STRENGTH/AEROELASTICITY RESEARCH AT MULTIDISCIPLINARY STRUCTURAL DESIGN OF HIGH ASPECT RATIO WING

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Abstract

The paper is devoted to application of methodology of preliminary aircraft design by using multidisciplinary analysis and optimization. The purpose of the design is decrease of aircraft structural weight at satisfying strength and aeroelasticity requirements. Two-level approach is used for a structural design of an airplane wing which is made of composite or metallic materials.

The flowchart of multidisciplinary analysis and optimization are discussed. Some results of design optimization under multiple constraints for wing of high aspect ratio are presented. Variants of the wing structure both metallic and composite have been considered. Aeroelasticity characteristics of high aspect ratio wing have been confirmed in TsAGI wind tunnel tests.

1 Introduction

The airplane is designed such that the aerodynamic/inertial forces and the structural stiffness characteristics can be exploited in a beneficial way to always adjust the flexible shape of the airframe to the optimum aerodynamic conditions. This design approach allows considerable reduction in structural weight, aerodynamic drag and potential operating costs. Choice of advanced middle-range passenger airplane configuration and determination of structural parameters is performed by using multidisciplinary approach for conceptual study of elastic deformations, loads and controls effectiveness on aircraft with flexible high aspect ratio wing under different flight conditions. Optimum angles of the wing twist are determined from the requirement of the maximum of lift-to-drag ratio for cruise flight regime. Typical airplane structural design problem is finding of the structural variants having minimum mass under strength, stiffness, buckling, static aeroelasticity, and flutter constraints.

Nowadays, the aircraft design process in aerospace industry generally consists of a 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. An interaction of design parameters on objective function and constraints should be investigated for obtaining of reasonable design solutions. Therefore the reasonable solution on structural design can be found based on results of multidisciplinary analysis and optimization. Important aspects for multidisciplinary 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. Different multidisciplinary approaches for developing unconventional or innovative aircraft configurations have been proposed in the papers [1-4].

This paper demonstrates application of two-level approach for structural design of high aspect ration wing of advanced passenger airplane. The paper briefly describes scheme of multidisciplinary procedure with using models of different fidelities for analysis and optimization with constraints coming from several disciplines. In particular the problems of lift-to-drag maximization of airplane and minimization of structural weight are discussed. Some results of design optimization under multiple constraints for wing of high aspect ratio are presented. Variants of the wing structure both metallic and composite have been considered. Experimental results of TsAGI wind tunnel tests on research of aeroelasticity characteristics are presented.

2 Methodology of multidisciplinary analysis and optimization

The integrated approach to structural design of airplane includes multidisciplinary analysis and design based on the developed software ARGON [5] and the MSC.Software programs. ARGON system is intended for fulfillment of structural design researches generally on the preliminary stage of design when airplane configuration, structural layout and materials have been defined. The design task is to determine the cross-sectional sizes of structural elements while satisfying multiple requirements which are imposed on different responses from many disciplines. The key ground for development of the software was shortening of time for design cycle at determination of reasonable structural parameters. Along with the problems solving by ARGON software the multidisciplinary design procedure also includes using of commercial codes NASTRAN and PATRAN. The flowchart of the procedure for analysis and optimization is presented in Fig. 1.

Preparing of mathematical models is performed by using preprocessor programs: PGEN – for generation of aerodynamic and structural plate-beam models, ARGEN – for finite element model and PATRAN is used in many cases when it is necessary to import preliminary prepared CAD geometry models with different graphics formats.

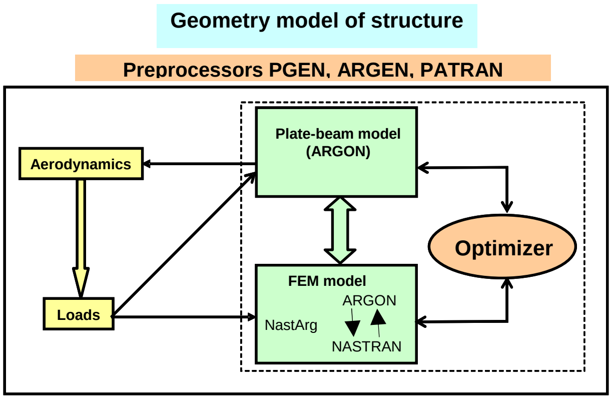

Fig. 1. Flowchart of multidisciplinary analysis/optimization procedure

The extreme flight load cases are chosen by using aerodynamics, loads and structural program modules. The problems of static aeroelasticity, flutter, structural dynamics and aeroservoelasticity can be solved with the modules available in ARGON. Some responses obtained from these programs can be considered as constraints at solution of structural optimization problem. Particularly, the distribution of skin thicknesses and spars/stringers section areas are determined for many load cases with taking into consideration the stress constraints. Then the loads for chosen extreme cases can be modeled in NASTRAN or translated on finite element model of ARGON system. Structural analysis and optimization can be performed with using both programs and special program NastArg accomplishes two-way data file exchange between the analysis programs.

3 Problem statement

It is well-known that increasing wing aspect ratio (AR) contributes to increase of lift-to-drag ratio. The preliminary investigations showed that better fuel efficiency of advanced airplanes could be achieved due to increase of wing aspect ratio. From other hand such increasing of wing AR can result in structural weight growth and increasing flexibility of wing. Therefore problem of structural strength and airplane aeroelasticity becomes more intensified.

