NUMERICAL STUDIES OF AEROELASTICITY/STRENGTH/AERODYNAMICS ON THE EUROPEAN RESEARCH AEROELASTIC MODEL (EURAM)

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The analytical-experimental prospecting researches for improving aircraft performance at the expense of aeroelasticity are performed in TsAGI within the framework of 3AS European project. The concept “use of elasticity” or “active aeroelasticity” is considered here with reference to wide-body passenger airplane having high-aspect-ratio wing and four engines on pylons. Two aspects of the concept were studied currently:

- using of the wing elasticity for increase of roll control characteristics and decrease of the induced drag with aid of controls locating in forward direction from the wing stiffness axis;
- using of the rotational elasticity of the axis of all-movable vertical tail of reduced size for improvement of lateral stability and controllability; in this case the vertical tail attachment is performed by using adaptive rotational stiffness versus flight speed.

A lot of analytical-experimental studies were carried out to learn these two aspects of concept. General review of the concepts and researches is presented in the papers [1], [2]. Results of analytical and experimental studies for dynamic scaled models (DSM) of cantilevered wings in VZLU and TsAGI are described in [3]. The paper [4] is dedicated to problems of designing, manufacturing and experimental studies of complete DSM and its compartments in TsAGI.

The interesting features of numerical researches of strength and aeroelasticity of EuRAM are considered in this paper.

Computational models

The computational beam models have been developed in the software packages ARGON [5] and KC-M [6] for the maintenance of design process and manufacturing of the beam-compartment DSM. Both developed models are based on the method of prescribed forms (Ritz polynomial method). The ARGON software has more possibilities for investigations of static aeroelasticity and analysis of quasi-static loads, and the KC-M software is preferable for the solution of dynamic problems. The structural parts of DSM are modeled by bending/torsion beams and concentrated masses in the computational models (Fig. 1). The structural parts are joined by rigid springs. The compartments of DSM were not modeled and the deformation of the lifting surfaces was considered to be smooth.

Finite element (FE) models of structural parts and the full DSM have been developed in

NASTRAN system. The beam structural scheme is also used in these models. Compartments of the lifting surfaces are modeled by rigid plate elements for visualization of displacements (Fig. 2). The displacement field for analysis of aerodynamic forces is defined by one-dimensional splines generated on the nodal displacements of the spars. The finite element models are described in the paper [7] in more details. The development and refinement of the analytical models were performed stepwise: preliminary models of structural parts, their refinement after design, manufacturing, ground vibration tests, wind tunnel tests, assembling of the full DSM, its ground vibration and wind tunnel tests.

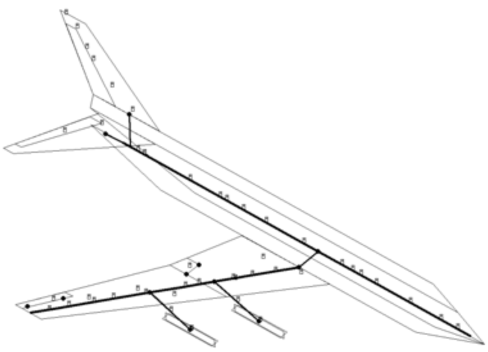


Fig. 1

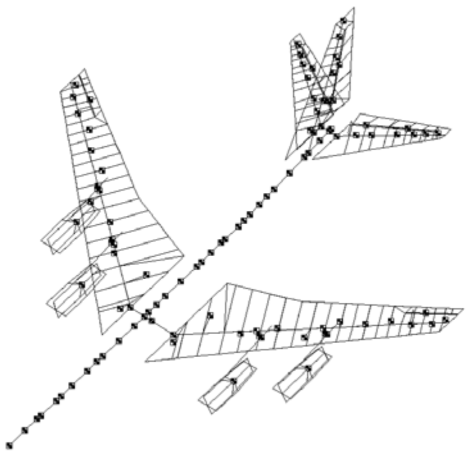


Fig. 2

It is necessary to validate the effectiveness of the considering concepts in the project on full scale airplane. One of research particularities is that the computational model of full scale airplane was developed on the basis of its DSM. The geometrical sizes of the mathematical model of the full scale airplane were defined by multiplication of the DSM sizes by the length scale coefficient.

