THE «ACTIVE AEROELASTICITY» CONCEPT – THE MAIN STAGES AND PROSPECTS OF DEVELOPMENT

1 G.A. Amiryants, 2 A.V. Grigorev, 3 Y.A. Nayko, 4 S.E. Paryshev,
1 Main scientific researcher, 2 Junior Scientific researcher, 3 Scientific researcher, 4 Head of department
Central Aero-hydrodynamic Institute – TsAGI, Russia
Keywords: *active aeroelasticity, multidisciplinary investigations, elastically scaled model*

From the very beginning of static aeroelasticity research it's important part was searching for rational ways of providing airplanes' safety from aileron reversal and divergence as well as providing weight efficiency and high aerodynamic performance of airplanes. The studies by Ja.M.. Parchomovsky, G.A. Amiryants, D.D. Evseev, S.Ja. Sirota, V.A. Tranovich, L.A. Tshai, Ju.F. Jaremchuk performed in 1950-1960 in TsAGI systematically demonstrated the possibilities to increase control surfaces effectiveness (and solving other static aeroelasticity problems) using "traditional" approaches: rational increase of wing stiffness (by changing wing skin thickness distribution, airfoil thickness, choosing the position of stiffness axis, wing spar stiffness), variation of position and shape of conventional ailerons and rudders, differential deflection of separate rudder sections, usage of spoilers. As it was shown these possibilities were often limited.

The analysis of the summary study [1] confirms that there is an ongoing search in US, especially since 1950, and especially since the introduction of swept wings and achieving transonic speeds, for new effective roll control surfaces. In particular there are studies that take into account structural elasticity of all-movable wing, various spoilers, jet control devices, differential stabilizer - those that are much more effective than conventional ailerons at high dynamic pressure [1, 2, 3].

Substantial results in the development of the new control surfaces were achieved in TsAGI in the same 1950-60s under the supervision by A.Z. Rekstin and V.G. Mikeladze. However, the common drawback of these control surfaces too was negative influence of structural elasticity on these surfaces' effectiveness.

One of the most promising directions of aircraft design worldwide today is related to the term of "exploitation of structural elasticity" or the "active aerolasticity" concept. The early 1960s faced the urgent need to increase stiffness of thin low-aspect-ratio wings of supersonic M-50 and R-020 airplanes to diminish negative influence of structural elastic deformations on roll control. As it turned out, even with the optimal increase of structural stiffness to solve severe aileron reversal problem the increase of the airframe weight was unacceptable. It was that time when a seemingly paradoxial solution was proposed: to stop struggle in vain against negative influence of structural elasticity, but to exploit it [4]. A new class of control surfaces positioned in front of the wing stiffness axis was proposed and launched into R&D in TsAGI at that time. Computational and experimental studies of control surfaces such as: pullout ailerons, external ailerons [5], forward ailerons (foreailerons) [6,7], as well as flap-ailerons [8], spoilers linked with deflecting wing leading edges proved that required decrease of negative influence of structural elasticity on control effectiveness could be achieved not only by fighting against elasticity but by putting it for a good use.

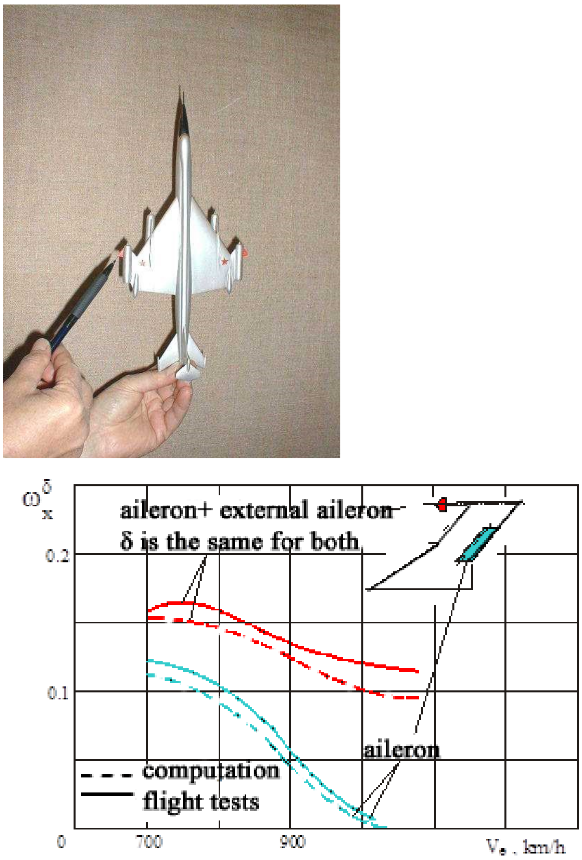

Fig. 1. External ailerons on wing tips of the M-50 airplane. The effectiveness of external (remote) ailerons on the wing tips of the Yak-28 aircraft: computation and flight tests results.

For the first time pullout and external ailerons were designed and tested in TsAGI T-109 wind tunnel on the elastically-scaled model of the M-50 airplane wing, and later on the models of R 020, MiG-25, Yak-28 [9]. The exploitation of structural elasticity of Yak-28 wing by using external ailerons, as flight tests showed, solved the difficult problem of roll control reversal of this aircraft arisen from the need to substantially increase maximum flight speed of one of the plane versions. Traditional approach required the unacceptable (several times the initial value) increase of skin thickness at the wing root area, while the use of external ailerons made it possible not only not to increase the thickness, but to reduce it.