The purpose of this work is design of wing structure and investigation of peculiarities in characteristics of strength and aeroelasticity for airplane with the wing of increased AR. It is supposed that airplane have conventional configuration as in real or designing airplanes with wing AR=10-11.

The middle-range passenger airplane having swept wing of large (AR=12.5) and take-off weight in the range between 70 and 80 tons. The cruise Mach number is 0.82. The following main parameters of airplane have been defined from preliminary researches and studies of prototypes:

- Low wing configuration, positive wing dihedral angle, no winglets;
- Two engines attached on pylons under wing;
- Conventional tail part.

The main parameters of airplane are given in Table 1.

Table 1. Main parameters of airplane

Maximum take-off weight	76.5 ton
Design weight	75 ton
Airplane length	42 m
Wing area	128 m^2
Wing span	40 m
Aspect ratio	12.5
Mean aerodynamic chord	3.576 m
Wing sweep angle of ¼ chord line	29.0°
Wing dihedral angle	5°

The problem is formulated to perform parametric design studies of strength and aeroelasticity characteristics for wing structure which can made of different materials under the following presumption:

- Geometry and aerodynamic model of airplanes is the same for all analyses;
- Total mass and mass distribution are identical (it is supposed that the difference in structural weight of wing can be approximately compensated by modification of fuel mass);
- Stiffness properties of fuselage and tail part are chosen from prototype airplane;
- Design load cases for determination of structural parameters of wing are the same but loads are different because flexibility of structures is different.

The researches of strength include determination of reasonable angles for stacking of composite material (CM) layers and evaluation of influence of allowable stresses on structural weight. At aeroelasticity analysis the comparative studies of flutter boundaries versus dynamic pressure, shape and frequencies of flutter vibration, mechanism of flutter emergence and aileron effectiveness in roll are performed.

4 Numerical studies of loads, structural strength and aeroelasticity

4.1 Mathematical models

The general view of airplane aerodynamic model is shown in Fig. 2. The model is intended for calculation of aerodynamic forces by using linear panel method for quasi-static problems and doublet lattice method for structural dynamics problems.

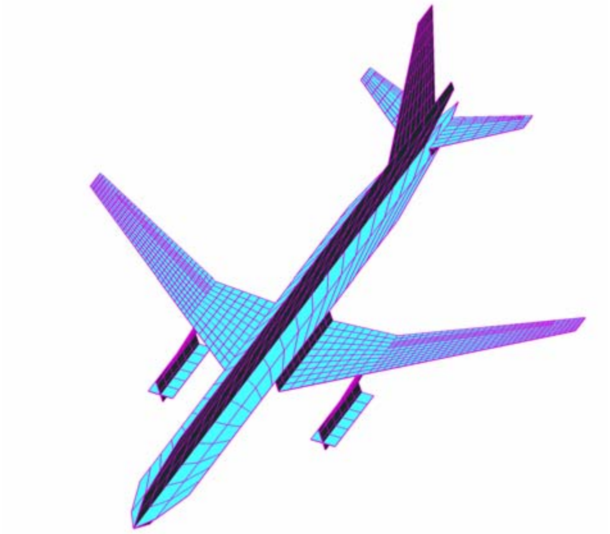

Fig.2. Aerodynamic mesh

The structural model is shown in Fig. 3. Distribution of beam stiffness characteristics for sections along fuselage span is chosen on the basis of available characteristics for prototypes. Structural layouts of horizontal and vertical tail are structural boxes which are inscribed into 10% airfoil. The structural box of wing consists of skins (panels) and longitudinal primary elements (beams) which models stringers and spars. Panel and beam elements are determined in optimization procedure to satisfy strength and buckling conditions for considered load cases.

Fuel mass is located along structural box of wing from the root section to beginning of aileron.

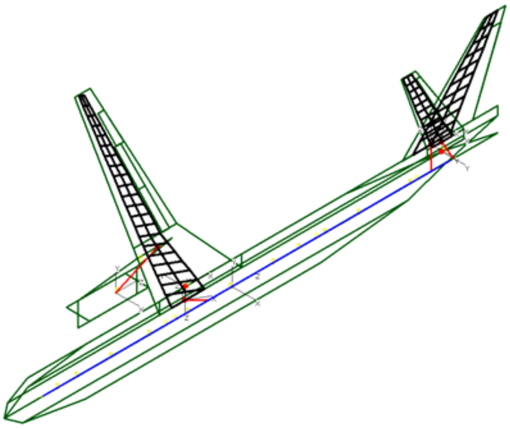

Fig.3. Structural model in ARGON

4.2 Lift-to-drag

One of the important parameter influencing both on loads and lift-to-drag (L/D) coefficient is set of twist angles for lifting surfaces. We consider wing twist angles in three base sections (root section, kink and tip section) and twist angles in lower and upper sections of engine pylon.

