ACTIVE AEROELASTICITY CONCEPT: NOVEL VIEW, METHODOLOGY AND RESULTS

Gennady Amiryants
Central Aerohydrodynamic Institute (TsAGI)
Prof., Chief Scientist

Keywords: *Use of Elasticity, Innovative Control*

Abstract

Innovative control devices based on Use of Aeroelasticity Concept are presented. Short historical review on employing Use of Aeroelasticity Concept in Central Aerohydrodynamic Institute (TsAGI), from the beginning of 1960-s to our days is presented. The main attention is dedicated to the analysis of differential leading edge control of the wing or tail (forward aileron - foraileron, forward rudder - forrudder), remote aileron, special combination of outer spoiler and aileron - spoileron. Comparison of control effectiveness of innovative and traditional control devices is shown. Results of theoretical investigations and results of subsonic and transonic wind tunnel tests of elastically scaled model are observed. The main advantage of suggested and investigated innovative controls is high effevtiveness in wide range of Mach number and dynamic pressure.

Slotless connection of aileron using "smart" element of Selective Deformable Structures (SDS) was investigated; results of wind tunnel tests of such kind adaptive control are presented.

The research results related to the use of divergent properties of the empennage on the base of rational selection of plan-form is demonstrated in solving the problem of following an assigned law of angular velocity variation in time to stabilize a missile motion along its trajectory.

1. Innovative controls

1.1. Remote aileron

The remote aileron was developed (and tested in TsAGI T-109 supersonic wind tunnel on elastically scaled model – ESM) at the beginning of 1960's. Ordinary aileron reversal problem was very dangerous at this time first of all for M-50 supersonic heavy bomber with triangular wing. High effectiveness of remote ailerons was shown both in transonic wind tunnel tests of ESM and in calculations. Use of elasticity of fighter Yak-28 wing structure with the aid of remote ailerons, as flight tests showed, solved the difficult problem of roll control reversal of the airplane when the need for sufficient increase of maximum flight speed for one of the airplane version arouse. Traditional approach required unacceptable (by several times) increasing of skin thickness in the area of wing root, while remote ailerons allowed it to be made even thinner [1].

Reversal problem essentially significant for high aspect ratio swept wings. Remote aileron can be helpful in this case also. Effectiveness of control greatly depends from position of remote aileron relatively to wing's elastic axis and in contrast with ordinary aileron can increased at high dynamic pressures (fig. 1).

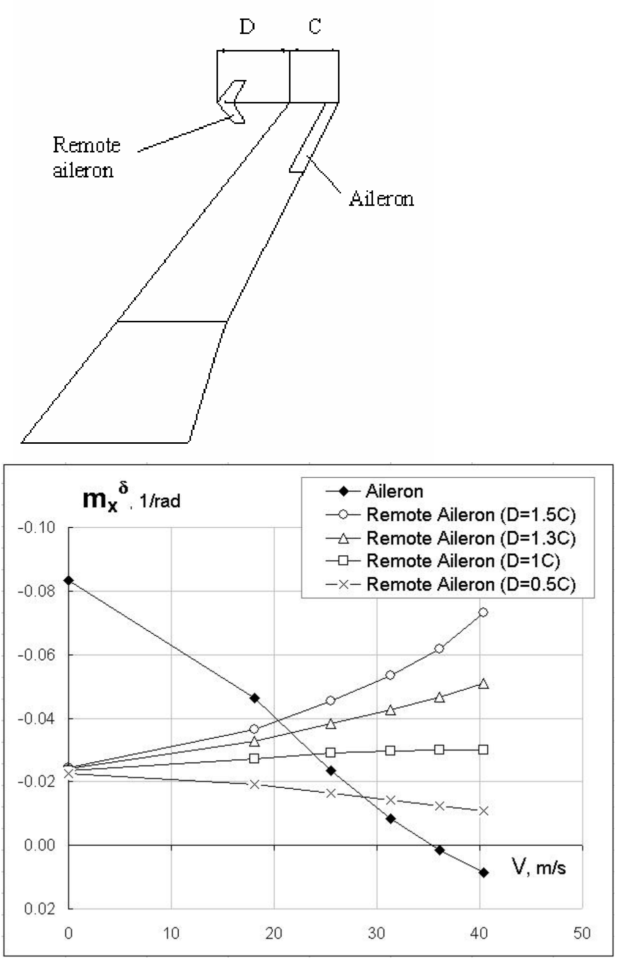

Fig. 1. Dependence of derivative of rolling moment due to angle of deflection of aileron and remote aileron versus flow speed. Calculation results (ARGON).

1.2. Differential leading edge - forward aileron (foraileron)

The suggestion to use differential deflection of leading edge (first of all deflection of leading edge up) was much more “aggressive” than remote aileron using [2, 3]. In contrast with remote aileron the foraileron did not need in additional elements on the wing tip. But it was necessary to do many transonic wind tunnel experiments on ESM (of MiG-29, Tu-22, Su-27, Tu-154, Tu-144, An-124 airplanes) to show that deflection of leading edge not only down, but also up may be very helpful for control – essentially at transonic and supersonic Mach number and high dynamic pressure values.

