Here a simplified approach based on harmonic assumption is used because low-frequency vibrations in the range of several first modes are of a main interest for considered problem:

$$Q^a = -\rho V D \dot{q} - \rho V^2 B q + \rho V D^w w,$$

where matrices D, B and vector D^w are calculated for small reduced frequency.

The foundation of the linear aerodynamics computational methods is a hypothesis about the smallness of the disturbance inducing into flow by a lifting surface. This hypothesis allows to consider linear equations of the fluid dynamics and to develop effective computational procedures for their solution. The necessity of an aerodynamic characteristic's linearization has also another reason: use the effective methods of the stability analysis of complex dynamic systems.

5.0 THEORETICAL STUDY OF TRANSONIC FLUTTER IN THE FREQUENCY AND TIME DOMAIN

In the last decades there have been extensive developments in computational methods in response to the need for computer codes, which is available to study fundamental aeroelastic problems in the critical transonic regime. The computational methods provide a new tool, which can be used in the combination with test facilities to reduce the cost and time of the aircraft designing. The determination of the unsteady aerodynamics forces is the most difficult part of the flutter problem. The application of the nonlinear aerodynamic theory has led to the creation of a new transonic flutter's approaches. One of such approaches has already been developed in TsAGI: the aerodynamic loads are determined using Godunov finite-difference method of Euler equation's integration.

It is necessary to note that in linear case the flutter mode is determined up to any factor, while in transonic

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case the vibrations with flutter frequency should have specified amplitude because unsteady pressure difference $\Delta p(x, y, t)$ depends on it. The iterative method was used; it connects two available algorithms: computation of classical linear flutter and computation of transonic flow near elastic wing, vibrating with given frequency and mode. The deformations of an elastic surface are expressed in the following way:

$$W(x, y, t) = F(x, y)e^{j\omega t}$$

where $F(x, y) = F_1 + jF_2$ is complex mode of vibration. For such harmonic mode the pressure distribution has been computed, and then the main Fourier harmonic coefficients are extracted.

$$\Delta p(x, y, t) \approx [\Delta p_1(x, y) + j\Delta p_2(x, y)]e^{j\omega t}$$

It is supposed that the linearized pressure is defined by the complex local angle of attack $\bar{\alpha} = \bar{\alpha}_1 + j\bar{\alpha}_2$:

$$\Delta p(x, y, t) = \frac{\rho V^2}{2} (C_{p1}^\alpha + jC_{p2}^\alpha)(\bar{\alpha}_1 + j\bar{\alpha}_2)$$

Dynamic angle of attack at harmonic vibrations is represented as follows:

$$\bar{\alpha}(x, y, t) = -\left(\frac{\partial F}{\partial x} + \frac{jkF}{c}\right),$$

where $k = \omega c/V$ is reduced frequency; c is reference chord. Then the coefficients of the unsteady pressure can be written as:

$$C_{p1}^\alpha = \frac{2}{\rho V^2} \frac{\Delta p_1\left(\frac{\partial F_1}{\partial x} - \frac{k}{c}F_2\right) + \Delta p_2\left(\frac{\partial F_2}{\partial x} + \frac{k}{c}F_1\right)}{\left(\frac{\partial F_1}{\partial x} - \frac{k}{c}F_2\right)^2 + \left(\frac{\partial F_2}{\partial x} + \frac{k}{c}F_1\right)^2}$$

$$C_{p2}^\alpha = \frac{2}{\rho V^2} \frac{-\Delta p_1\left(\frac{\partial F_2}{\partial x} + \frac{k}{c}F_1\right) + \Delta p_2\left(\frac{\partial F_1}{\partial x} - \frac{k}{c}F_2\right)}{\left(\frac{\partial F_1}{\partial x} - \frac{k}{c}F_2\right)^2 + \left(\frac{\partial F_2}{\partial x} + \frac{k}{c}F_1\right)^2}$$

The coefficients of the aerodynamic matrixes B and D can be written in the following form:

$$b_{ij} = \frac{1}{2} \iint_S f_i(C_{p1}^\alpha(x, y)) \frac{\partial f_j}{\partial x} - k C_{p2}^\alpha(x, y) f_j dx dy$$

$$d_{ij} = \frac{1}{2} \iint_S f_i(C_{p1}^\alpha(x, y)) f_j + \frac{1}{k} C_{p2}^\alpha(x, y) \frac{\partial f_j}{\partial x} dx dy$$