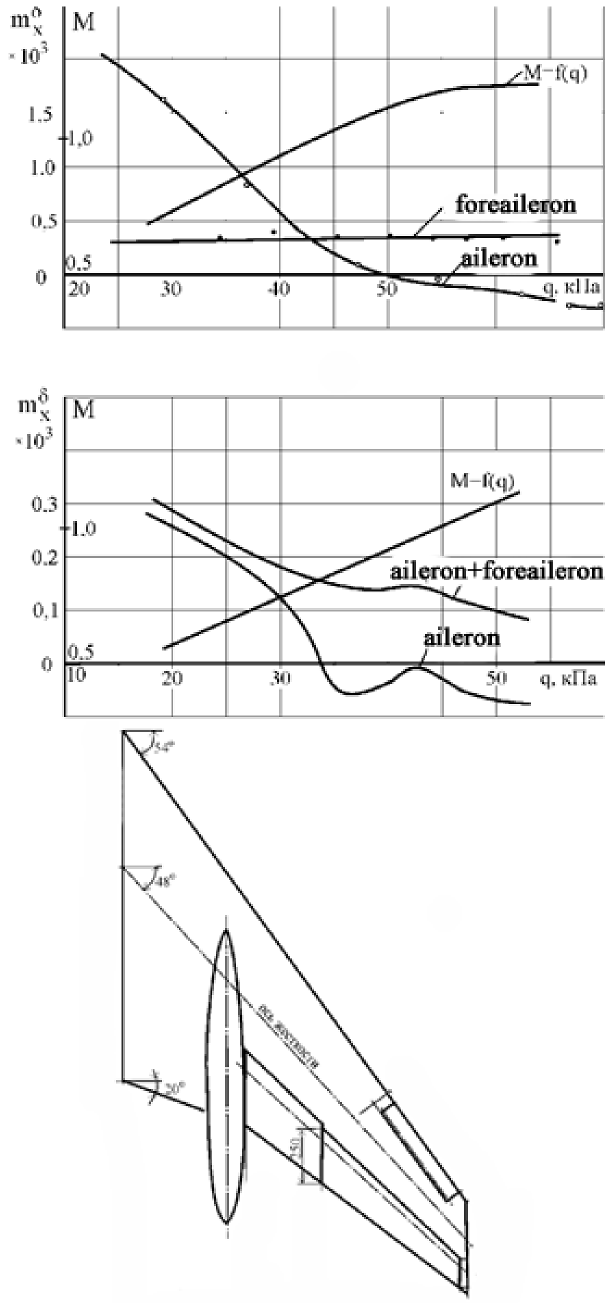

Fig. 2 . The wing with a foreaileron; the aileron and foreaileron effectiveness, T-109 wind tunnel tests.

Since 1963 the studies started on especially promising control surface that “uses structural elasticity”, i.e. differentially deflected leading edge segments (forward aileron or foreaileron) [7]. The wind tunnel tests of the elastically-scaled models of the Su-27, MiG-29, Tu-22 airplanes (Fig. 2) and respective analysis confirmed the effectiveness of use of differential leading edge segments as well as the prospects of the whole new concept. The first open information about TsAGI studies in the area of exploiting structural elasticity (particularly the results of foreaileron research) was published in 1980, at the Soviet-French Symposium in Paris [10] and even more thoroughly in 1991 during the working meeting of TsAGI and Boeing specialists in Seattle.

The actually flying aircraft that proved, during the flight tests (in USA) in late 90-s, the prospects of the new control surfaces and the concept of active usage of structural elasticity firstly proposed by TsAGI, was the modified F/A-18 [11]. The actual problem of increasing roll control effictiveness was solved for this aircraft using the same approach that was proposed in TsAGI in 1960s for fast maneuverable and other airplanes. The system implemented on the F/A-18 was the same system (outboard sections of foreaileron and aileron) that the Aeroelasticity department of TsAGI was recommending for Sukhoi and Mikoyan Design Bureaus for several years at the beginning of MiG-29 and Su-27 development. It was found then that to meet the requirements on lateral control effectiveness of Su-27 by using ailerons, the added weight of 30% of total detachable wing part weight (above that needed due to static strength conditions) is required. In the case of using traditional differential stabilizer, the added weight is approximately 35% due to the need to strengthen the rear fuselage part because of fatigue problems. The overall conclusion was as follows: the most perspective in terms of weight efficiency was implementation of foreaileron as the means for lateral control. The implementation of this control surface required no more than 10% of total added weight of the wing. By that time, in early 1970s it was already proven that the foreaileron effectiveness had a very complex dependence on Mach number, angle of attack and dynamic pressure. The usage of foreaileron caused the increase of control system complexity. That was the main obstacle preventing its implementation for Su-27 airplanes.

The concept of exploiting structural elasticity as well as appropriate multidisciplinary computational and experimental research techniques were worldwide recognized as innovatory ways of solving the problems of the development of advanced aircraft in the XXI century. Today this is the one of the most intensively developing fields in aeromechanics. This is confirmed by the approaches developed and by the very important results of computational-experimental multidisciplinary studies (flutter, loads, stresses) proving the good prospects of the concept to provide the safety with regard to aeroelasticity, high weight efficiency and competitiveness of advanced airplanes [5], [12], [13].

The possibility of using differentially deflecting leading edge segments to solve aeroelasticity problems got the name of "the active aeroelastic wing concept - AAW" [14]. In 1980s Rockwell further advanced the "active aeroelastic wing" concept as a continuation of previously proposed principles of "use of aeroelasticity" with the development of the fighter jet for the Advanced Tactical Fighter (ATF) program as well as with finding the solution for aileron reversal problem. Based on the successful wind tunnel tests performed by USAF, NASA and Rockwell, the modified F/A18 flight test program was initiated to demonstrate the efficiency of the AAW concept [15]. The usage of differentially deflecting leading edge segments (foreailerons) was the main part of this modification. Thus, it confirmed, in particular, the validity of TsAGI proposal to cancel the use of a tail with a differential capability for roll control. The use of a differential tail in the case of F/A-18 airplane also caused the strength issues, particularly the airplane tail area fatigue problems.

The AAW concept became the subject of intensive studies in various countries, like Russia, USA, as well as in European ones, as indicated by recent publications. The contribution of Russia in the developing of principally new aerodynamic control devices that "use" elastic deformations was reported at IFASD and ICAS International forums [12, 13].