The optimum twist angles for these sections are defined from the condition of maximum lift-to-drag for cruise flight M=0.82, H=11 km. In this case coefficient of full drag is calculated as $c_x = c_{xF} + c_{xW} + c_{xi}$ where two first summands (friction drag and wave drag) are defined by semi-empirical formulae and the induced drag is calculated in Trefftz plane by using distribution of lift force for chosen load case. As a result the *L/D* can be calculated as function of twist angles in the base sections. Maximum of this function can be determined numerically by using method of sequential quadratic programming. Then we by iterations define jig shape as difference between optimum twist angles and obtained elastic twist angles. This jig shape is used for loads analysis with taken into consideration airplane structural flexibility.

The dependence of *L/D* on lift force coefficient is shown in Fig. 4. As can be seen the maximum lift-to-drag achieved the value of 19 and the cruise *L/D* is about 18.6. The cruise flight regime corresponds to lift force coefficient C_L=0.54. The neglect of structural flexibility at determination of twist angles would result to appreciable lost of lift-to-drag ($\Delta(L/D)\approx 0.6$, see low curve in Fig. 4).

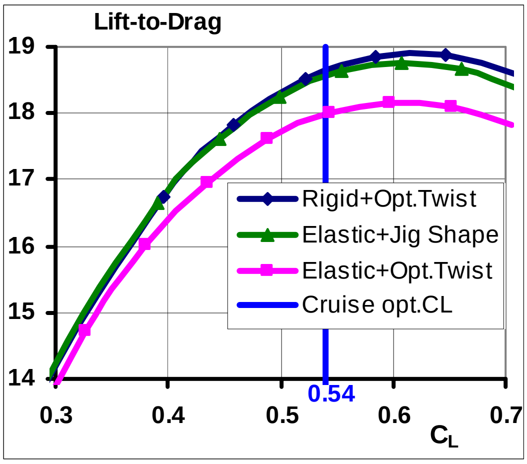

Fig.4. Dependence of *L/D* on lift force coefficient

4.3 Determination of structural parameters of wing

Wing is the most important airplane component from the viewpoint of aeroelasticity and loads and here we consider the problem of structural design of wing-box. The design airspeeds are chosen on the basis of available prototypes and Airworthiness Regulations for airplane of considered class (see Table 2).

Table 2. Design airspeeds

V_D=670 km/h EAS	M_D=0.89	q_D=21.2 kPa
V_C=580 km/h EAS	M_C=0.82	q_C=15.9 kPa
V_A=450 km/h EAS	M_A=0.37	q_A=9.57 kPa

Six load cases for quasi-static maneuvers with positive and negative load factors have been chosen in preliminary analyses for determination of structural parameters. It is impossible in practice to take into account simultaneously all requirements of Airworthiness Regulations on determination of gust loads. Therefore we choose two most dominant load cases due to vertical gust for optimization procedure and rest of them should be verified with analysis of designed structure.

Two materials have been considered. Aluminum has the following mechanical properties: Young modulus E=7.2·10^7 kPa, mass density ρ=2.8 ton/m^3, allowable stress σ = 400 MPa.

Parametric computations have been done to determine reasonable angles for stacking of composite material layers. Computational results have shown that the reasonable quasi-orthotropic composite material skin have 50 percent of layers stacking in direction of rear spar (0° direction), 20 percent of layers are in +45° direction, 20 percent of layers are in -45° direction and 10 percent are in 90° direction. The mechanical properties have been calculated for composite laminate: Young moduli E_1=8.32·10^7 kPa, E_2=3.44·10^7 kPa, shear modulus G=1.79·10^7 kPa, Poison coefficient μ=0.418, mass density ρ=1.55 ton/m^3.

Skin thicknesses and cross-sectional areas of spar/stringer elements are calculated with fully-stressed design algorithm. Von Mises criterion is used for metallic structure and Tsai-Hill criterion is used for evaluation of strength of composite laminate. Constraints on minimum skin thicknesses of 2 mm and minimum section areas of 500 mm^2 are imposed. As example in Fig. 12 (curve "Strength") the obtained skin thicknesses for metallic wing are introduced. Structural weight of metallic wing is 1.889 ton. The weight of spar/stringer elements in metallic wing is about 47 percent of total weight. Structural weight of composite wing is 1.329 ton. In this case the weight of spar/stringer elements is about 46 percent of total weight.

4.4. Research of structural strength by using FE model

The chosen six extreme flight load cases were modeled in NASTRAN program for fulfillment of design investigations on finite element (FE) model of wing-box with center-wing. The plan view of the FE model together with the aerodynamic model is shown in Fig. 5.

Comparison of loads obtained in two programs shown that difference from each other is inessential. The difference in bending moment for the load case with maximum bending moment in wing root section is illustrated in Fig. 6.

