USE OF AEROELASTICITY; MULTIDISCIPLINARY INVESTIGATIONS

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Abstract

One of the very promising areas in aircraft design today is associated with the "use of aeroelasticity" concept. This concept is based on earlier TsAGI's proposals of innovative aerodynamic controls (such as differential leading edge – forward aileron, special combination of spoiler and aileron etc). Efficient integrated analytical and experimental methods of multidisciplinary studies also originated in TsAGI in conjunction with the concept. Results of wind tunnel experimental and theoretical investigations of effectiveness of different controls for different airplanes are presented. The efficiency of appropriate developments is proved by the experience of several past decades, but this is as well the matter of future to guarantee safety, weight and aerodynamic perfection, and finally the competitiveness of airplanes of the next generation.

1 Introduction

In the early 1960's aroused necessity for increasing of structural stiffness of thin wings of the M-50 and R-020 airplanes to alleviate negative effect of elastic deformations on roll control efficiency. However the required weight increase of primary structure to solve aileron reversal problem appeared to be far beyond acceptable limits, even if this was done with use of optimization procedures. That was the time when a solution, paradoxical at first glance, was proposed: don't fight wastefully against elasticity, just use it [1].

The remote aileron (outboard tip aileron shifted forward with respect to elastic axis) and extension aileron were developed and tested in TsAGI T-109 wind tunnel on an elastically scaled model (ESM) of the M-50, then on the models of R-020, MiG-25, and Yak-28 planes [2, 3, 4].

Another firstly suggested in TsAGI type of "using elasticity" innovative control surface, namely differentially deflected wing leading edge (forward aileron - foraileron), was under investigation since 1963 [3, 4, 5]. Both wind tunnel testing on ESM of Su-27 and MiG-29 fighters and analysis confirmed effectiveness of leading edges differential deflections, as well as of the new concept in general.

2 Effectiveness of traditional roll controls

2.1 Influence of primary structure parameters on aileron effectiveness

For observing of difficulties with traditional approach to roll control problem solving systematic calculations of influence of primary structures main parameters of a) high, b) medium and c) small aspect ratio wings on aileron effectiveness were done.

Systematic calculations show that 10% - increasing of initial effectiveness of ailerons at the relative dynamic pressure value equal 75% of maximum dynamic pressure q_D ($\bar{q} = q/q_D$=0.75) and Mach number M=0.9 can be achieved by following means.

a) For the high aspect ratio wing (Tu-154 type):

- due to 20% -increasing of primary structures profile thickness (structural depth) practically on all span of the wing, excluding only the wing's end,
- due to optimal increasing of primary structures skin weight using additional value equal to 40% of initial weight of the wing skin (ΔG=0.4G_{skin}).

b) For the medium aspect ratio wing (MiG-29 type):

- due to 20% -increasing of primary structures profile thickness on the inner, most "sensitive" half of the span of the wing,
- due to optimal increasing of primary structures skin weight using additional value equal to 19% of initial weight of the wing skin (ΔG =0.19G_{skin}).

c) For the small aspect ratio wing (Tu-144 type):

- due to 20% -increasing of primary structures profile thickness practically on the inner, most "sensitive" half of the span of the wing,
- due to optimal increasing of primary structures skin weight using additional value equal to 12% of initial weight of the wing skin (ΔG=0.12G_{skin});

d) For the variable sweep angle high aspect ratio wing (MiG-23 type):

- at the sweep angle χ=16° - due to 100% - increasing of the wing torsional stiffness on the one-third (most rational) medium part of the wing span,
- at the sweep angle χ=72° - due to 100% - increasing of the wing bending stiffness practically on the all wing span.

Evidently that the possibilities of changes in primary structure are small taking into account that required increasing of aileron effectiveness for many contemporary aircrafts not less than 30%.

2.2 Influence of aileron geometry

The possibilities of advantageous changes in aerodynamic scheme, for example in aileron chord size and span location, also are very limited. 10% -increasing of effectiveness of aileron outer section of high, medium and small aspect ratio wings at $\bar{q}$ =0.75 and M=0.9 can be achieved:

- due to shifting of the aileron on inner, more rigid parts of the wing, corresponding: on 10%, 20%, 25% of the wing span,
- due to increasing of initial aileron chord size corresponding: to 17%, 8%, 10% of the local wing chord; in this case only change of location of aileron leading edge (but not rear edge) is advantageous. According calculations and flight test results the change of elevon rear edges sweep angle, at which root chord of inner section of elevon was increased and tip chord of outer section was decreased on 30%, leads to increasing of the effectiveness of pitch control, but not so significant: decreasing of the elevon balancing angle at $\bar{q}$ =0.75 was less than 5%.

2.3 Effectiveness of other traditional roll controls

Effectiveness of spoilers and differential horizontal tail (DHT) in many cases also greatly decreases with dynamic pressure elevation.