The results of linear flutter problem are usually used as initial approximation. After that the flow near the wing vibrating with specified frequency and mode is analyzed using nonlinear transonic theory. Then the sine and cosine components of main frequency are extracted from the calculated dynamic pressure distribution $\Delta p(x, y, t)$ and new aerodynamic matrixes are computed. The equations of vibration in the flow

are solved anew. The process is repeated up to flutter frequency convergence. Usually the linear flutter analysis is performed for the structure in the beginning. But there may be some regions of parameters (Mach number, reduced frequency, air density) in which linear flutter is absent. For this reason one of the vibration natural mode and frequency (calculated or experimental) may be taken as the first approximation.

A lot of additional useful information about dynamic response can be obtained from time domain analysis in the case of essentially nonlinear system. When investigating the transonic aeroelastic phenomena the direct coupling numerical integration of the dynamic equations of motion and Euler equations of transonic flow is executed in time domain. On each step of integration the whole field of the velocities, pressure and density are determined by the Godunov method. Boundary conditions in the points of the aerodynamic grid of moving elastic surface $\dot{W}, \frac{\partial W}{\partial x}, \frac{\partial W}{\partial y}$ are calculated through the vectors of generalized coordinates and velocities

$$\begin{aligned} \dot{W} &= XU \dot{q} - w(x, y, t); \\ \frac{\partial W}{\partial x} &= X^x U q; \quad \frac{\partial W}{\partial y} = X^y U q, \end{aligned}$$

where X, X^x, X^y are corresponding polynomial transformation matrices;

U is modal matrix;

$w(x, y, t)$ is distribution of the gust velocities.

Obtained dynamic pressure difference $\Delta p(x, y, t)$ is summed through the vibration modes for the determination of the generalized aerodynamic forces:

$$Q^a = X^T U^T S \Delta p,$$

where S is diagonal matrix of the aerodynamic element areas.

Thus to determine the right hand of the equations of motion at the given time moment all field of the flow parameters depending on the preceding process, vibration amplitude and the motion of shock waves is used. Integration of the equations is executed by Euler method. For choosing the optimal integration step the system with linear aerodynamic is investigated beforehand. Usually the step size is limited by the stability of Godunov finite-difference procedure rather than elastic oscillations. The example illustrating the possibilities of the proposed method of transonic flutter computation is considered below.

6.0 STUDY OF AMVT CONCEPT

Numerical researches are presented on the example of a 4-engine passenger airplane, which was studied within the European research project "Active Aeroelastic Aircraft Structures" (3AS). The mathematical models of the baseline airplane and of its dynamically scaled model intended for fulfillment of computational researches of active aeroelasticity concepts have been developed. The modular dynamically scaled wind tunnel model EuRAM was fabricated and tested for multidisciplinary studies of various aeroelastic design concepts on the wing and vertical tail.

All Movable Vertical Tail (AMVT) concept [5] suggests a reduction of vertical tail dimensions in such a way that the jaw moment effectiveness of new tail will be equal to the effectiveness of initial (traditional)

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rudder. So it will be possible to reduce vertical tail dimensions by a factor of about 1.5. Because of the new tail location and its shape does not practically differ from the corresponding parameters of traditional tail with rudder then the tail area reduction will lead to the accordant decrease of the derivative m_z^β value, and also correspondently to the reduction of the airplane natural lateral frequency of vibrations around the center of mass. In order to compensate of the derivative m_z^β decreasing and ensure the lateral vibrations frequency not less than for the given airplane it is necessary to provide of the tail deflection on additional angle $\Delta\beta \geq 0.5\beta$ at an arising of the slip angle β . For this purpose the rotational axis should be located behind the center of pressure, and the rotational stiffness value of the attachment should satisfy the following condition:

$$m_z^\beta qSb(\beta + \Delta\beta) = G\Delta\beta.$$

It is obvious that the smaller the stiffness the more the additional angle value $\Delta\beta$. For the minimum required value $\Delta\beta = 0.5\beta$ the condition determines the maximum allowable stiffness of the attachment:

$$G = 3m_z^\beta qSb.$$

The problems of the airplane flutter and transonic vertical tail oscillations concerned with the realization of AMVT concept are considered in this paper. Calculations of unsteady flow parameters at transonic velocities of flight are carried out for two variants of vertical tail motion: forced tail oscillations with given amplitude and frequency $\delta(t) = \delta_0 \cos(\omega t)$ and self excited oscillations with one degree of freedom under an action of aerodynamic moment and stiffness of an attachment. Aerodynamic moment is represented as: $m_z = m_{z_0} + m_z^\delta \delta + m_z^{\dot{\delta}} \dot{\delta}$, where coefficients are determined by least-squares method at the interval equals to one period of oscillation.