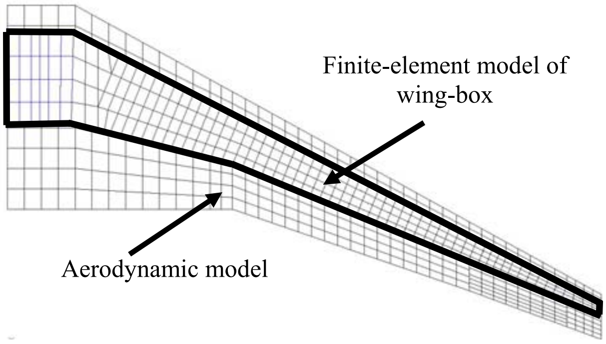

Fig. 5. Finite-element and aerodynamic model of wing

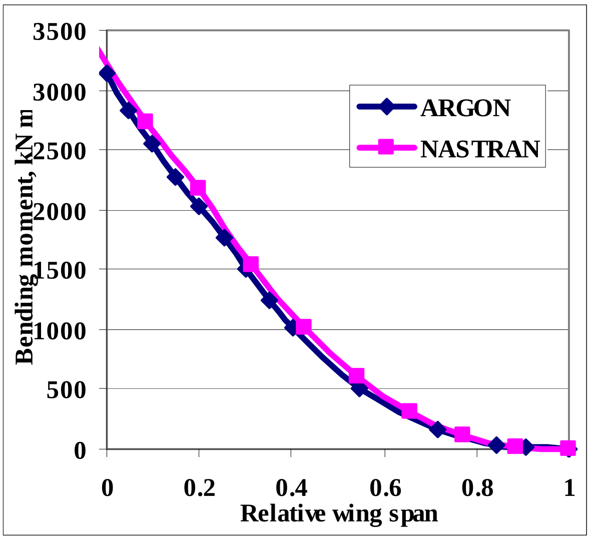

Fig. 6. Comparison of bending moments

Structural optimization of wing box with including aeroelastic analysis (SOL144) have been performed for seven levels of allowable stresses for structure with composite elements and also for aluminum wing with allowable stress of 400 MPa. Structural mass versus allowable stress is shown in Fig. 7.

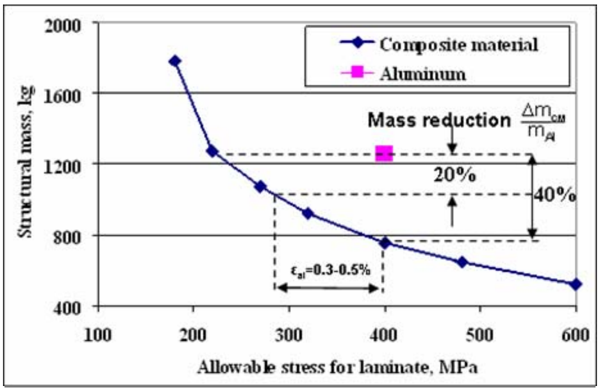

Fig. 7. Dependence of optimum mass of structural box on level of allowable stress

It is obviously that using of composite material in wing structure is reasonable when allowable stress for laminate is above 250 MPa in upper and lower panels. Analysis results showed that primary mass of composite wing can be reduced up to 40 percent if compared with metallic variant. For this case it is necessary to have allowable stresses of 400 MPa both in upper and lower panels of wing-box. The required skin thicknesses for this allowable stresses are shown in Fig. 8.

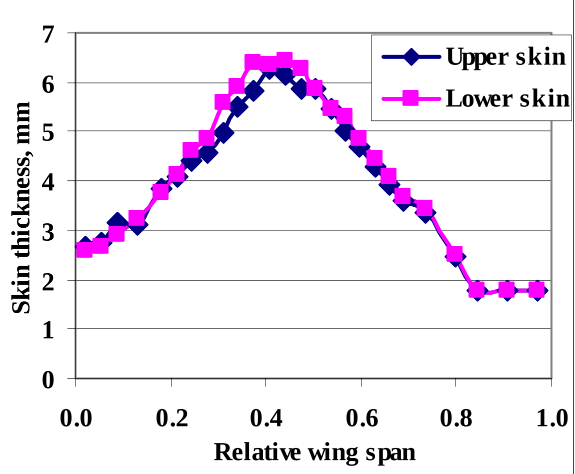

Fig. 8. Skin thicknesses

The picture of von Mises stresses in lower skin for one of extreme load cases is illustrated in Fig. 9. These stresses achieve limit value for flight load (266 MPa) practically along all wing-box excluding the tip part of wing. So the optimum structure of wing-box is fully-stressed design.

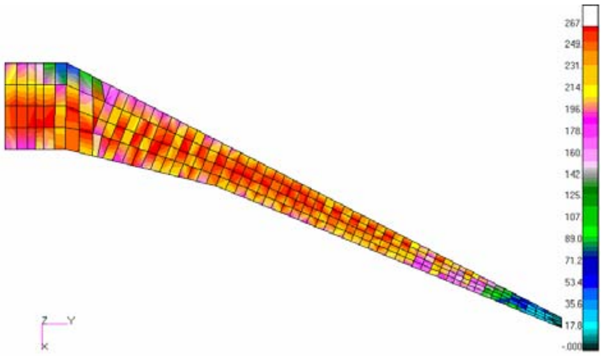

Fig. 9. Von Mises stresses in lower skin after optimization

Usually structure of high-aspect-ratio wing designed with only strength constraints should be reinforced to meet the aeroelasticity requirements. In this case the most appropriate approach to determination of the required additional stiffness parameters is an approach based on multidisciplinary design optimization with mutual account of strength and aeroelasticity requirements. Preliminary flutter analysis of wing has been accomplished with using the finite-element model. This analysis identified three flutter critical points. The first flutter shape takes place on flight speed 232 m/s and corresponds to frequency 2.88 Hz. The second flutter speed is 314 m/s and corresponding flutter frequency is 5.03 Hz. The third flutter speed is 368 m/s and corresponding flutter frequency is 8.1 Hz. All three flutter speeds are in feasible range of flight of airplane but the first flutter speed is principally on the boundary of feasible domain because $V_{f1}<1.2V_D$=234 m/s. Therefore the designed structure of wing-box satisfies to both strength and flutter requirements. It is worth to note that in the obtained results the flutter margins are minimal and account of engine vibration is also important for flutter analysis. That is why additional researches on aeroelasticity were performed by using first-level model of ARGON software. Below the principal results on aeroelasticity analysis are given.