In their work the US specialists Cesnik C. E. S. and Brown E. L. [16] mentioned that the concept of AAW had been proposed two decades earlier. The concept means that instead of fighting against structural elasticity while producing maneuverable aerodynamic loads by means of the traditional controls, specific control surfaces are used that allow the wing to be deformed in a proper way. As a result the decrease of structural weight is achieved. So a modified F/A-18 version was designed and created with a relatively flexible wing, and its flight tests started. This one and some other Western studies display the lack of the objective knowledge that the AAW concept development started much earlier in 1960s in USSR. The study [16] is valuable in other way. It evolves the concept in its own quite perspective direction. The study is devoted to the subject of controlling deformations of the airplane ("Sensorcraft") with "compound" wing. This works implies the use of the technology of anisotropic piezoelectric composite materials that serve as actuators integrated into wing structure.

The Active Aeroelastic Structures (3AS) became the first prominent European research project [12] that did had the goal to improve aircraft efficiency by use of elastic deformations for benefit in contrast with the traditional approach of increasing structural stiffness (and hence the weight). The project participants from 9 countries led by the main coordinator of the project J. Schweiger (EADS, Germany) noted the Russian priority in this area [12, 13] and invited TsAGI specialists with great experience in the AAW concept development. Aside from theoretical ones, the experimental studies were performed that confirmed fruitfulness of several directions of active aeroelastic structures development.

Fig. 3. Dynamically-scaled model (EURAM) with external (remote) aileron

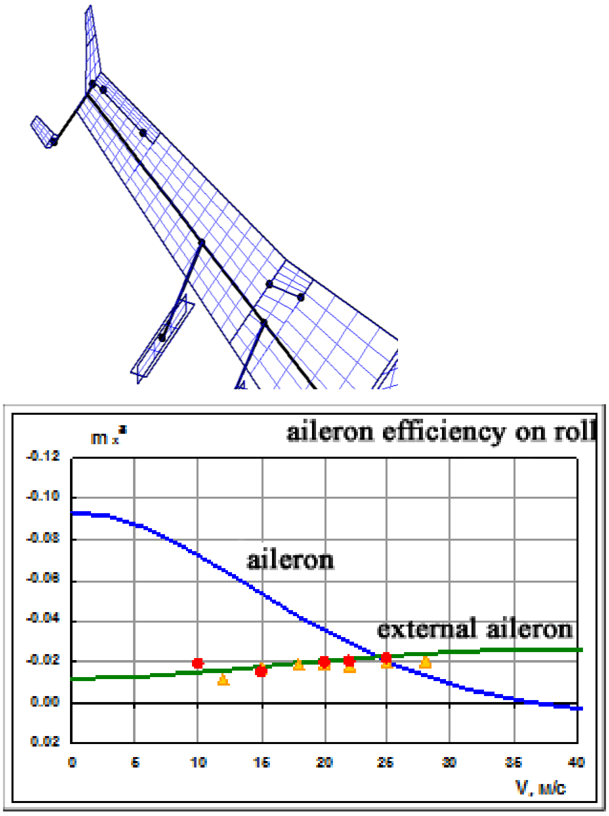

Fig.4. The model (EURAM) with pullout under-wing aileron, computational model of the wing with external aileron on a wing tip. The effectiveness comparison of conventional and external (remote) ailerons: calculation results (ARGON), T-104 wind tunnel test results.

Further evolution of "active aeroelasticity" concept is in the use of wing deformations produced by a system of actuators inside the wing [17]. The similar system based on the use of "smart structures" can be instrumental for the effective solution of flutter, buffeting and strength problems. Approximatelly in the same direction the active aeroelasticity concept finds its further development in the Russian proposal for direct wing-box deformation control by changing tension of cords located inside spar caps [18, 19].

It becomes a commonplace of understanding that the perspective technology of solving the problem of detrimental aeroelastic deformations as well as the problem of aileron reversal is the active use of elastic deformations of structure, or the technology of "active aeroelastic wing". It is defined as multidisciplinary synergistic technology integrating aerodynamics, active control and structure for the maximum improvement of the aircraft capabilities [14]. The key words in this definition are "multidisciplinary" and "synergistic". The latter one implies the interaction of multiple factors that strengthen the effect of one another.

The essence of active aeroelastic wing concept and its principal difference from the traditional approach that presumes the use of control surfaces on the trailing edge is correctly treated by such authors as Pendleton E. W., Flick P. M., Love M.H. and others as the deflection of the leading edge that turns elastic deformations of the wing into benefit. In line with the "active aeroelasticity" concept the proposal was made to use mass distribution to improve airplane aerodynamic performance, particularly its stability margin [20, 21]. As mentioned above, these were the problems of static aeroelasticity that produced initial impact to evolution of active aeroelasticity concept. However the researches, particularly within Active Aeroelastic Structures (3AS) project, revealed that the new control surfaces exploiting structural elasticity turned out to be very promising for solving the strength and dynamic aeroelasticity problems. The analysis of the results of complex studies under 3AS project with regard to a transport category airplane revealed the following [22]: the weight of the wing primary structure with the aileron moved forward (relative to the stiffness axis) could be reduced by 4% while meeting the strength and aeroelasticity requirements and retaining the roll control efficiency; meantime surface area of the external aileron is only 30% of that of conventional aileron; External ailerons are most effective at maximum flight speed, and their effectiveness at maximum speed could be even doubled; they also could be used for active alleviation of dynamic loads (bending moment) caused by single wind gusts. While using simple control laws, the reduction of maximum bending moment in the wing root under the single singular sinusoidal gust reached 10-15%.