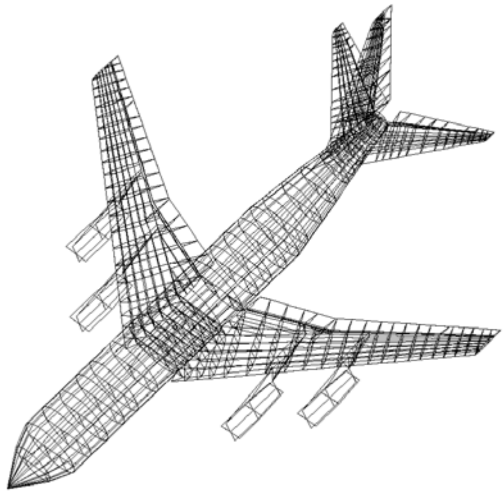


Fig. 3

Structural layouts of structural parts were chosen on the basis of known structural layouts of existing wide body airplanes and experience. The traditional approach of modeling by two-dimensional shell elements and one-dimensional beam elements was employed at the development of the model of full scale airplane (Fig. 3). Detailed description of creation of this model is given in [7].

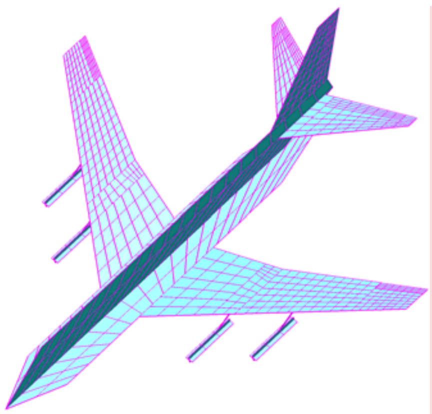


Fig. 4

The aerodynamic model used for all structural models is shown in Fig. 4. It includes a set of lifting surfaces used in panel methods.

Static aeroelasticity

The considering concepts of "using of aeroelasticity" are mainly related with the characteristics of static aeroelasticity. Therefore, a great attention was paid to the static aeroelasticity researches. Largely, the elastic wing displacements due to aerodynamic and inertial forces define all characteristics of static aeroelasticity. Elastic displacements and streamwise twist angles along wing spar at angle of attack α=5° and flow speed V=25m/s are shown in Figs. 5-6.

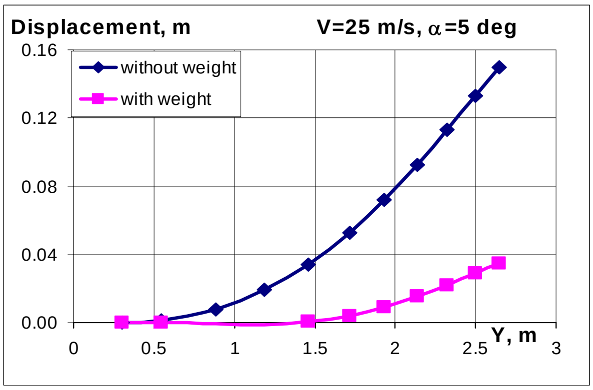


Fig. 5

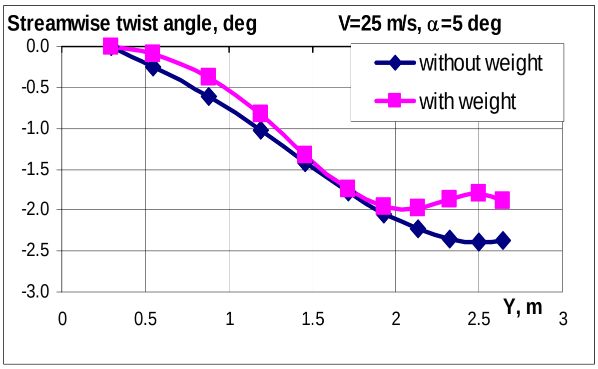


Fig. 6

The wing tip displacement is 15 cm in upward direction and decrease of angles of attack in the tip section $\Delta\alpha$=-2.4° for analysis without account of gravity forces. Account of structural weight reduces the wing tip displacement almost by 12 cm. The roles of bending (φ) and torsion (ψ) angles in the streamwise angle of attack $\Delta\alpha=\varphi\cos(\chi)-\psi\sin(\chi)$ (χ is wing sweeping angle) are shown in Fig. 7. The large contribution of the bending angle to the streamwise angle of attack can be seen from the figure.