4.5 Modal characteristics

Normal modes analysis has been done to compare eigen modes of two structures made of metal and composite. Comparative analysis shows the eigen modes of two structures are mainly correspond to each other and they are typical for airplane of such configuration. However wing bending mode frequencies of composite structure are appreciably higher and torsion frequencies are on the contrary appreciably lower. This is caused by stacking of composite layers.

Fig.10 presents for example the comparison of mode shapes and frequencies of symmetrical elastic oscillations of free airplane structure with metal and composite wings. Engine attachment stiffness for yaw and pitch were specified by following values: G_{yaw}=60000 kN×m/rad, G_{pitch}=75000 kN×m/rad, which approximately correspond to prototypes characteristics (partial oscillation frequencies of engine for fixed rigid wing are 4.8 Hz in yaw and 6 Hz in pitch).

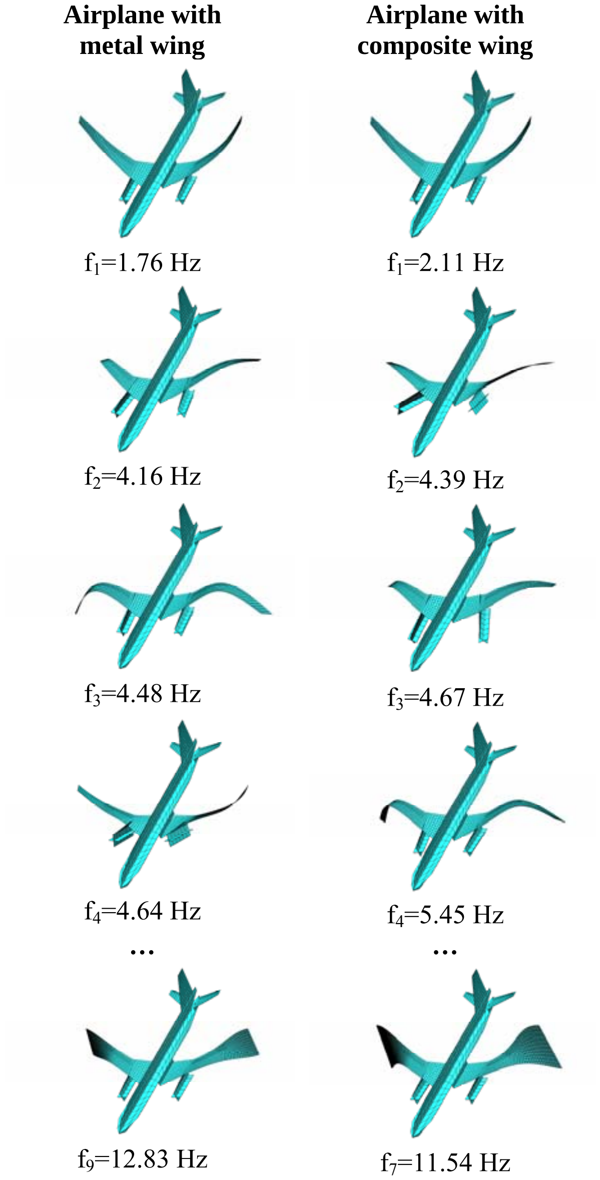

Fig. 10. Comparison of mode shapes and frequencies of airplane with metal and composite wings

4.6 Flutter analysis

One of the principal problems for design the wing with such enlarged aspect ratio and under-wing engine is to ensure safety on flutter. Here the flutter analysis has been performed by computation of complex solutions of flutter equation (damping and frequencies of oscillations) in dependence on flow speed. Unsteady aerodynamic forces have been determined by doublet-lattice method, using iterations on reduced frequency for each value of airspeed. The following characteristics have been obtained as a result of calculations: decrements and frequencies of elastic vibrations as functions of the flow speed (V-g plot, Fig.11), critical dynamic pressure, frequencies and shapes of flutter oscillations. Since the limit dynamic pressure is q_D=21.2 kPa (V_D=670 km/h), therefore to ensure flutter safety margin the following condition should be satisfied: $q_{FL} \geq 1.44 q_D = 30.5$ kPa.