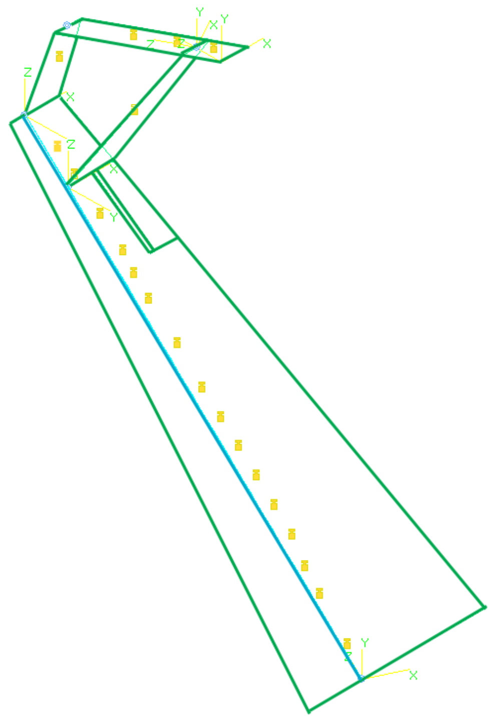

Fig. 5. The computational model of the perspective high aspect-ratio swept wing with active biplane winglet

Results of theoretical investigations on static aeroelasticity of the elastically-dynamically-scaled reference model (Fig. 5) intended for transonic wind tunnel tests (dynamic pressure scale is about 2) are presented below. Analysis was performed with the use of ARGON multidisciplinary software package, and they illustrate comparative possibilities to solve problems of control of an advanced plane with a high aspect ratio swept wing by means of various control surfaces exploiting structural elasticity. Presented in Fig. 6 are the computational model as well as dependences of the rolling moment derivative with respect to angle of deflection of an ordinary aileron on dynamic pressure for various Mach numbers.

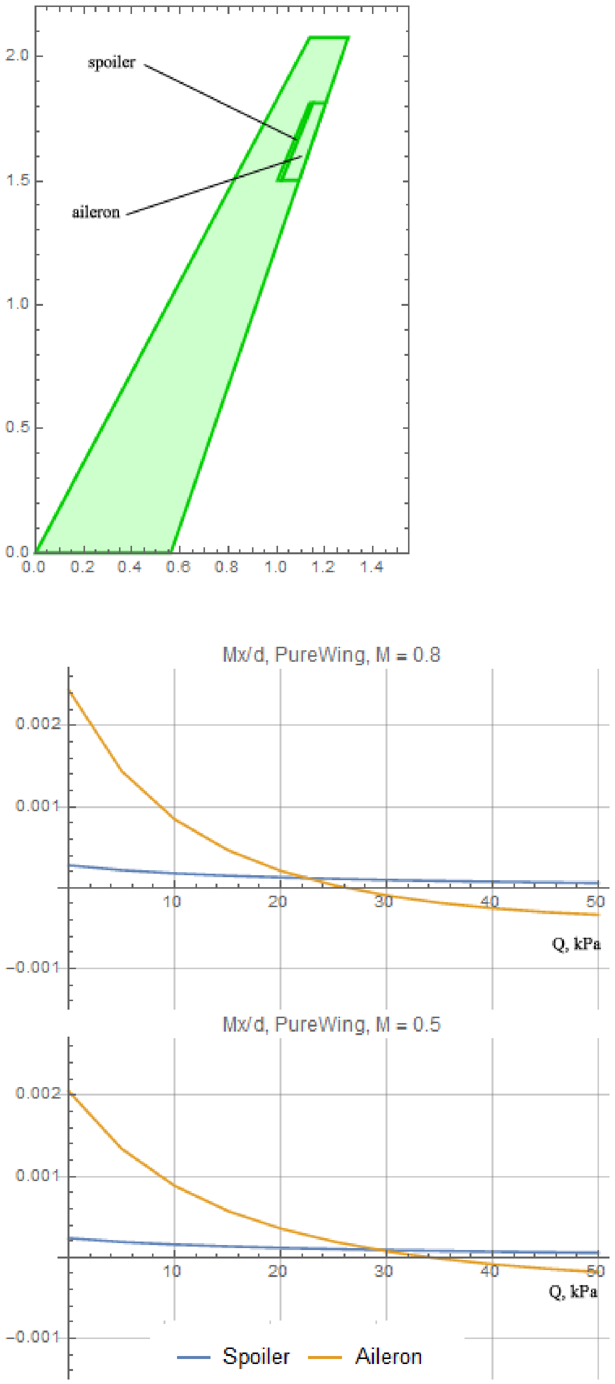

Fig. 6. Computational model and rolling moment derivative with respect to angle of deflection of an ordinary aileron versus dynamic pressure for various Mach numbers

Apparently, the efficiency of the ordinary aileron considerably decreases with growth of dynamic pressure, with aileron reversal occurring at around Mach number of 1 because of adverse bending and torsional wing deformations. Analysis shows that negative influence of elastic deformations on the efficiency of spoilers placed before aileron is much smaller. In the analysis considered the spoiler had the same length and span position as the aileron, and its chord is 25% of the aileron chord. Apparently, as seen in Fig. 6, though the effectiveness of such a spoiler at subsonic Mach numbers is rather insignificant, it only slightly decreases with growth of dynamic pressure. It is impossible to tell about effectiveness of a spoiler at supersonic Mach numbers: its effectiveness decreases with dynamic pressure growth rather considerably.

More reliable, for this case, experimental results obtained on elastically-scaled models [8] also testify the considerable possibilities to increase effectiveness of aileron control by means of spoiler/aileron combination, or spoileron. This works as follows: the spoiler is deflected, or extended at 90° angle into the air stream from a gap between aileron leading edge and the aft spar of the wing box. This is done alternatively both on upper and lower wing surfaces: when aileron trailing edge goes down, the spoiler deflects on the lower surface (or extended into stream downwards). When aileron trailing edge goes up, the spoiler deflects on the upper surface (or extended into stream upwards). In case of the deflected spoiler, the angle of its deflection is several times the angle of the aileron deflection.

Refusal of using traditional spoilers occupying considerable span of upper wing surface in favor of the spoilers placed before the aileron seems promising as it simplifies wing design and improve the quality of wing upper surface. Like the traditional spoiler, a spoileron is also intended for the plane glide path control and aerodynamic braking. A drawback of spoilers including those offered as part of a spoileron is considerable dynamic loading of the structure.