For example, the spoilers investigated on ESM at transonic flow speed (fig. 1, 2) achieved maximum value of their effectiveness (nondimensional roll rate) at dynamic pressure and Mach number quantities near to critical for aileron M_{crit} and q_{crit}. Next growth of q and M leads to decreasing of spoiler effectiveness, which achieved at maximal investigated dynamic pressure and Mach number quantities 40% of initial value. As a result available effectiveness of spoilers (and all the more ailerons and flaperons of investigated aircraft) were smaller than required roll control effectiveness $\omega_{x\ requir}$.

Decreasing of effectiveness of DHT as roll control due to structural elastic deformations is many times smaller than loss of aileron effectiveness at the same flow parameters (fig. 2). But for some types of aircraft, essentially when DHT connected with the wing using rear fuselage beams, significant loss of effectiveness is possible. For one maneuverable aircraft such loss of effectiveness at $M \approx 1.0$, $\bar{q}=1.0$ was equal 40% : partly due to elastic deformations of tail consoles, but mainly due to unfavorable deformations of the wing root part between rear fuselage beams.

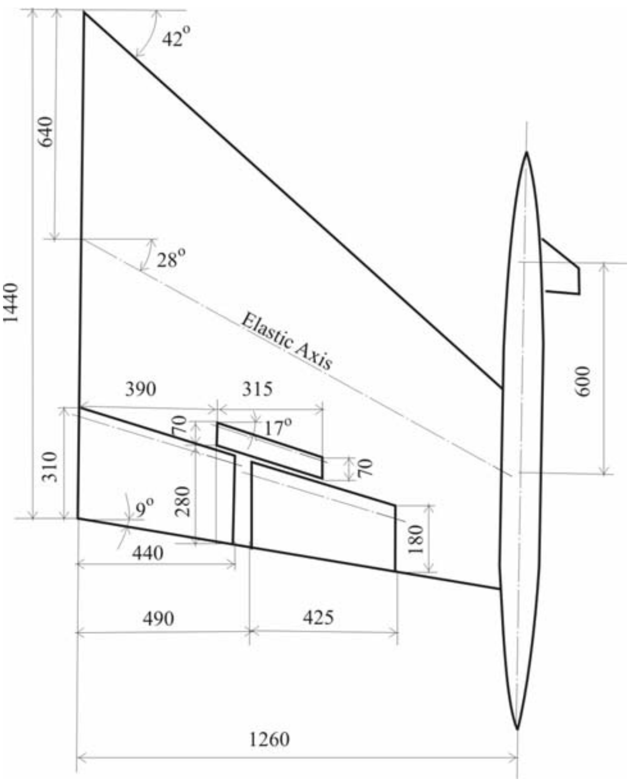


Fig. 1. Elastically scaled model (ESM) with different roll controls: aileron, remote aileron, spoiler, flaperon

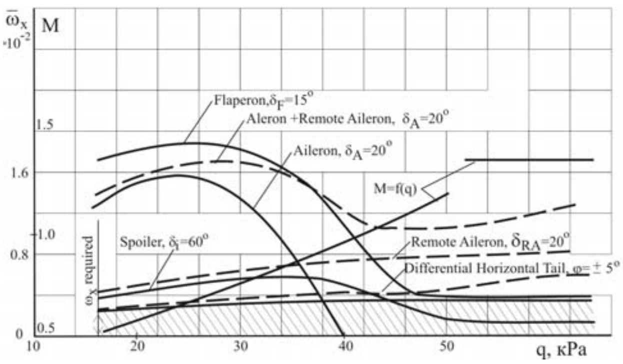


Fig. 2. Roll effectiveness of aileron, spoiler, flaperon, horizontal tail, remote aileron; ESM wind tunnel test results

3 Innovative controls

3.1 Remote aileron

The remote aileron and extension aileron were developed and tested in TsAGI T-109 supersonic wind tunnel on ESM at the beginning of 1960's [2, 3, 4]. High effectiveness of remote ailerons was shown both in wind tunnel tests of ESM (fig. 1, 2) and in calculations. Use of elasticity of 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 plane version arouse [6]. Traditional approach required unacceptable (by several times) increase of skin thickness in the area of wing root, while remote ailerons allowed it to be made even thinner.

3.2 Differential leading edge - forward aileron

The suggestion to use differential deflection of leading edge (first of all deflection of leading edge up – previously absolutely unbelievable and prohibited from traditional aerodynamicists point of view) was much more "aggressive" than remote aileron using, but also much more prospective. It was evidently that in contrast with remote aileron the foraileron did not need in additional elements on the wing tip. But it was necessary to do many 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 up may be very helpful for control – essentially at transonic and supersonic Mach number and high dynamic pressure values.

Wind tunnel tests of the high aspect ratio wing's ESM show (fig. 3, 4) 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 $\delta_{forailer}=0 \div 48^o$) and down ($\delta_{forailer}=0 \div -32^o$) at the angle of attack near to zero ($\alpha \approx 0$) 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.