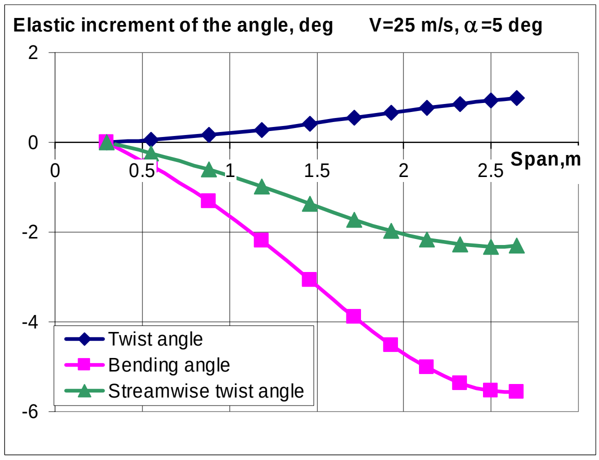


Fig. 7

A lot of analytical investigations of the influence of structural elasticity on aerodynamic characteristics are performed. The obtained results are in good agreement with each other and experimental data. One of important static aeroelasticity characteristics is an effectiveness of outer aileron. It is essentially reduced due to aeroelasticity and it achieves the reversal on lifting force at flow speed V=25 m/s and reversal on roll moment at flow speed V=36 m/s. A different look on this phenomenon is presented in Figs. 8-9. Here an influence of flow speed and structural elasticity on distribution of aerodynamic forces is shown. Fixed structure with the aileron deflection of 1 degree is considered. The shear force in the wing root achieves maximum value at flow speeds about V=15-20 m/s and becomes practically zero at flow speed V=25 m/s (Fig. 8). The bending moment also achieves maximum value at flow speeds about V=20 m/s and decreases for further increase of the flow speed (Fig. 9).

It is necessary to bear in mind at using of the DSM static aeroelasticity characteristics for full scale airplane that they were defined for fixed structure of DSM. Additional inertial forces are applied to real structure in free flight and they also cause additional displacements and redistribution of aerodynamic forces.

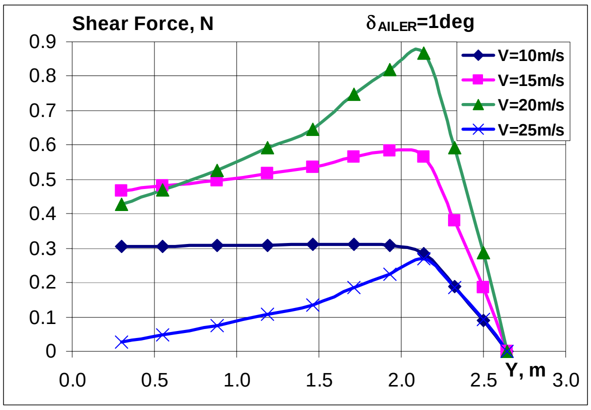


Fig. 8

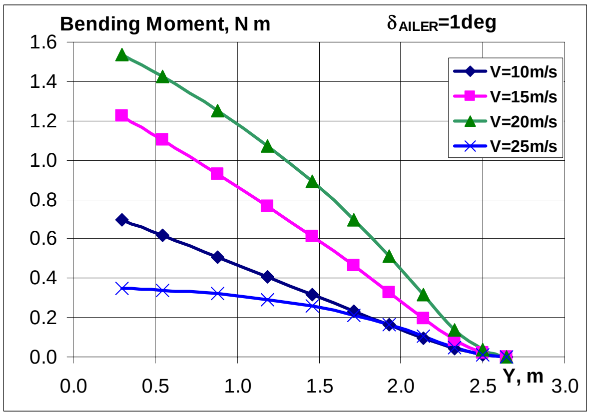


Fig. 9

The influence of structural elasticity on the location of airplane aerodynamic center X_F^α for the actual airplane scale of dynamic pressures is shown in Fig. 10. The analytical and experimental results are in good agreement for fixed structure in incompressible airflow (M=0.07). The characteristics of free structures are different from ones of fixed structure. Besides, it is necessary to take into account the influence of Mach number for full scale airplane (for instance, in cruise flight M=0.84). Therefore the location of aerodynamic center of full scale airplane in free flight is sufficiently different from the location found in wind tunnel tests (Fig. 10).

It is interesting to carry out the analogous comparison for the roll effectiveness of the wing tip aileron (Fig. 11).