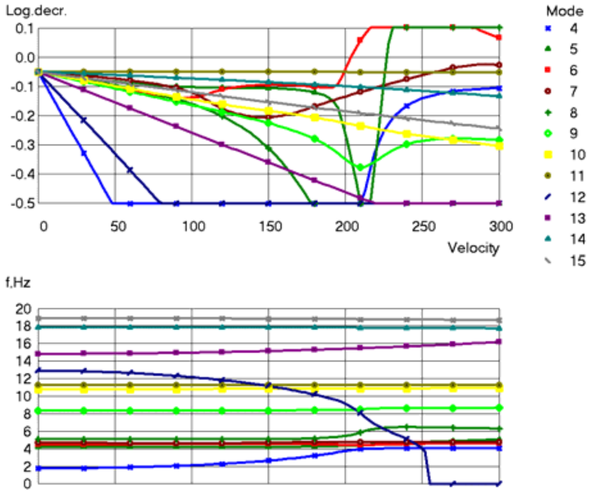

Fig. 11. V-g plot for airplane with metal wing (M=0.82, symmetrical case)

The results of calculation have shown that two flutter forms are mainly proper to both structural variants of the wing. The first form with the frequency about 3.5-4.5 Hz is due to vibrations of the engine on the pylon and bending vibrations of the wing. The second mode with the higher frequency about 6-8 Hz is due to the bending-torsion vibrations of the wing tip. The characteristic feature of this structure in comparison with the prototypes is the significant influence of the horizontal deformations of the wing on flutter vibrations. Another characteristic feature is the presence of anti-symmetrical flutter forms at relatively low air speed, which is uncommon for the similar configuration with the smaller aspect ratio wing.

Flutter dynamic pressure margins were insufficient for both structural variants, while composite wing having smaller margin. It should be noted that this was the case for the given stacking of the composite material. It is possible that there was no need to increase the bending stiffness while weakening the torsion stiffness; but changing the stacking to more quasi-isotropic variant would improve the aeroelastic characteristics.

The following traditional means to increase the speed of considered flutter modes should be used:

- Increase of wing stiffness;
- Increase of stiffness of the engine attachment;
- Redistribution of masses and/or adding the balance weight;
- Change of composite stacking.

In our case the stiffness of the engine attachment was sufficiently high so the further increase of the stiffness might prove not possible. Redistribution of masses and adding the balance weight to meet flutter requirements need more detailed design of the structure and determination of mass distribution. Moreover these measures are appropriate for only one specific flutter mode.

For these reasons it is reasonable to consider a strengthening of the wing box structure. As a result of flutter analysis it was determined that flutter forms are mainly due to the bending and especially torsion deformations of the wing tip. The local increase of the skin thickness have been found which ensure sufficient dynamic pressure margin for all flutter forms. The spar/stringer cross areas are not changed.

The skin thicknesses obtained for the metal wing are shown in Fig. 12. Structural weight has increased by 0.112ton, i.e. by 6%. The dynamic pressures have increased by $q_{FL\,1}$=30.1 kPa, $q_{FL\,2}$=42.8 kPa (symmetry), $q_{FL\,1}$=30.7 kPa, $q_{FL\,2}$=44.2 kPa (anti-symmetry).

For the composite wing the increment in the structural weight is 0.246ton (18%). Dynamic pressure has been increased: $q_{FL\,1}$=30.4 kPa, $q_{FL\,2}$=43.5 kPa for the symmetrical flutter modes; $q_{FL\,1}$=31.6 kPa, $q_{FL\,2}$=45.2 kPa for the anti-symmetrical modes.

The most important component of stiffness influencing on flutter characteristics is pitch stiffness of engine attachment. Figure 13 represents dependence of flutter speed from the pitch stiffness of the engine attachment.

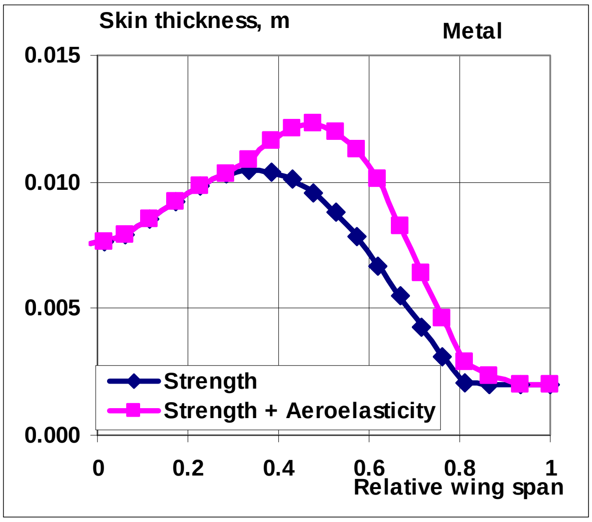

Fig. 12. Skin thickness of metal wing which was reinforced to meet aeroelasticity requirements

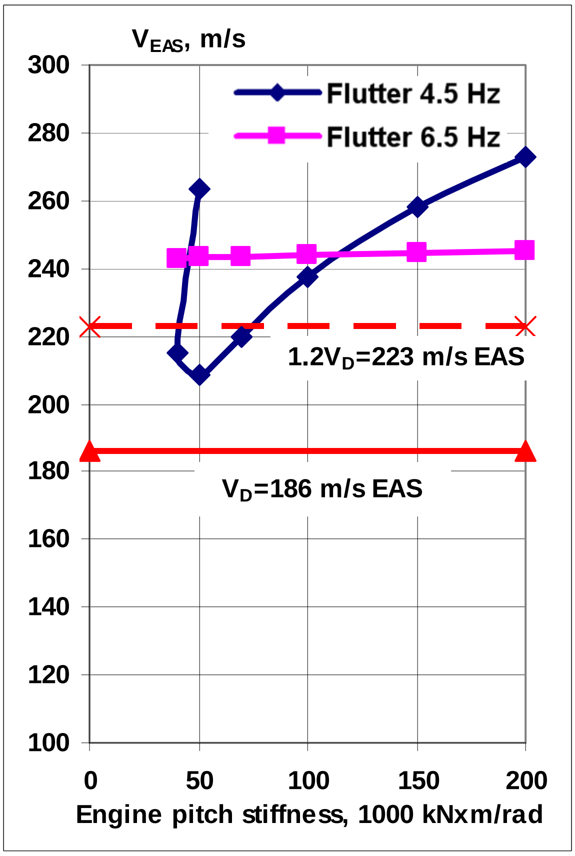

Fig. 13. Dependence of flutter speed from engine pitch stiffness: symmetrical case, M=0.82