A new version of American F/A-18 fighter was another example, for which the prospects of firstly proposed in TsAGI controls and use of elasticity were confirmed in late 1990-th [4]. The vital problem of higher efficiency of lateral control was solved just in the same manner as it had been suggested by TsAGI in the mid of 1960-s for high speed manoeuvrable and other aircraft types. The major new elements of the F/A-18 new wing, “the real breakthrough in control system development”, as the program was called, are differentially deflected outboard sections of leading edge, located in front of the ailerons – these are just the same forward ailerons. Inboard leading edge sections, flaperons, and stabilizers are not used for lateral control. Thus, the system has been realized (“outboard forward and conventional ailerons”) that had been persistently recommended for several years to Mikoyan and Sukhoi Design Bureaus by Aeroelasticity Department of TsAGI at the early stages of MiG-29 and Su-27 development.

Wind tunnel tests of the high aspect ratio wing’s ESM show that dependencies of roll moment, lifting force, pitch moment m_x, c_L, $m_y = f(\delta_{forailer})$ both for deflection of foraileron up (in diapason $\delta_{forailer} = 0 \div 30^o$) and down ($\delta_{forailer} = 0 \div -30^o$) at the angle of attack near to zero are practically linear, despite to the nonlinearity in dependence of pressure distribution in some points of the wing cross-section near to foraileron due to its deflection.

Practically effectiveness of foraileron (in contrast to effectiveness of aileron) doesn't decrease with growth of dynamic pressure and Mach number. Wind tunnel test of another high aspect ratio ESM showed significant and favorable interference between aileron and foraileron.

Significant results were received in wind tunnel tests of medium aspect ratio wing's ESM with different sections of foraileron. Outer section of foraileron (at the tip of the wing) has most preferable characteristics (as roll, pitch, lifting force control).

Effectiveness of mutual working ailerons and forailerons (in contrast to effectiveness of aileron, which has practically zero effectiveness at $\bar{q} = q/q_D = 0.8$, M = 1.1) achieves sufficient level for all investigated values of dynamic pressure including q_D ($\bar{q} = 1$ and angles of attack $\alpha = 0; 3°; 6°; 9°$)

Effectiveness of foraileron greatly depends from angles of attack. From this point of view it seems to be quite attractive opportunity to use forward rudder - forrudder (fig. 2), because angles of yaw range as a rule smaller than angles of attack range.

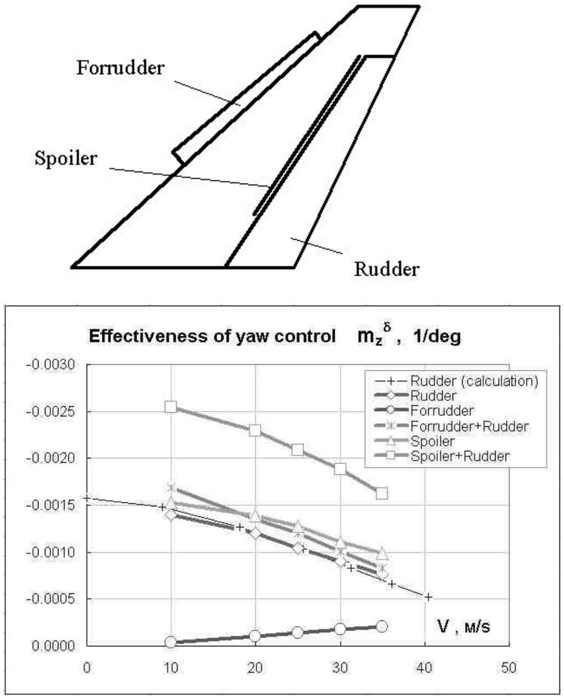

Fig. 2. Dynamically scaled model of the vertical tail of passenger aircraft. Rudder, forward rudder and spoiler-rudder combination yaw control effectiveness at different subsonic wind tunnel speed.

1.3. Combination of spoiler and aileron (spoileron)

Effectiveness of SST low aspect ratio wing elevons greatly decreased due to wing elastic deformations (and increasing of dynamic pressure). Supersonic wind tunnel tests of such wing's ESM showed that effectiveness of roll and pitch control can be improved using spoilers placed on upper and down surfaces in forward position near to elevon leading edge in addition to traditional elevons [6]. Spoiler of this combination (spoilevon) can be rotatable or extendable (in last case angle of spoiler deflection equal to 90°).

High effectiveness of spoilevon as roll and pitch control remains up to investigated angle of attack $\alpha = 8°$. As for forelevon, most suitable range of dynamic pressure and Mach number range for spoilevon are near to critical reversal values M_{crit} and q_{crit} for ordinary elevon. Angles of attack (or angles of yaw) are limited in this case and it is possible to "use" torsional elastic deformations most effectively.

Combination of spoiler and elevon (aileron or rudder) is attractive not only for small aspect ratio wings, but also – for high or medium aspect ratio wings or tails. Such combination has good prospects not only as roll (fig. 3, 4) and pitch, but also (essentially) as yaw control (fig. 2, 5).