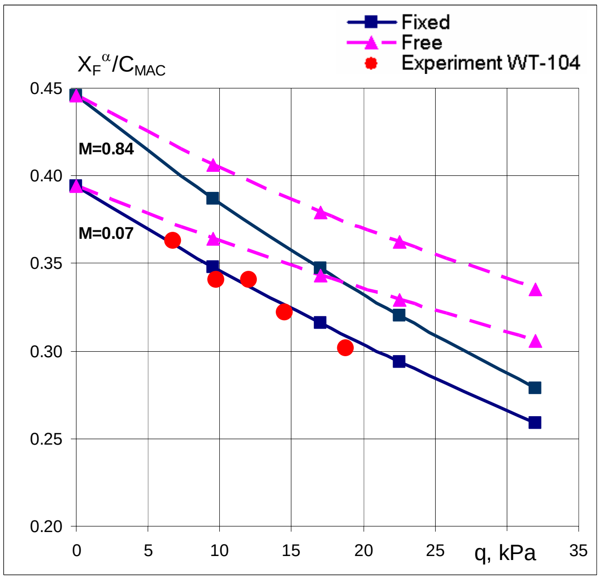


Fig. 10

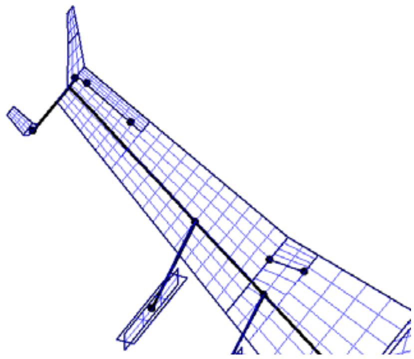


Fig. 11

For the fixed structure the analytical results are also in good agreement with the experimental ones (recalculated for scales of actual airplane). Unlike regular aileron the effectiveness of wing tip aileron practically is not decreased. On free structure the inertial forces arising because of roll angular acceleration additionally twist wing to “useful” angles. Therefore, the effectiveness of the wing tip aileron on full scale airplane distinctly increases. Note that account of inertial forces must be performed for full scale (FS) structure because the DSM is not similar to full scale airplane on mass-inertial characteristics. From other hand it is difficult to adjust fixation of three-dimensional FS model to correspond to the fixation of DSM. Therefore, it is reasonable to use simplified beam-plate analytical models of FS structure.

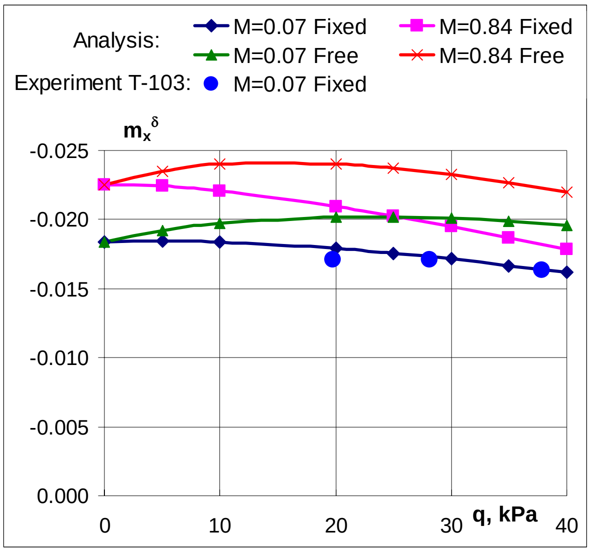


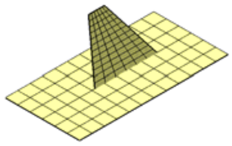
Fig. 12

Flutter

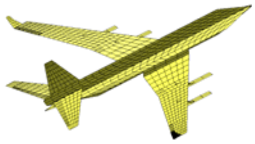
A lot of analytical and experimental researches on flutter characteristics of wing models with different tip controls, regular and all movable vertical tail (AMVT), complete DSM, and computational model of FS airplane were performed.

An inherent feature of the cantilevered wing and the complete model with regular VT is the flutter shape with horizontal oscillations of outer engine. Flutter speed depends on engine position in vertical and chord-wise directions, but these weak-damping oscillations degrade dynamic characteristics of the airplane even when sufficient flutter margin is available. Therefore it would be reasonable to find a method for considerable increase of engine oscillations damping in future work in this project.