Almost ideal from the architectural point of view is the differentially deflected leading edge (forward aileron – foreaileron) shown in Fig. 7.

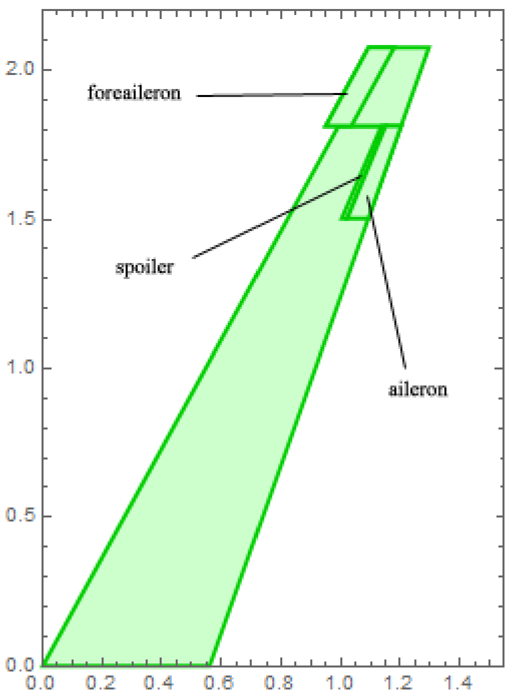

Fig. 7. Wing with foreaileron (top view)

Shown in Fig. 8 are analysis results for the effectiveness of differentially deflected leading edge (forward aileron – foreaileron) placed at the end of the wing. The foreaileron chord is approximately 34% of local chord of the wing, and its area is approximately equal to the aileron area. Effectiveness of foreaileron at small dynamic pressure is rather insignificant (in comparison with efficiency of aileron). It is a little above the efficiency of a spoiler, however it does not decrease with growth of dynamic pressure, including that above critical dynamic pressure of aileron reversal. Results of analysis, and also experiments on elastically scaled models prove especially the considerable effectiveness of foreaileron at supersonic speeds.

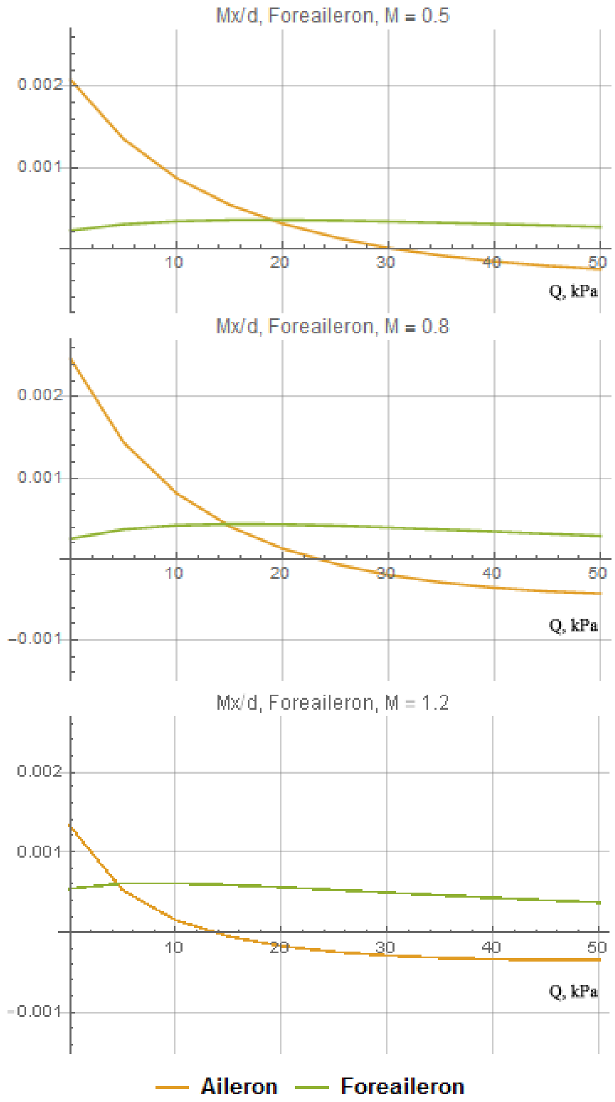

Fig. 8. Comparison of the aileron and foreaileron effectiveness

Rather strong dependence of its efficiency on airplane angle of attack is a specific feature of the foreaileron. The dependence is the stronger the smaller is the chord of foreaileron. The experiments on elastically-scaled models in high-speed wind tunnels show that reversal of foreaileron control occurs at angle of attack above 10^o, the reversal being of aerodynamic nature. Thus corresponding on-line updating of the control laws of deflection on the left and right wings depending on airplane angle of attack is necessary to achieve the required efficiency of foreaileron control. Researches show also that for roll control and the control of distribution of spanwise wing aerodynamic loading, it is advantageous to use differential deflection of leading edge sections not only at the wing end, but also along the whole span. Thus the control law of various leading edge sections deflection especially strongly depends on angle of attack, dynamic pressure and Mach number. Other known ways of control exploiting the concept of active aeroelasticity are also not free of a disadvantage. The external ailerons with rater small area investigated earlier were installed either on engines nacelles at the wing tips (Fig.1), or on standard wing struts (Fig.4), "spoiling" wing architecture in a minimum way. It is not the case if it is necessary to install special portable struts at the wing tip. Other drawback of such a pushed forward external aileron is the adverse flow downwash on a wing. The possibility to eliminate this drawback thanks to the realization of the offered concept of so-called active biplane winglet - ABW seems to be perspective.

Fig. 9. Biplane winglet of the Gulf Stream airplane.