The formation of local supersonic zones and connected with them shock waves is the essential feature of transonic flow around a lifting surface. The shock waves are located near the trailing edge and can change their intensity and location at change of the vertical tail deflection angle. Dependences of aerodynamic coefficients, computed by the method of forced oscillation, from reduced frequency $k = \omega b/V$, amplitude and location of the rotation axes are presented on Figure 5. Represented results show that for every axis position there is a critical frequency value for which the damping coefficient changes its sign. For less vibration frequencies transonic oscillations will be unstable at small amplitudes. This frequency value defines the minimal allowable rotational stiffness of the movable vertical tail:

$$G_{\min} = \omega_{\min}^2 I_z - m_z^\delta(\omega_{\min})qSb$$

where I_z - moment of inertia of the tail with respect to axis of rotation, S - tail area, b – mean aerodynamic chord.

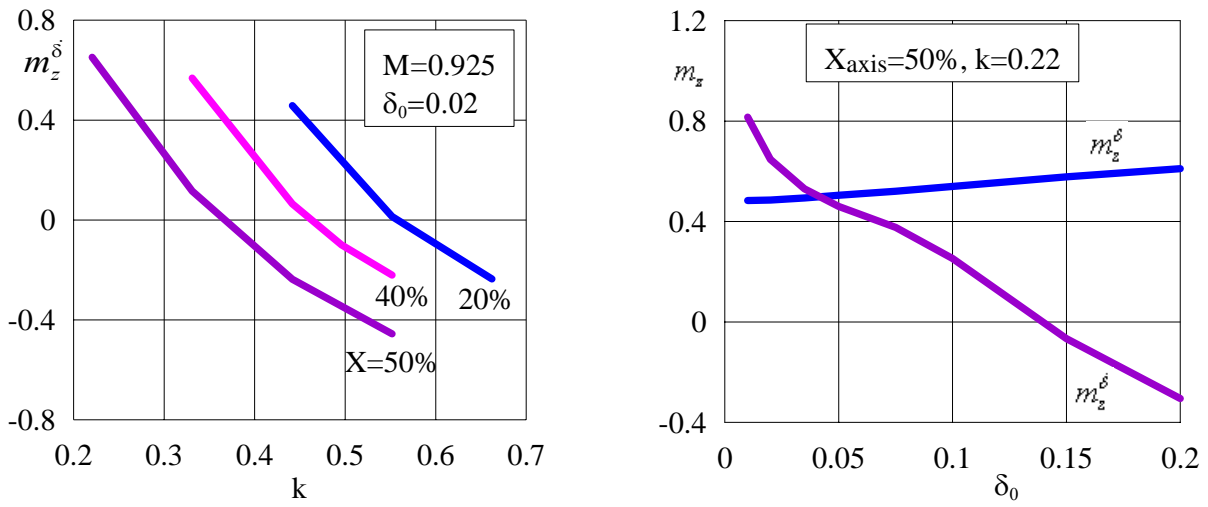


Fig. 5 Influence of reduced frequency and amplitude

Dependences of minimal and maximal rotational stiffness from indicated speed are shown on Figs.6-8. On these figures flutter velocity of the complete airplane is shown for the case of subsonic flight also. Analysis of presented results shows that for the realization of the AMVT concept the big value of the stiffness is needed, and correspondently, large distance between the center of pressure and axes of rotation (45% - 50% MAC). The flutter margin is not sufficient for lower distance between the center of pressure and axes of rotation, in other case oscillations becomes unstable in transonic flow at small indicated speed values which are corresponded to transonic flight regimes at the altitude more than 7km-8km (Fig. 7).