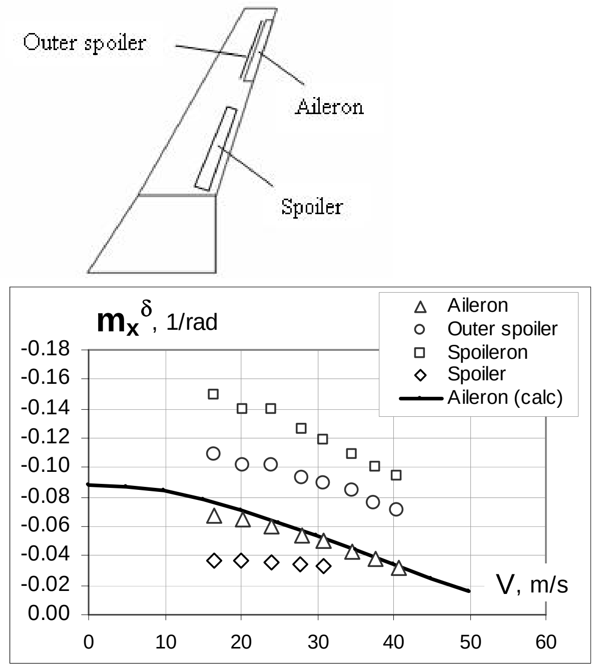

Fig. 3. Derivatives of rolling moment due to angle of control deflection vs wind tunnel speed. Calculation results for aileron (ARGON).

Influence of wind tunnel flow speed on the derivatives of rolling moment due to angle of deflection of different roll controls is presented in the fig. 4 for ESM of the medium range passenger airplane wing with forward swept wing tip aileron (FSWT). According experimental and calculation results much more preferable is combination of FSWT-aileron and outer spoiler.

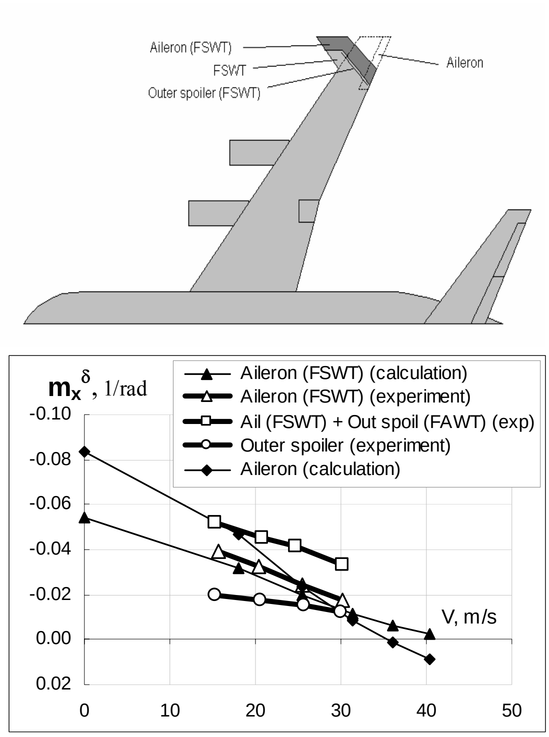

Fig. 4. Influence of flow speed on derivatives of the rolling moment due to angle of deflection of roll controls. TsAGI wind tunnel T-103 ESM of the medium range passenger airplane wing test results. Comparison of experimental and ARGON calculation results.

Yaw control effectiveness of rudder and spoiler-rudder combination (spoilrudder) was investigated in TsAGI subsonic T-103 and T-104 wind tunnels. Dynamically-scaled models (DSM) of the medium range passenger airplane fin (fig. 2, 5) were equipped with extendable spoiler (in all cases angle of spoiler deflection was equal to 90° and height of spoiler equal to thickness of the gap between wing (or fin) box and leading edge of the aileron (or rudder). It is evident attractiveness of spoileron, spoilrudder using at high dynamic pressure in comparison with ordinary aileron, rudder or ordinary spoiler

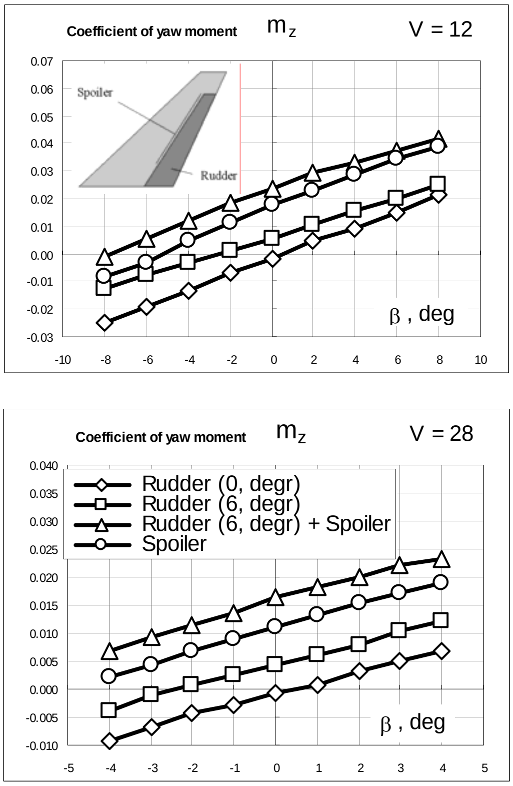

Fig. 5. Influence of yaw angle and flow speed on the yaw control effectiveness of rudder, spoiler and combination of spoiler and rudder (spoilrudder). TsAGI wind tunnel T-104 ESM of the medium range passenger airplane fin test results.