Results of theoretical investigations of the active biplane winglet – ABW, similar to those offered by Gulf Stream (Fig. 9) but equipped with forward or back external ailerons shifted with respect to an elastic axis of a wing are presented below. The upper horizontal part of the ABW with positive sweep occupies up to 15 % of wing semispan. It is located ahead of an elastic axis of the wing end part. Two positions are considered: the more, and the less pushed forward. In the first case, the ABW leading edge is pushed forward with respect to the wing leading edge by the distance equal to 85% of a the wing tip chord. In the second case it is pushed forward by the distance equal to 36% of the wing tip chord.

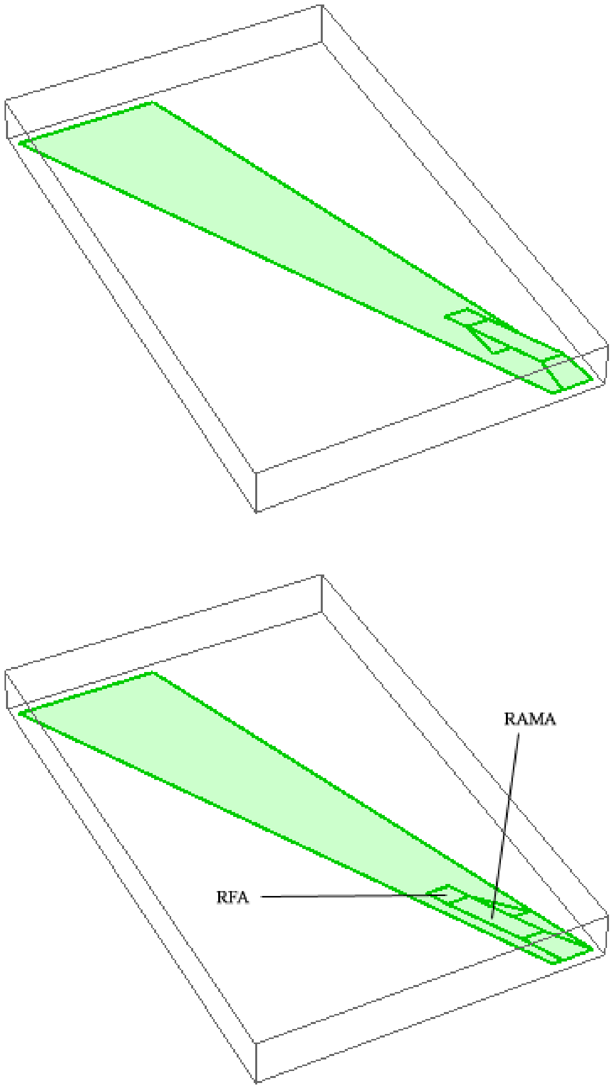

Fig. 10. Pushed forward versions of the ABW (RFA – Remote Front Aileron, RAMA- Remote All-Movable Aileron)

ABW is put on the wingbox with the help of the backward swept fins. In the first version of ABW, the fins sweep angle is naturally a little greater than in the second. The top horizontal part of ABW is made as totally deflected, or with an external aileron. Apparently, the effectiveness of roll control M_x^{δ} (q, M) of all-moving ABW part and ABW external aileron practically does not decrease with growth of dynamic pressure. Apparently the analysis results (Fig. 11) show that under the reduction of ABW shifting forward towards elastic axis of the wing, the efficiency of roll control M_x^δ (k, M) provided either by all-moving ABW part and ABW portable aileron also practically does not decrease with growth of dynamic pressure.

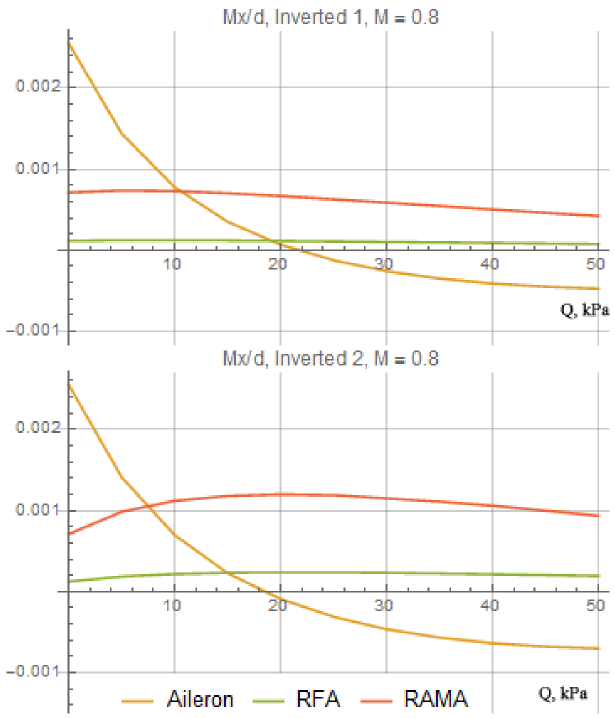

Fig. 11. Pushed forward ABW control effectivness. Upper picture for 36%, lower for 85% of pushing forward with respect to chord value

For an airplane of flying wing configuration, probably, the more perspective version of wing ABW located behind an elastic axis at the end part of its span is offered (Fig. 12). Thus, the upper horizontal part of ABW with positive sweep angle is attached to the wing box with the help of fins with positive sweep angle. Apparently, efficiency of roll control M_x^δ (k, M) of all-movable part of ABW is much more strongly than that for a conventional aileron but decreases with growth of dynamic pressure. The essence of the concept of exploiting elasticity in this case is to change the sign of deflection angles of all-movable part of ABW or of an aileron when dynamic pressure exceeds the critical value for ABW. Thus the total effectiveness of roll control by means of a conventional aileron and all-movable part of ABW (dashed line in Fig. 14) also practically does not decrease with growth of dynamic pressure.