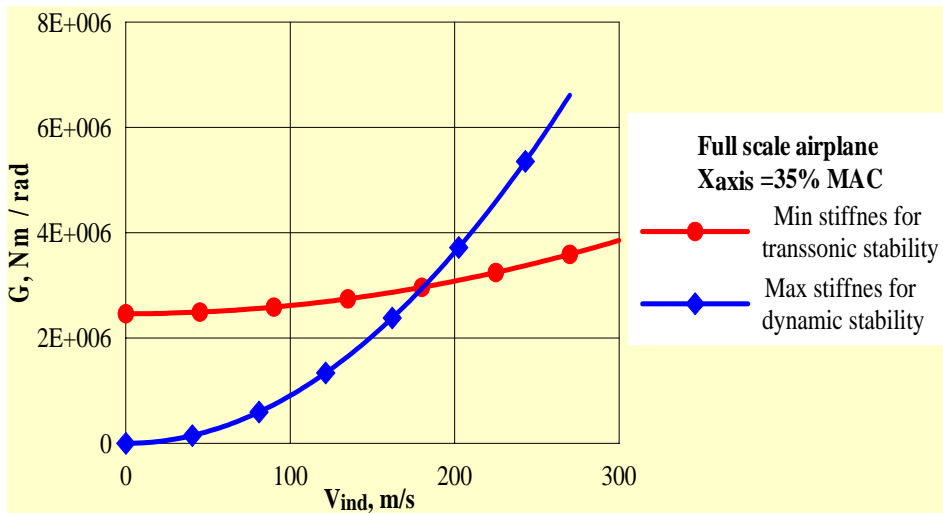


Fig. 6 Dependences of minimal and maximal rotational stiffness on indicated speed