It is shown that in the range of stiffness from 40000 to 75000 kN×m/rad the flutter margin is not sufficient for the first flutter form. In the further researches as the baseline variant the stiffness value 100000 kN×m/rad is specified, which ensures sufficient margins of all flutter forms in symmetrical and anti symmetrical cases for all considered Mach numbers.

4.7 Characteristics of static aeroelasticity

For static aeroelasticity analysis numerical studies of aerodynamic coefficients depending on dynamic pressure were carried out at different Mach numbers. The influence of elasticity on aerodynamic characteristics is within the allowable bounds for considered structure variants.

For example, lift slope coefficient C_L^α decreases on 13%-15% at high values of dynamic pressure. As it was expected for aircraft of the given configuration, there is no tendency to aeroelastic divergence. The shift of the aerodynamic center position increases up to 5% C_{MAC}. A danger of static stability loss due to elastic deformations does not exist.

The influence of the structure elasticity on control efficiency has been calculated and analyzed as well. The most significant is a loss of aileron efficiency on roll. For the airplane with composite wing after reinforcement the margin on dynamic pressure of the aileron reversal is sufficient. At dynamic pressure $q=q_D$ aileron efficiency there is still about 30%.

It should be noted that before the reinforcement the reversal margin for the composite wing variant was not sufficient. In Fig. 14 the comparison of the aileron roll efficiency is presented for M=0.89 regime for both variants of the structure before and after the reinforcement to meet the flutter safety requirements. It could be seen that in this case the reinforcement to meet flutter requirements ensures the margins of dynamic pressure for reversal. In the case of metal wing the reinforcement has not affected practically on the aileron roll effectiveness, but the effectiveness was sufficient even before the reinforcement (Fig. 14).

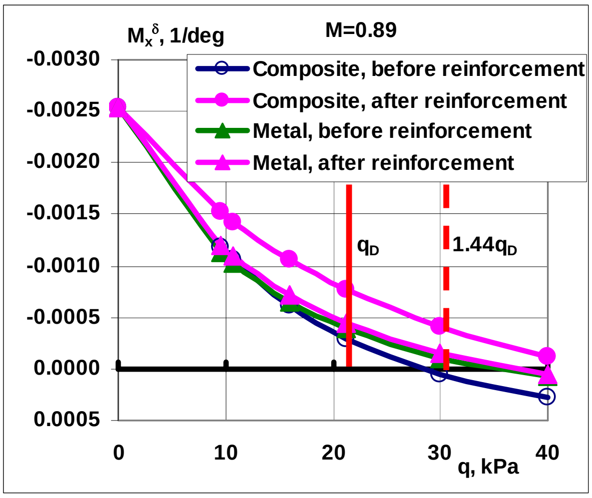

Fig. 14. Comparison of aileron roll efficiency for different variants of the structure

5 WT Tests for Demonstrator

Experimental validation of flutter characteristics of enlarged aspect ratio wing has been performed on demonstrator with dynamically scaled model (DSM) of fixed half-wing with AR=12.5 and the main parameters affecting on flutter characteristics have been determined.

DSM is a flexible beam (spar) with compartments modeling aerodynamic shape and masses. It also includes an engine with a canal, flexible pylon, and aileron. The pylon has changeable springs of different stiffness which are used for attachment of engine to the wing spar. Aileron has elastic joint to simulate different its rotation frequencies.

Wing spar structure is a beam of varying cross section with given distribution of bending stiffness in vertical plane EJ_{vert}, torsion stiffness GJ, and bending stiffness in horizontal plane EJ_{hor}. The spar consists of plywood core with composite sheet laminations stacked together symmetrically, which thickness and width are variable along the wing span. The model scheme with its compartments is shown in Fig. 15.

Specialists of TsAGI aeroelasticity division designed and manufactured this demonstrator and performed lab tests. Wind tunnel tests have been done in subsonic WT T-103 with open test section.

The variation of the engine attachment stiffness (6 springs) has been used in the model structure for preconceptual parametric study in the wind tunnel. The photo of the model in the WT working part is presented in Fig. 16. To provide flow boundary conditions the flat screen was located at the wing root section.