1.4. About dynamic effectiveness of innovative controls

The alleviation of dynamic loads due to wind gust is one of the topical tasks for large transport airplanes. Aileron and spoilers deflections are usually considered in gust load alleviation systems. The using of spoilers is often difficult because of the complex aerodynamics; besides they are deflected only in one direction. The using of the symmetrically deflecting outer sections of ailerons is more attractive. But the effectiveness of ailerons considerably degrades due to structural elasticity at large airspeed when the load alleviation is needed. The use of new control surfaces, which save high effectiveness at large airspeed, could remove this disadvantage.

Analytical-experimental study of static aeroelastic characteristics and essentialities of using different control surfaces to alleviate dynamic loads was significant part of 3AS project (the 5th FP EC Project “Active Aeroelastic Aircraft Structures“) [7-11].

Dynamic effectiveness of wing tip controls, i.e. their possibility to affect accelerations and loads in the region of low frequency elastic oscillations, was studied in the papers [10, 11]. The results show that a behavior of the dynamic effectiveness of the controls is similar to static effectiveness. Dynamic effectiveness also demonstrates advantageous effects of "use of elasticity" concept. Computational and experimental results for different models were in quite good agreement.

Wind gust loads alleviation was demonstrated in frequency and time domain using a simple control system on the basis of wing tip accelerometer and investigated wing tip control surfaces.

The main criterion, which was used for development and study of nontraditional remote aeroelastic wing tip controls (AWTC), was the augmentation of roll controllability under weight and aerodynamic constraints. Such remote controls (fig. 6, 7) were designed and investigated, their parameters were determined. It was established that roll effectiveness of tip aileron (TA) and under-wing aileron (UWA) is considerable higher than the effectiveness of regular aileron at high speed regimes.

The dynamic effectiveness of AWTC as the capability to influence on load factors and loads for the specified sections of the structure was studied in [11]. The determination of possibilities to apply AWTC for active load control (load alleviation in specified wing sections and comfort enhancement for airplane crew and passengers) was the purpose of this research. The performed studies contain analyses of dynamically-scaled model (DSM), results of tests in wind tunnel and analyses of full-scale airplane.

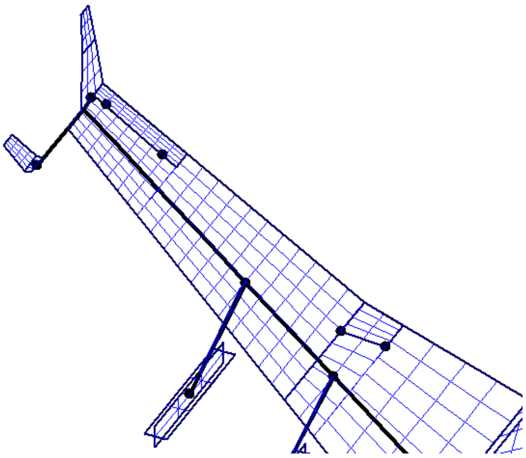

Fig 6. Analytical model of the wing with remote tip aileron.

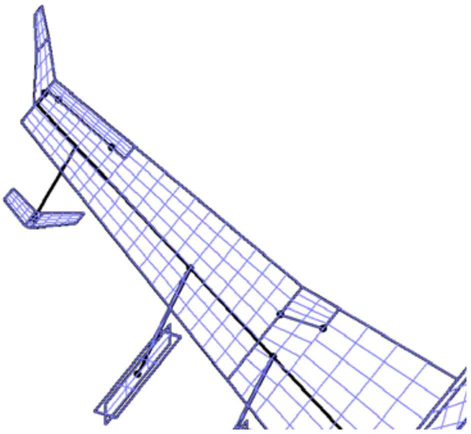

Fig 7. Analytical model of the wing with remote underwing aileron.

It is interesting to compare dynamic effectiveness of different wing controls: usual aileron, remote tip aileron located in forward direction and remote aileron on pylon under wing. We consider the comparison of their effectiveness on bending moment in root wing section in frequency domain at different flow speeds (fig. 8). Dynamic effectiveness of usual aileron at flow speed V=22 m/s remains higher than for other types of ailerons. But at flow speed V=30 m/s TA and UWA have sufficiently larger effectiveness in the range of first modes of elastic vibrations. The effectiveness of usual aileron remains larger in the range of higher frequencies.