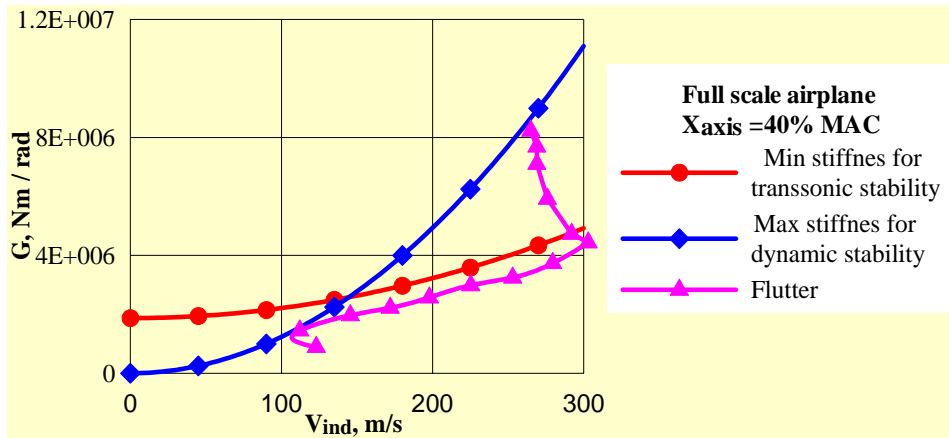


Fig. 7 Stability boundaries at Xaxis =40% MAC

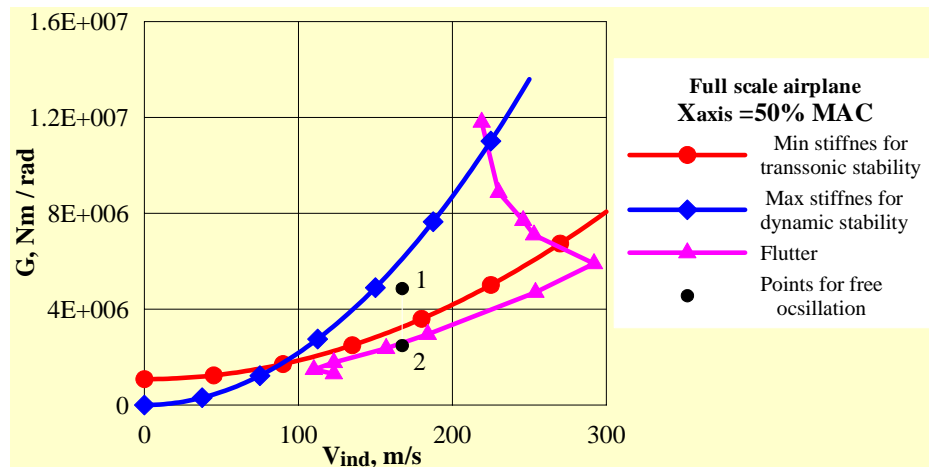


Fig. 8 Stability boundaries at Xaxis =50% MAC

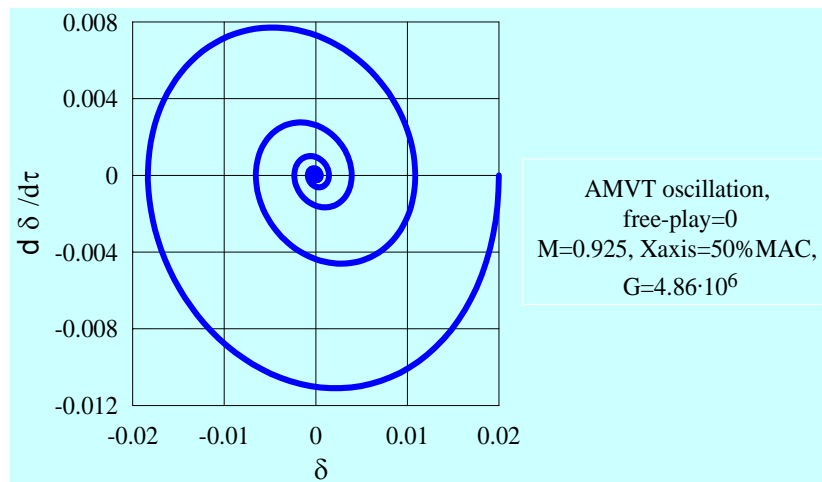


Fig. 9 Phase trajectories: stable oscillation

For a demonstration of possible limit cycle oscillations the numerical analysis of the free tail vibrations has been carried out. In this case the equation of motion is integrated together with the aerodynamic equations describing transonic flow around the vertical tail surface. Analysis has been performed for both cases: the linear dependence of the stiffness moment from the deflection angle and with the taking into account nonlinearities in the attachment. In common case the moment from the stiffness of attachment is determined by formula:

$$M_{stiff} = \begin{cases} 0, & \text{at } |\delta| \leq \Delta \\ G(\delta - \Delta \text{sign}(\delta)), & \text{at } |\delta| > \Delta \end{cases}$$

where value of Δ determines the magnitude of dead zone.

Results of calculations for two stiffness values, which had been marked on Fig. 8, are represented as the phase trajectories on Figs. 9-11. For the attachment stiffness value greater than minimal allowable rotational stiffness (point 1 on figure 8), and the linear dependence of the moment from the deflection angle, the oscillation frequency will be greater than critical, and for this reason the oscillations are stable (fig. 9). If the nonlinearities in the attachment are presented (dead zone or low stiffness region) the vibration frequency will be less than critical value, and therefore the oscillations will be unstable at small amplitudes. At the amplitude increasing the vibration frequency increases up to value corresponding to linear dependence from deflection angle, and oscillations will be stable. Thus, limit cycle oscillations have been realized with the small amplitude, which is comparable with the dead zone value (Fig.10).

For the attachment stiffness value lower than minimal allowable rotational stiffness (point 2 on figure 8) the oscillations with the small amplitude are unstable for both: linear dependence of moment from deflection angle, and moreover at the presence of nonlinearity. In this case the limit cycle oscillations are realized with the big amplitude; LCO are generated by nonlinearity of an aerodynamic damping at transonic speeds (fig.11, red curve). On the same picture for a comparison of amplitudes the LCO that are specified by nonlinearity of an attachment (blue curve) is represented. The amplitude of LCO induced by nonlinear aerodynamic damping practically is unallowable big when we estimate loads acting on the control surface. Thus for the presented result the amplitude of the airplane lateral load factor induced by these oscillations is about 0.4.