Many characteristics of AMVT (and airplane with AMVT) were in detail studied in the paper [8]. We consider here comparative flutter characteristics of isolated AMVT (Fig.13, a) and complete model with AMVT (Fig.13, b).



a)



b)

Fig. 13

Antisymmetrical oscillations of the complete DSM cardinally change their behavior in the airflow in the presence of adaptive attached AMVT. Divergence and different flutter speeds in dependence on AMVT rotational stiffness are shown in the Fig.14 and 15 for rotational axis position of 40% MAC. Except bending-rotational flutter ("Flutter 10 Hz") two other flutter modes appear in the case of complete model.

Low-frequency flutter mode "AMVT rotation + rigid body yaw" appears for free DSM ("Flutter 0.3-1.0 Hz") instead of divergence for isolated AMVT at low rotational stiffness. Absolutely new flutter mode appears. It is due to interaction of rotational oscillations of AMVT with second antisymmetrical wing bending mode and fuselage horizontal bending ("Flutter 3.7-4 Hz", Fig.15).

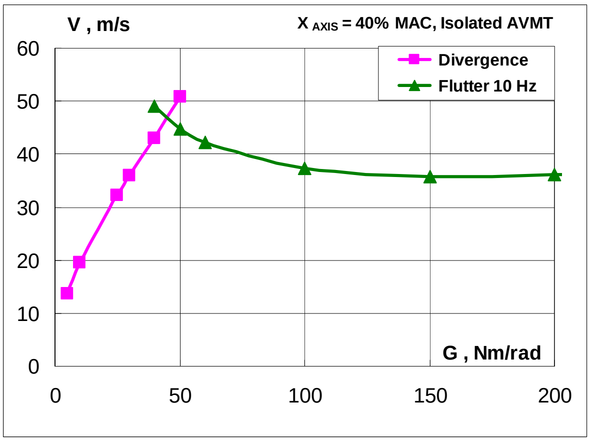


Fig. 14

The Fig.15 also illustrates the required flow speed versus rotational stiffness for which side stability and controllability is increased by 1.5 times (under this condition the AMVT reduced by 1.5 times in sizes is supposed to use). It can be seen that the flutter margin is not sufficient for stiffness range 20-30 Nm/rad. An augmentation of flutter margin can be reached by using of active damping in AMVT actuator.

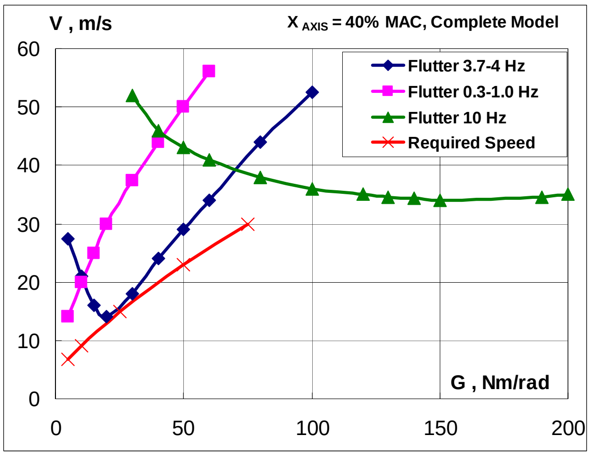


Fig. 15

Dynamic effectiveness of control surfaces

One of the aspects of "active aeroelasticity" concept is an active control system application. Frequency response functions (FRF) for load factors at various structural sections and for wing root loads are computed to evaluate the possibilities of using of AWTC for active control system. Results of this analysis are in satisfactory agreement with the experimental data. For example, a comparison of FRF for load factor at the wing tip (N_w) and wing root bending moment (M_b) due to symmetrical harmonic deflection of regular ailerons is shown in the Figs. 16 and 17 for airflow speed V=22m/s. The figures show that analysis characteristics follow well to experimental data both on amplitude and phase. Some disagreement in amplitude characteristics can be explained by well known defect of linear panel aerodynamics – it amplifies somewhat lifting properties of surfaces. Besides, some difference in structural damping would be available.

It is interesting to compare dynamic effectiveness of different wing control surfaces: regular (basic) aileron, tip aileron (TA), and aileron on the pylon under wing (UWA). Their effectiveness for gust load alleviation system was studied in the paper [9]. Here we consider a comparison of the aeroelastic wing tip controls (AWTC) effectiveness on wing root bending moment in frequency domain for different airflow speed (Figs. 18, 19). Dynamic effectiveness of the basic aileron remains still greater at airspeed V=22m/s, but at V=30m/s the AWTC have considerably higher effectiveness in the frequency range of the first elastic modes. Basic aileron has larger effectiveness in the frequency range of higher elastic modes.