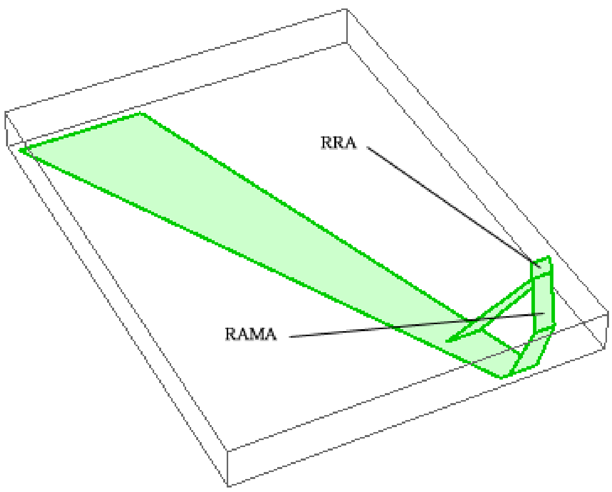

Fig. 12 ABW located behind an elastic axis on the end part of the wingspan (RRA-Remote Rear Aileron)

For flying wing scheme, active biplane winglet (ABW) appears to be especially attractive as such a control increase both yaw and longitudinal stability and controllability. Fig. 13 shows dependence of dynamic pressure on pitch moment derivative with respect to deflection of a conventional aileron and all-movable part of ABW (RAMA).

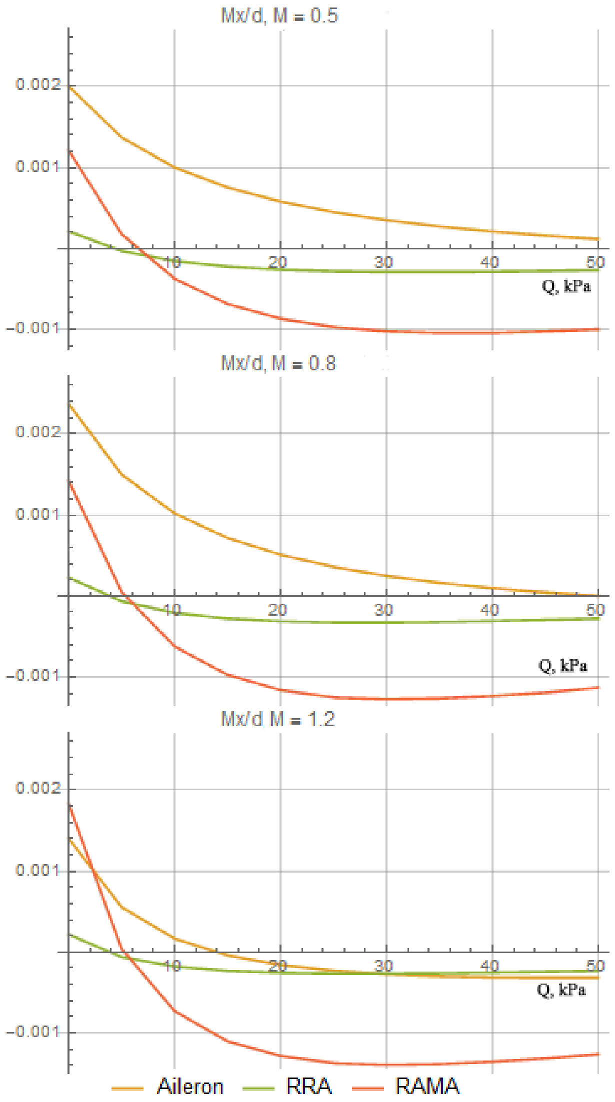

Fig. 13 Efficiency of ABW located behind an elastic axis at the end part of wingspan

(Yaw control in this case can be carried out by means of split rudders of a fin or by means of fin spoilers [23]).

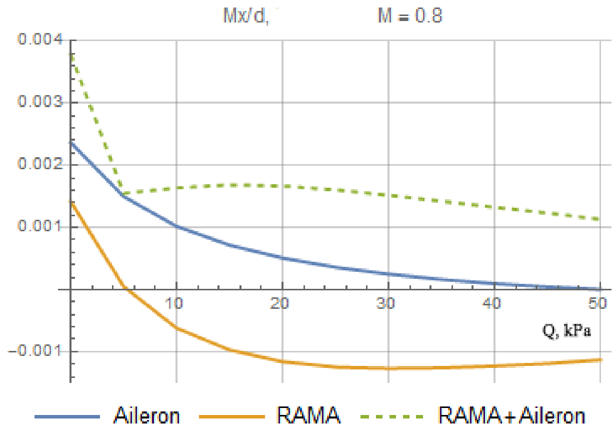

Fig. 14. Combined efficiency of the aileron and all-movable part of ABW

In Fig. 15 the results of analysis of derivatives of lifting force and pitch moment with respect to angle of attack, and also the characteristics of longitudinal stability (derivative of pitch moment due to lifting force coefficient) depending on dynamic pressure at different Mach numbers are presented. Obviously, derivatives of the lifting force for rather flexible wing considerably decrease with growth of dynamic pressure