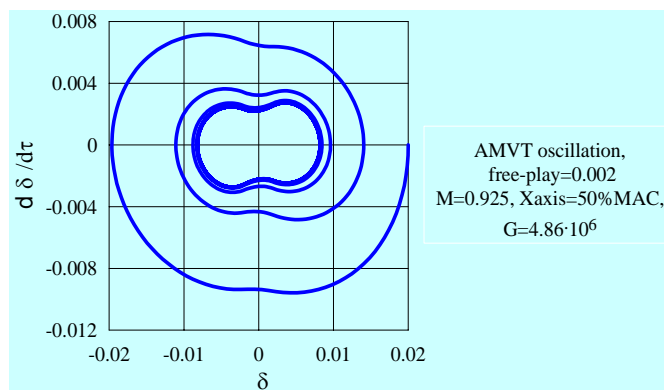


Fig.10 Limit cycle oscillations with small amplitude

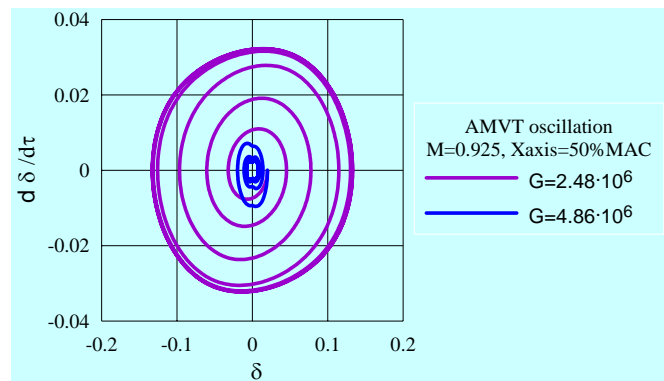


Fig. 11 Limit cycle oscillations for two stiffness values

7.0 APPLICATION OF NOVEL CONTROLS FOR AIRCRAFT LOADS ALLEVIATION

One of new aspects on application of novel controls is the use of joint deflections of an aileron and a spoiler located before the aileron. The modern airplane structure is very flexible, and aeroelasticity problems are significant at its design. Analysis of combination aileron+spoiler effectiveness for the loads alleviation was performed. Transonic code based on the solution of an equation for a full velocity potential was used to optimize wing airfoils in basic cross sections. The optimum angles of the wing twist were determined from the requirement of the maximum of lift-to-drag ratio for cruise flight regime (Fig.12).

Within the framework of the ARGON the procedure was developed for the pressure distribution correction in the chord sections of the lifting surface of high aspect ratio wing at deflections of both a trailing edge control and a spoiler. In an aileron deflection problem the wing thickness is taking into account, and viscosity of a stream across a boundary layer is taking into consideration also. In case of the spoiler the semi-empirical correction of pressure differences for the stripe is applied. The set of aerodynamic computations was carried out on the base of 2-D approach with using Navier-Stokes equation to obtain correction factors for spoiler effectiveness. The flow about typical section of the wing near spoiler location was considered (Fig.13) at Mach number, which is approximately corresponded to cruise regime.

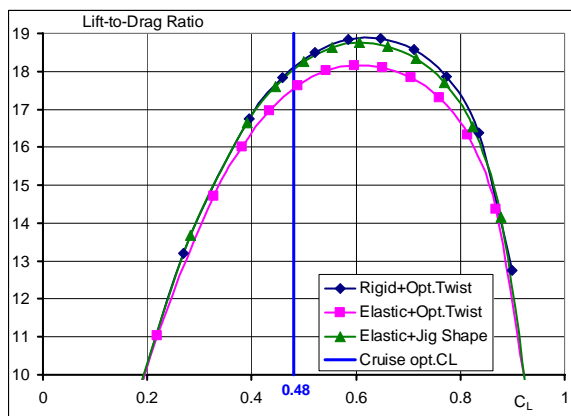


Fig. 12 Lift-to-drag

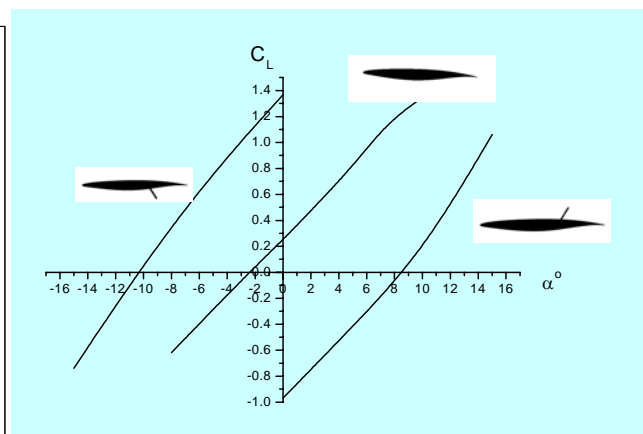


Fig. 13 Lift coefficient versus angle of attack for spoiler deflections

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