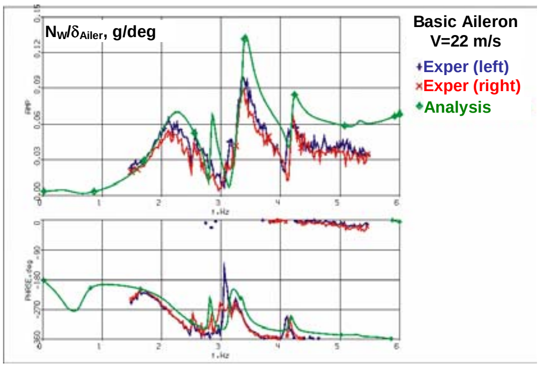


Fig. 16

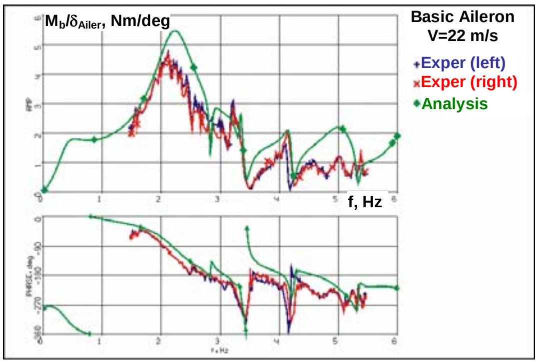


Fig. 17

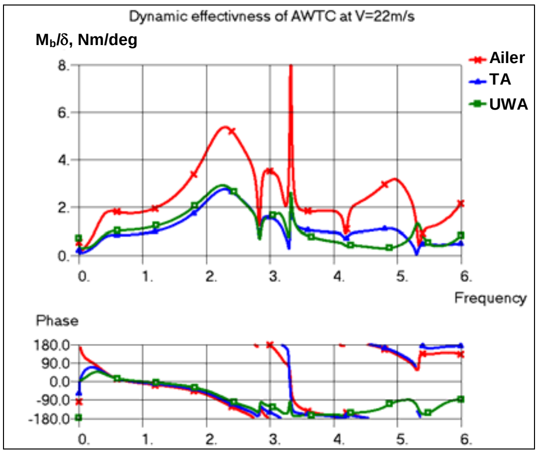


Fig. 18

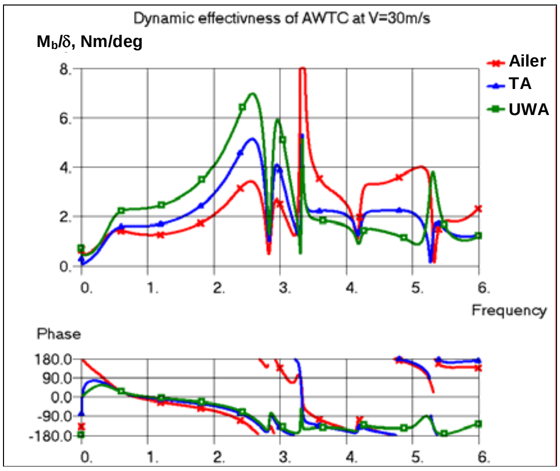


Fig. 19

EuRAM Full-Scale Airplane

As mentioned above, one special feature of studies in our project is that full scale computational model of the airplane was developed on the basis of DSM. This causes the problem of choice of extreme load cases for strength analysis because the DSM does not corresponded to any actual airplane.

The load cases for EuRAM full scale airplane were chosen according to prototype data and the results of parametric load and stress analysis on the ARGON computational first and second level models. Mainly the primary structure of the wing is considered for flight load cases to study of AWTC characteristics. The following design speeds, Mach numbers and altitudes were chosen (see table 1).

Table 1

V, km/h EAS	Mach number	Dynamic pressure, kPa	Altitude, m
V_D=690	M_D=0.90	q_D=22.5	7400
V_C=600	M_C=0.84	q_C=17.0	8400
V_A=450	M_A=0.37	q_A=9.57	0

Design weight for load analysis was chosen to be equal 215 tons. It includes 80% mass of the fuel. As a result of parametric flight load analyses by using ARGON first-level model four extreme load cases (LC) were found:

1) Maximum lift coefficient and maximum load factor at M_A, q_A near ground;
2) Maximum load factor at M_C, q_C;
3) Maximum load factor at M_D, q_D;
4) Half of maximum load factor at M_C, q_C and deflection of the wing control surfaces to provide roll rate of 10 degrees per second.