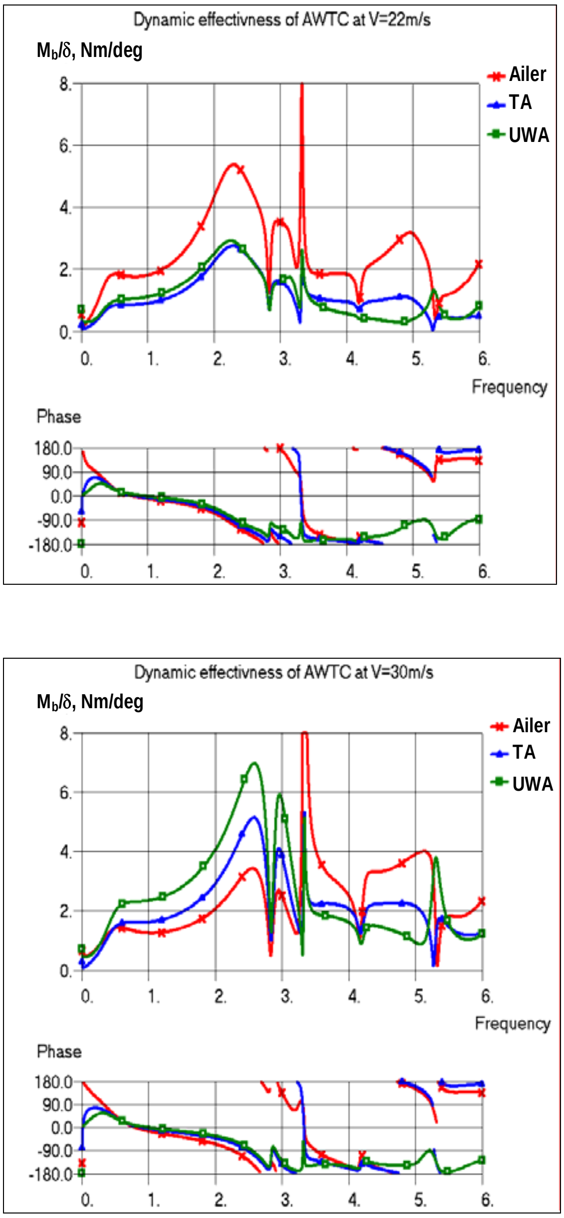

Fig. 8. Comparison of computational frequency response function (FRF) on bending moment due to different controls excitation (free complete DSM).

Frequency response functions (FRF) on bending moment in the wing root due to harmonic gust (in the case of opened and closed systems using remote wing tip aileron are shown in fig. 9. The alleviation of bending moment is 8% at V=22 m/s and 14% at V=30 m/s. These values for the remote under wing aileron are 10% and 22%, correspondingly.

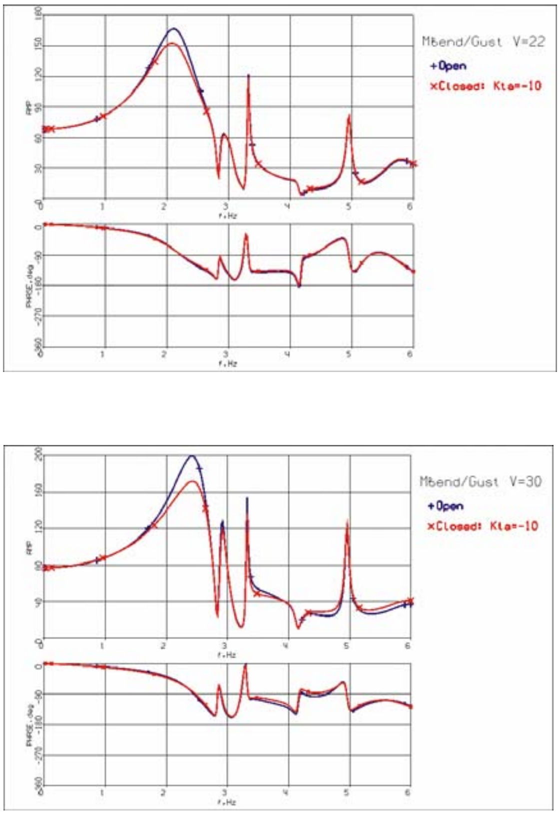

Fig. 9. Computational FRF on bending moment due to harmonic gust for opened and closed systems using remote TA.

Dynamic effectiveness of the controls in the time domain also was investigated [10, 11]. Time domain processes are considered to study the possibilities of discrete gust load alleviation. Gust shape is specified as "1-cos". Fig. 10 shows the model response due to discrete gust for open and closed systems using remote UWA at flow speed V=22m/s for clamped wing. In this case the alleviations of first maximum of bending moment increment are 9% and 19%, correspondingly.

The close results were obtained in experimental study. Approximately 10% decrease of first maximum of wing bending moment and damping of the next oscillations are provided by active control system.

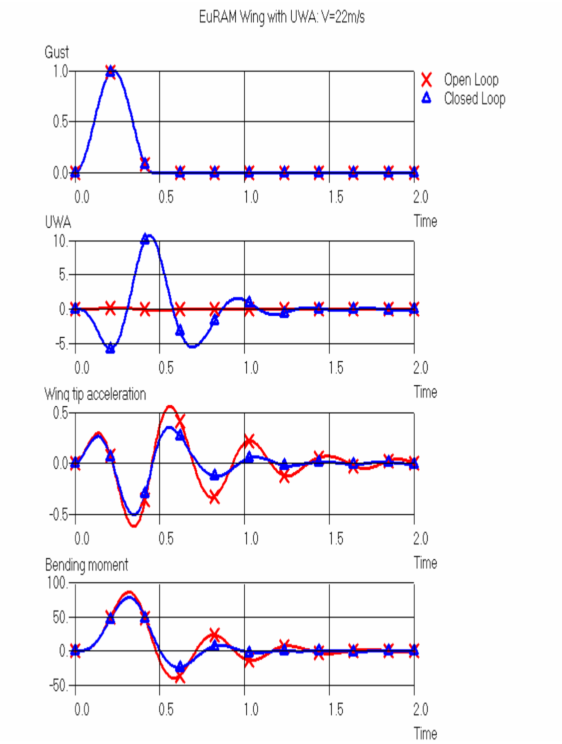

Fig. 10. Model response due to discrete gust for open and closed systems using remote UWA at flow speed V=22m/s (clamped wing, analysis).