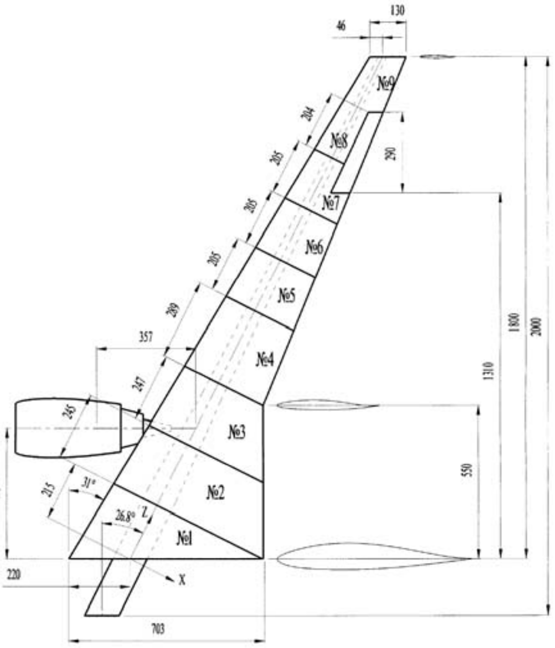

Fig. 15. Scheme of DSM

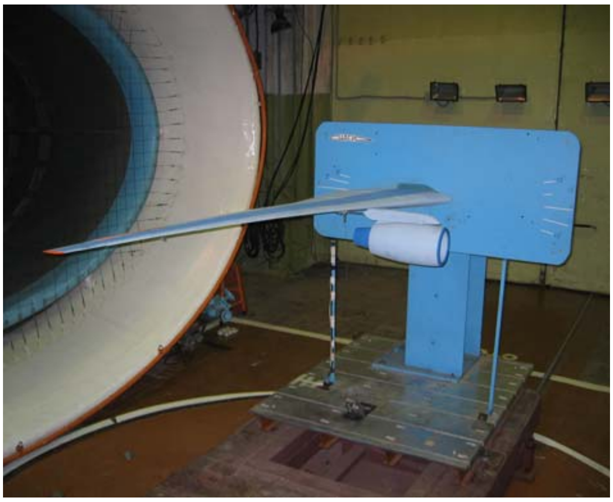

Fig. 16. DSM in working part of WT T-103

The dependence of flutter speed from the test-bench frequency of vertical engine oscillations f_{pitch}, and test results are represented in Fig.17 and in Table 3. The obtained results show that in considered frequency range 5-10 Hz the low frequency flutter with first vertical wing bending and vertical engine oscillations has arisen. Critical flutter speed of this form is V_{FL}=35m/s. At flow speed V=44.5m/s and frequency f_{pitch}=3.48Hz the high-frequency bending-torsion form flutter has been obtained.

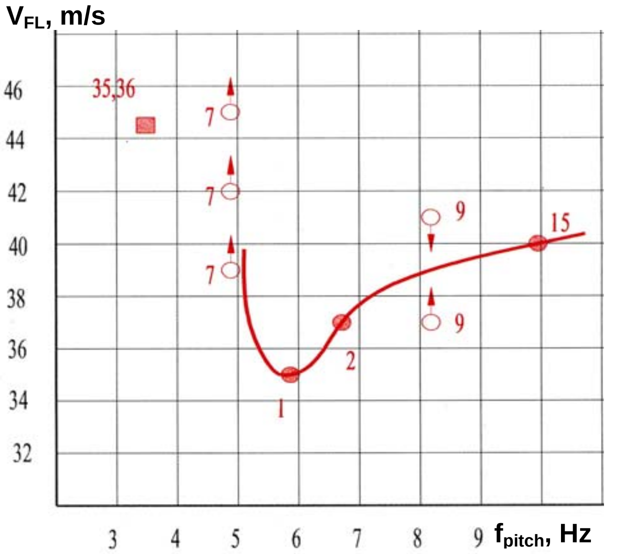

Fig. 17. Dependence of flutter speed from frequency of engine pitch (filled circles correspond to flutter boundary obtained in WT test)

Table 3. Extract from test record

Run #	**Spring #**	**f_{pitch}, Hz**	**V_{FL}, m/s**	**f_{FL}, Hz**	**Flutter shape**
1	5	5.86	35	4.58	EP + WB-1
2	1	6.71	37	5.0	EP + WB-1
7	4	4.88	42		No flutter
9	3	8.18	39	5.49	EP + WB-1
15	6	9.95	40	6.1	EP + WB-1
35, 36	2	3.48	44.5	12.54	WT + WB-3

EP – Engine Pitch, WB – Wing Bending

Thus, the model tests have confirmed the main flutter characteristics of enlarged aspect ratio wing. Test results show that main (limitative) flutter form is flutter with the wing bending and the vertical engine oscillation on pylon. The second high-frequency flutter form with higher critical speed will arise, which may be obtained in the WT test at soft engine attachment when the first flutter form has disappeared.

6 Conclusions

In the paper the main mechanism of the parameters influence on loads, strength and aeroelasticity of the airplane with enlarged aspect ratio wing has been determined.

Application of multidisciplinary analysis and optimization has allowed obtaining a rational structural parameter distribution which satisfies many functional restrictions at minimum structural weight. Conceptual studies have shown that the use of advanced composite materials will allow solving a problem of design of high aspect ratio wing.

The main mechanisms of the structural and flow parameter's influence on flutter characteristics have been confirmed by experimental results of the methodical dynamically scaled model in subsonic wind tunnel TsAGI T-103.

In future at design of advanced passenger airplane with high fuel efficiency it is supposed to perform joint aerodynamic and strength design of enlarged aspect ratio wing with taking into account an control system operation.

Acknowledgement

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