Fixed and free parameters of trim analysis are shown in the table 2.

Table 2

LC No	Fixed trim parameters	Free trim parameters
1	n_z=2.5 ω_y=0. $\dot{\omega}_y$=0.	α $\delta_{ELEVATOR}$
2	n_z=2.5 $\omega_y \neq 0$. $\dot{\omega}_y$=0.	α $\delta_{ELEVATOR}$
3	n_z=2.5 $\omega_y \neq 0$. $\dot{\omega}_y$=0.	α $\delta_{ELEVATOR}$
4	n_z=1.25 ω_x=10 deg/s ω_y=0. $\dot{\omega}_y$=0.	α $\delta_{ELEVATOR}$ $\delta_{AILERON}$

Note that in the cases 2 and 3 the pitch rate is given as $\omega_y = 9.81(n_z - 1)/V_T$, where V_T is true airspeed. The cases 1-3 are the same for all configurations. The LC #4 is modified for TA and UWA configurations: parameters δ_{TA} and δ_{UWA} are used instead of $\delta_{AILERON}$.

Strength ensuring under quasi-steady loads for considered cases leads to the material distribution which is close to results of recalculations of DSM stiffness according to similarity scale coefficients. For example, the displacements and stresses under loads of LC #4 for basic configuration are shown in the Fig.20.

An application of these load cases for the wing structural optimization under strength and aeroelasticity constraints for different AWTC configurations is considered in the paper [10] using ARGON second level (FE) model.

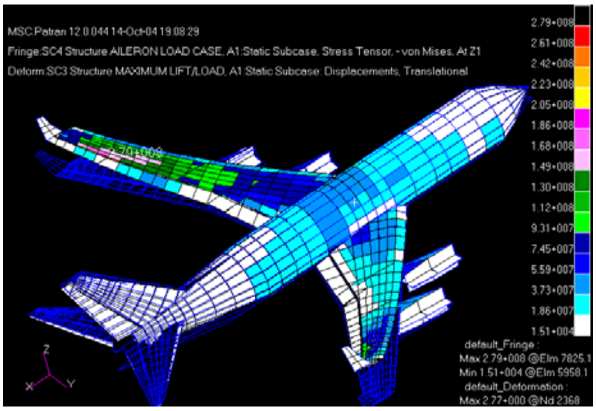


Fig. 20

Generated mathematical model of the full-scale airplane has quite reasonable lift-to-drag ratio at cruise flight regime. Supercritical airfoils with thickness-to-chord ratio 14.4% at the wing root and 9% at the wing tip are used. Jig twist angles are 3° at the wing root and -1° at the wing tip. A comparison of lift-to-drag ratios for different configurations is shown in Fig.21. The configuration with tip aileron has slightly greater value of lift-to-drag ratio mainly due to its larger effective aspect ratio.

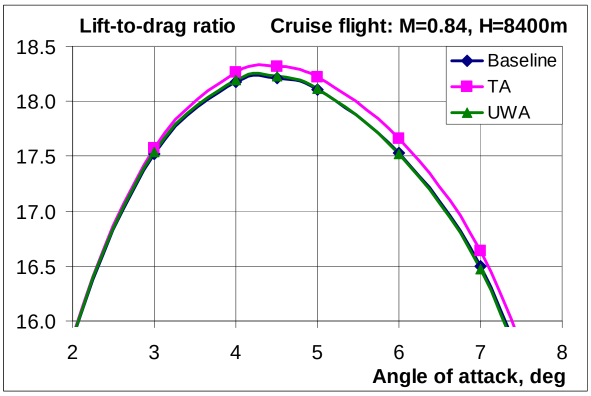


Fig. 21

In further studies it would be interesting to optimize jig shape of lifting surfaces and use adaptive deflection of AWTC for decrease induced drag and increase lift-to-drag ratio.

Conclusion

A lot of interesting numerical results in the framework of the project were obtained in TsAGI. Only part of them is presented here due to limited size of the paper. Versatile investigations of aeroelastic characteristics, strength and questions on actualization of the research concepts for full scale airplane will be carried out in future.

Acknowledgements

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