1.5. SDS –adaptive controls

Wind tunnel test of the dynamically scaled model of high aspect ratio wing equipped with adaptive and ordinary inner aileron was done in TsAGI subsonic T-103 wind tunnel. Plan view of the wing model with inner (and outer) aileron is shown in fig. 11. Photo picture of tested dynamically scaled model with WT equipment (external strain gage balance) and internal strain gage balance of models compartment with inner aileron is presented in fig. 12. Main aim of wind tunnel tests was comparison of aerodynamic characteristics of adaptive and ordinary inner ailerons.

For presented dynamically scaled model flexible connection of aileron leading edge with wing box was designed. Slotless connection using "smart" element of Selectively Deformable Structures (SDS) was investigated [12]. The primary cell (with box-like structure) is used as such element. Such elementary cell has a relative little stiffness on one degree of freedom and large stiffness on the rest degrees of freedom. Specific mutual position of elementary cells along aileron's span and in chord direction was used (fig. 12).

As structural material - fiberglass, as main technological process – bonding and as elastomeric filler foamed rubber was used. For real airplane it's possible to use another materials and technologies. Two variants of "adaptive" aileron were designed. The difference between these design variants consists in number and position of primary cells, in shape of the cells. It's supposed, that the stiffness of foamed rubber insight and between the cells is enough to translate the aerodynamic loads keeping acceptable external surface quality.

The variant, more preferable from some point of view, was fabricated and attached to the wing box. For chosen variant due to smoothing properties of filling rubber the external surface has relatively small values of roughness, the heights of these were about 0.9 % of reference height of aileron cross section. Fixation of aileron on different angles of deflection about hinge axis for wind tunnel tests was provided. After choosing the structure design the more detailed FE-model was developed.

The given results show, that the filling with foamed rubber leads to increment the stiffness of the structure on the value about 19%. The contribution of aerodynamic load to the total sum of hinge moments is about 7%. A main part of aerodynamic load in the structure is translated to the wing structure via flexible leading part of aileron, not with hinges and the actuator.

The preliminary analysis of strength and dynamic properties of a designed adaptive controllable structure shows that this structure has ability to bear the working loads of the part of airplane structure - typical aerodynamic loads and load from actuator during deflection.

Fig. 11. Compartment-beam aeroelastic wing model with inner, outer and remote ailerons.

Fig. 12. Adaptive inner aileron; compartment 3-component strain gage balance; SDS prime structure (without elastomeric filler)

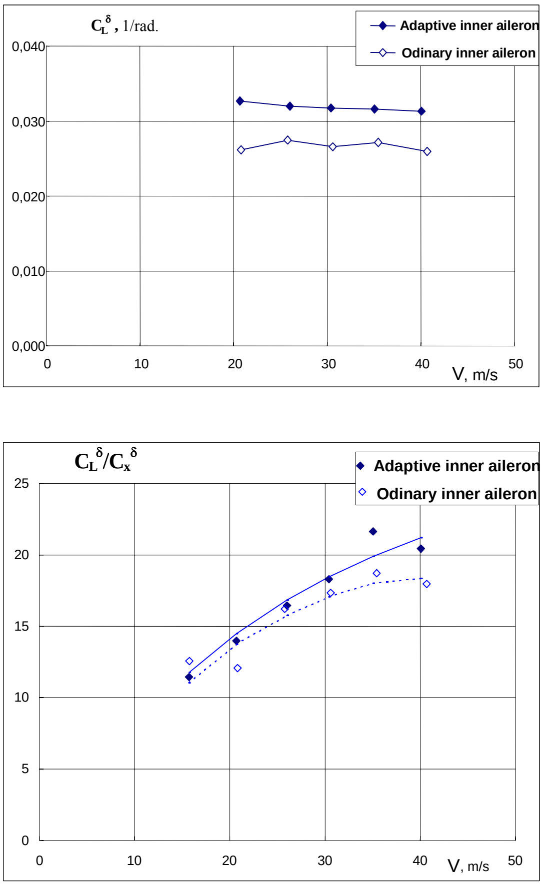

Fig. 13. Lift to drag ratio for ordinary and adaptive inner aileron versus wind tunnel flow speed.

Comparison of measured characteristics of ordinary and adaptive inner aileron was done in the fig. 13. Lifting force derivatives of adaptive aileron primarily 1.2 times greater than lifting force derivatives of ordinary aileron. Pitch moment derivatives of adaptive aileron primarily 1.1 times greater than pitch moment derivatives of ordinary aileron. Drag force derivatives differs slightly. As a result, ratio of lifting force derivatives to drag force derivatives of adaptive aileron (fig. 13) primarily 1.15 times greater than lifting force derivatives to drag force derivatives of ordinary aileron.

2. About use of divergent properties of empennage

In the mid of 1990-s it was suggested in TsAGI to use divergent properties of missile empennage [13]. It was necessary to stabilize angular rotation speed of missile along trajectory without using active system. Necessary missile characteristics were achieved due to change of only one parameter of empennage plan form: sign of sweep angle of leading edge was changed from positive to negative. Such away it was possible to achieve necessary damping characteristics (derivative of rolling moment due to angular rotation speed) and wishful time dependence of angular rotation speed of missile along trajectory. It was possible also to save all other characteristics (longitudinal and lateral stability, flutter characteristics) in wishful order.