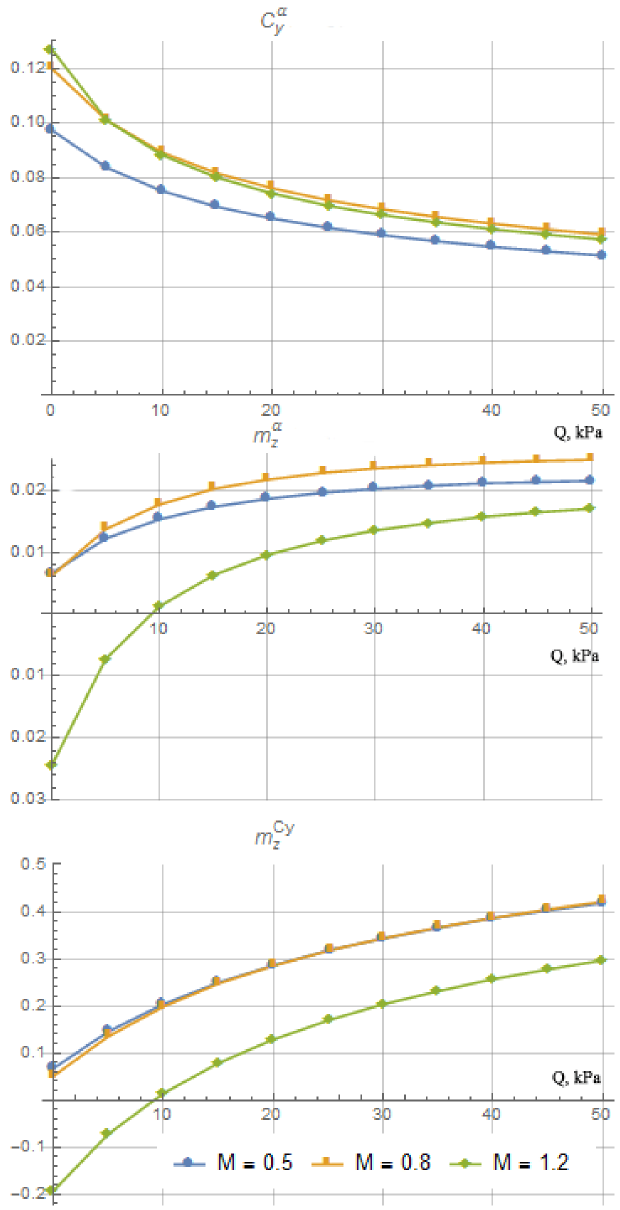

Fig. 15. Aerodynamic derivatives for the wing with ABW

Conclusion

The goal of this investigation is to show some of the benefits associated with Active Aeroelastic Wing – AAW concept. Some of the results of fulfilled investigations give opportunities for future conceptual designers to use the benefits of AAW technology.

References

[1] Hanna R.H. *Study of Control Devices* - North American Rockwell, NR 71H - 317, 1973

[2] Gilyard G., Espana M. *On the Use of Controls for Subsonic Transport Performance Improvement: Overview and Future Directions.* NASA TM 4605, 1994.

[3] Grasser W. *A Transonic Speed Wind Tunnel Investigation of the Rolling Effectiveness of a Large Swept Wing Transport Aircraft with Conventional Type Ailerons and Various Spoiler Configurations.* AIAA Paper 65 - 789, 1965.

[4] G.A. Amiryants. *The Lateral Control Method of Winged Flying Vehicles.* "The Author's Rights Witness" (Certificate of Invention), № 31962, 1964, (in Russian).

[5] 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.

[6] Amiryants G. A. *A way of a lateral control by airplane and the device for implementation of this way*. Russian Patent № 628677, 1976.

[7] G.A. Amiryants. *About Effectiveness of Differential Leading Edge (Forward Aileron) on Elastic Wing*. TVF № 7, 1970 (in Russian).

[8] Amiryants G. A, Barinov N.F., Vasiliev G. A. *A spoiler-elevon as means of longitudinal and lateral control of the aeroplane with small aspect ratio wing*. TsAGI works, 1976 (in Russian).

[9] G.A. Amiryants. *About one Method of Ailerons Reversal Critical Dynamic Pressure Increasing*. Technika Vozdushnogo Flota Journal, TVF №4, 1967 (in Russian).

[10] G.A. Amiryants, Ya.M.Parchomovsky. *About Influence of Structural Elastic Deformations on Aerodynamic Characteristics of Aircrafts*. Presentation on Soviet-France ONERA-TsAGI Workshop. Paris, 1980.

[11] Pendleton Ed, Sanders B., Flick P., Sensburg O. *Controllable Aeroelastic Lifting Systems*. International Forum on Aeroelasticity and Structural Dynamics, Madrid, 2001.

[12] Schweiger J., Suleman A. *The European Research Project: "Active Aeroelastic Aircraft Structures"*. International Forum on Aeroelasticity and Structural Dynamics, Amsterdam, 2003.

[13] 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.

[14] Pendleton E., Griffin K.E., Kehoe M.W., Perry B. A *Flight Research Program for Active Aeroelastic Wing Technology.* AIAA-96-1574-CP, 1996.

[15] Boehm, B. and others. *Static Aeroelastic Response Predictions of the Active Aeroelastic Wing (AAW) Flight Research Vehicle*. AIAA Paper 2001-1372. AIAA/ ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Long Beach, 2001.

[16] Cesnik C. E. S., Brown E. L. *Active Warping Control of Joined Wing Aircraft.* International Forum on Aeroelasticity and Structural Dynamics, Amsterdam, 2003.

[17] Khot N.S., Zweber J.V., Veley D.E., Oez H., Eastep F.E. *Flexible Composite Wing with Internal Actuation for Roll Maneuver*. Proceedings of 22-nd ICAS Congress, Harrogate, 2000.

[18] G.A.Amiryants, V.A.Timohin, V.A.Malyutin, A.V.Chedrik. *Active use of elasticity concept and adaptive structures*. 22nd AIAA/ASME/AHS Adaptive Structures Conference. 2014

[19] G,A.Amiryants. *Control over bending and twisting deformations of lifting surfaces and device to this end* Russian Patent № 2574 491, 2014

[20] G.A.Amiryants *Theoretical Investigation of Influence of Elasticity and Mass Distribution on aerodynamic Characteristics of Aircraft in quasi-steady Motion*. TsAGI Scientific Notes, v. X, № 1, 1979 (in Russian)

[21] G.A.Amiryants, F.Z.Ishmuratov. *Inertia forces role in static aeroelasticity*. Proceedings of 25-th ICAS Congress, Hamburg, 2006.

[22] G.A.Amiryants, M.C.Zichenkov, F.Z.Ishmuratov, S.I.Kuzmina. *Development of the concept of active aeroelasticity.* The all-Russian technological journal "Polyet", Special extension of 90 years of a TsAGI, 2008 (in Russian)

[23] G.A.Amiryants. *A way (versions) of control of a flight vehicle and the device (versions) for its implementation.* (The patent of Russian Federation RU 2299834, 2005)

Contact Author Email Address

mailto: stataer@tsagi.ru

Copyright Statement