As was mentioned, 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 [9-11]. The concept “use of elasticity” or “active aeroelasticity” is considered here with reference to wide-body passenger airplane having high-aspect-ratio wing. Among others one additional aspect of the concept (connected with "use of divergence") was studied: 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 investigated aspects of concept.

3. About methods of multidisciplinary theoretical and experimental investigations

3.1. Theoretical methods

Effective theoretical methods of flutter and static aeroelasticity problem investigations based on polynomial Ritz method and influence coefficient method were suggested in [14, 15].

The ARGON software package [15] is designed to analyze and predict stress, levels, stiffness-mass distributions, aerodynamic characteristics, loads and aeroelastic characteristics of the airplane at the conceptual and preliminary design stages and in the course of the parametric studies associated with any modification of existing airplanes.

The ARGON program complex makes it possible to solve static and dynamic aircraft aeroelasticity problems. The solutions of these problems are based on the use of a common aerodynamic and dynamic structural models, but they are performed by different interrelated methods:

static aeroelasticity problems are solved by using the influence coefficients method;

dynamic aeroelasticity problems are solved by using the assumed displacement (or Rayleigh-Ritz) method.

The use of different methods is associated with a number of features in obtaining, presenting and using the results of the solution of static and dynamic problems. Both methods have merits and shortcomings, and their combined application improves efficiency of the ARGON program complex.

The aerodynamic calculations are based on the linear theory. However, the functions obtained can be nonlinear with respect to angles of attack and high-lift device deflections. These nonlinearities are artificial, they are introduced correct the known defect of the linear theory that gives too high, physically unrealistic pressure gradients over the leading edge. Therefore, the pressure differential coefficient can be computed.

3.2. Multi-purpose aeroelastic modular model

It's evidently that for active aeroelasticity concept investigation necessary to use multidisciplinary approach – and not only in theoretical but also in experimental areas.

Model with exchangeable elements (core and skin, fig. 14) is designed for multidisciplinary investigations in high-speed wind tunnels of total and distributed aerodynamic characteristics of elastic aircraft, flutter, divergence, reversal of control, buffeting, gust response, dynamic interaction with automatic control system (aeroservoelasticity) [16].

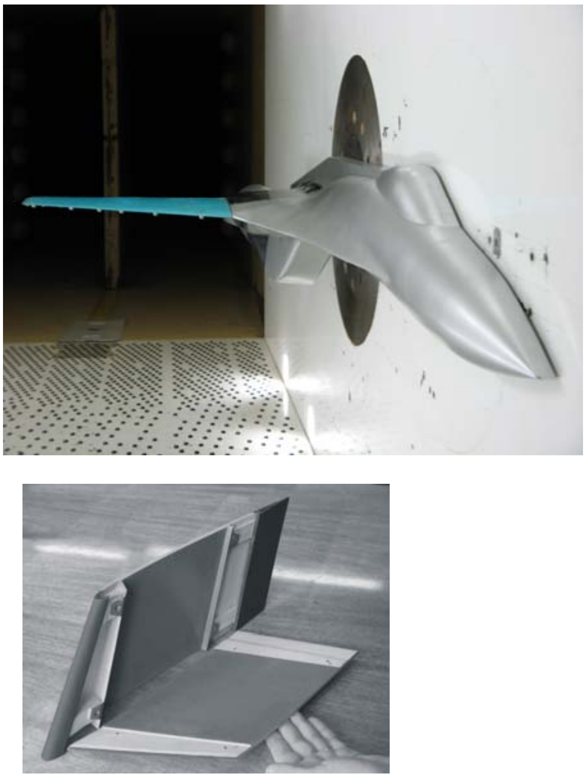

Fig. 14. Multi-purpose aeroelastic modular halfmodel; maquette of separable wing box skin.

High accuracy of stiffness, geometry and mass-inertia characteristics modeling has been achieved by using of composite materials and technologies, using modern sole, common mould design/fabrication methods (including

CAD/CAM systems and laser stereolitogfaphy, SLA-technology), using nonlinear programming for optimization of model stiffness parameters.

Low cost and wide range area of model parameters variation, short duration of design/fabrication and certification processes gives opportunity to achieve a quality of multidisciplinary investigations in wind tunnels, which necessary for fast receiving of sufficiently accurate and complete information about aerodynamic/aeroelastic characteristics for developing of safe and competitive aircraft.

The aircraft model (or its units - a wing, a fuselage, vertical & horizontal tails) represents the separable construction made with use of composite materials. Such essentiality (separability) of the model allows to use replaceable elements. High accuracy of modeling of stiffness characteristics is provided due to use of developed in TsAGI theoretical-experimental optimization procedures. High quality of aerodynamic contours is provided due to application of high-quality press-moulds and technologies of composite materials. The compression mould made once can be used many times – for different type models, that gives opportunity to reduce the price of process of aircraft investigation in WT. The model has good opportunities for adjustment with various inside-model devices (for measurement of pressure distribution, measurement of vibrations, deformations, stresses, the hinge moments of controls, for equipment of models by controls drives, etc.).

Similar approach (elastically-dynamically scaled separable model with exchangeable elements - core and skin) quite attractive also for manufacturing of such kind metallic models using computer controlled milling machine and iterative procedure for achieving of high accuracy in stiffness modeling [16].

3.3. Robotic system of models stiffness characteristics measurements

One of the key parameters, influencing quality of WT investigations with elastically,-dynamically-scaled and so called “rigid” aerodynamic models, is quality of their stiffness characteristics modeling. Stiffness parameters of models (stiffness or influence coefficients matrix) are obtained in the process of stiffness tests, which frequently are not exact enough and operative.

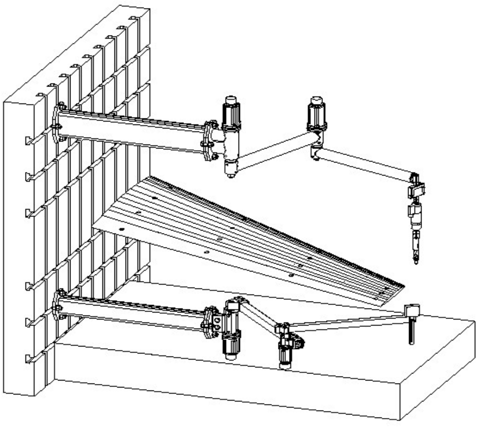

Fig. 15. Photo and scheme of robotic system for models stiffness characteristics measurements and calibration of strain gage system of models elastic deformations and aerodynamic loads measurements.

Invented in TsAGI the modern automated system of models stiffness characteristics measurements consists of two parts: loading system and system of displacement measurements (fig. 15). Due to automation of process of measurements, using contemporary data acquisition system and also due to using of precision gauges of linear and angular displacements (including laser gauges) it is possible to achieve significant decreasing of stiffness tests time and increasing of their accuracy. This system can be used also as calibration equipment for measurements of aerodynamic loadings and elastic deformations of aerodynamic models using their strain gage system.

References

[1] Amiryants G.A. The lateral control method of winged flying vehicles. *The author's rights witness (Certificate of invention)*, № 31962, 1964, (in Russian).

[2] Amiryants G.A. About one method of ailerons reversal critical dynamic pressure increasing. *Technika vozdushnogo flota journal, TVF* № 4, 1967 (in Russian).

[3] Amiryants G.A.. About effectiveness of differential leading edge (Forward aileron) on elastic wing. *TVF* № 7, 1970 (in Russian).

[4] Rick Lind - An H∞ approach to control synthesis with load minimization for F/A 18 active aeroelastic wing. *CEAS/ AIAA/ ICASE/ NASA Langley international forum on aeroelasticity and structural dynamics*, 1999.

[5] Amiryants G.A., Barynov N.F., Vasilyev G.A. Spoiler-elevon as lateral and longitudinal control of airplane with small aspect ratio wing. *Trudy TsAGI*, 1976 (in Russian).

[6] Amiryants G.A. The flying vehicle's method of control (variants) and device for its realization. *Russian patent* № 2299834, 2005.

[7] Kuzmina S.I., Amiryants G.A., Ishmuratov F.Z., Mosunov V.A., Chedrik V.V. Some applications of active aeroelasticity concepts to aircraft design. *International forum on aeroelasticity and structural dynamics*, Madrid, 2001.

[8] Kuzmina S., Amiryants G., Schweiger J., Cooper J., Amprikidis M., Sensburg O. Review and outlook on active and passive aeroelastic design concept for future aircraft. *Proceedings of 23-rd ICAS Congress*, Toronto, 2002.

[9] Simpson J., Anguita-Delgado L., Kawieski G., Nilsson B., Vaccaro V. Review of european research project "Active Aeroelastic Aircraft Structures" (3AS). *European conference for aerospace sciences (EUCASS)*, Moscow, Russia, July 2005.

[10] Kuzmina S., Ishmuratov F., Zichenkov M., and Chedrik V. Analytical-experimental study on using different control surfaces to alleviate dynamic loads. *47-th AIAA/ASME/ASCE/AHS/ASC structures, structural dynamics, and materials conference*, Newport, Rhode Island, USA, May 2006. *AIAA Paper* 2006-2164, 13p.

[11] Kuzmina S., Ishmuratov F., Chedrik V., Kudryashov A., Mosunov V., Naiko Yu.. Numerical studies of aeroelasticity/strength/aerodynamics on the European Research Aeroelastic Model (EuRAM). *European conference for aerospace sciences (EUCASS)*, Moscow, Russia, July 2005.

[12] 12Amiryants G.A. Adaptive selectively deformable structures. *Proceedings of congress ICAS*, Melbourne, 1998.

[13] Amiryants G.A., Krapivko A.V., Mamedov O.S. , Redko A.A. About using of tail divergence. *TVF*, v. LXXVII, №5-6, (664-665), 2003. (in Russian).

[14] Amiryants G.A. Theoretical estimation of influence of structural elasticity and mass distribution on aircraft aerodynamic characteristics. *Uchenye Zapisky TsAGI*, vol. X, № 1, 1979 (in Russian).

[15] Evseev D.D., Ishmuratov F.Z., Chedrik V.V. and other. Multidisciplinary software package "ARGON". *Uchenye Zapisky TsAGI*, vol. XXII, № 5, 1991 (in Russian).

[16] Amiryants G.A., Ishmuratov F.Z. Multi-purpose modular aerodynamic/Aeroelastic Model. *International Forum on Aeroelasticity and Structural Dynamics*, Madrid, 2001.

Copyright Statement