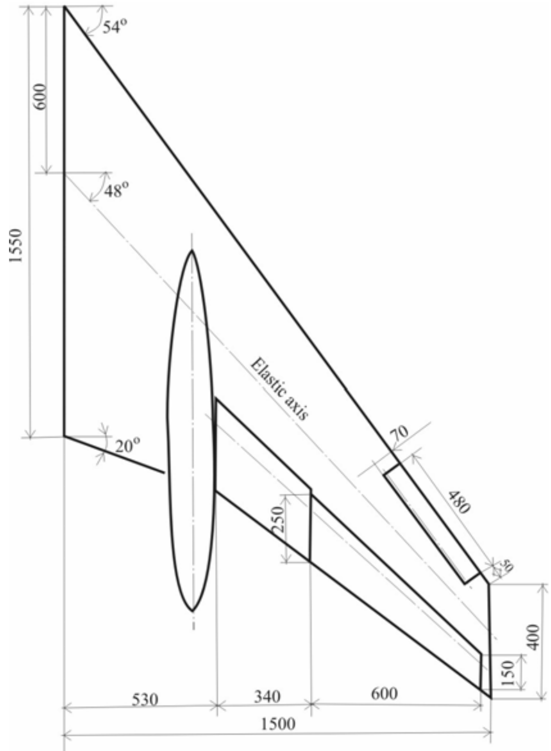


Fig.3. ESM of the high aspect ratio wing with aileron, forward aileron (foraileron), flaperon as roll controls

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 $\bar{q}$=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 α=0; 3°; 6°; 9°), fig. 5-7.

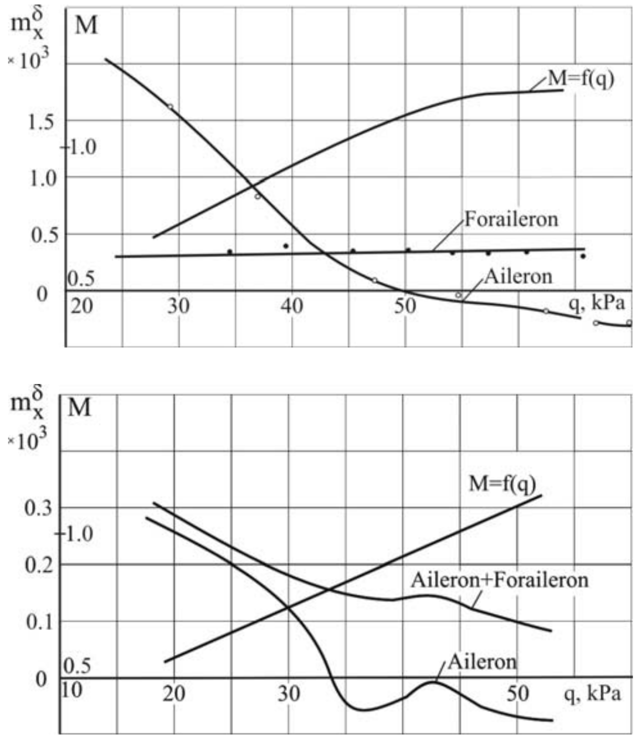


Fig. 4. Roll control effectiveness of aileron and foraileron; high aspect ratio wing's ESM wind tunnel test results

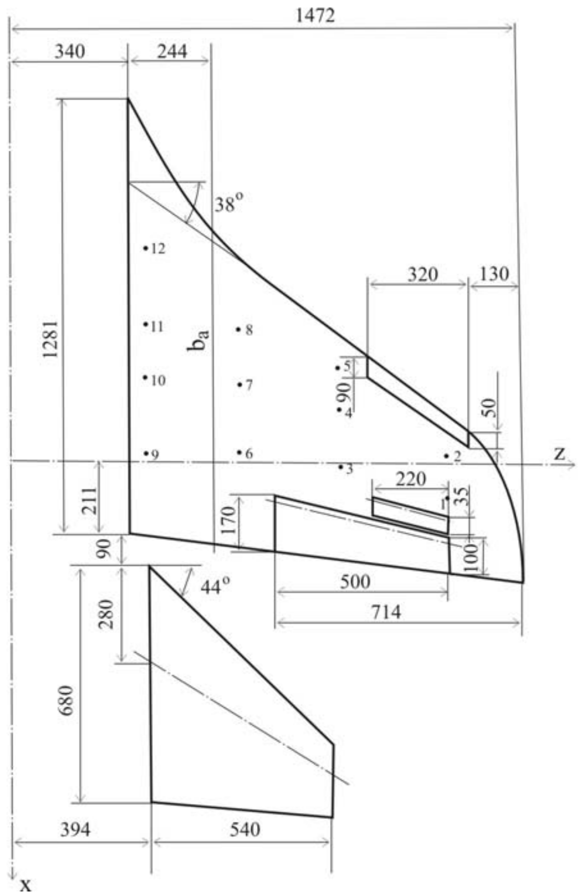


Fig. 5. Elastically scaled halfmodel with aileron, spoiler, DHT and foraileron as roll controls

Effectiveness of foraileron practically increases with growth of q and M. Both deflection of foraileron up and down gives approximately equal and substantial input to the total effectiveness of foraileron till to maximal investigated in supersonic wind tunnel angle of attack $\alpha=9^o$.

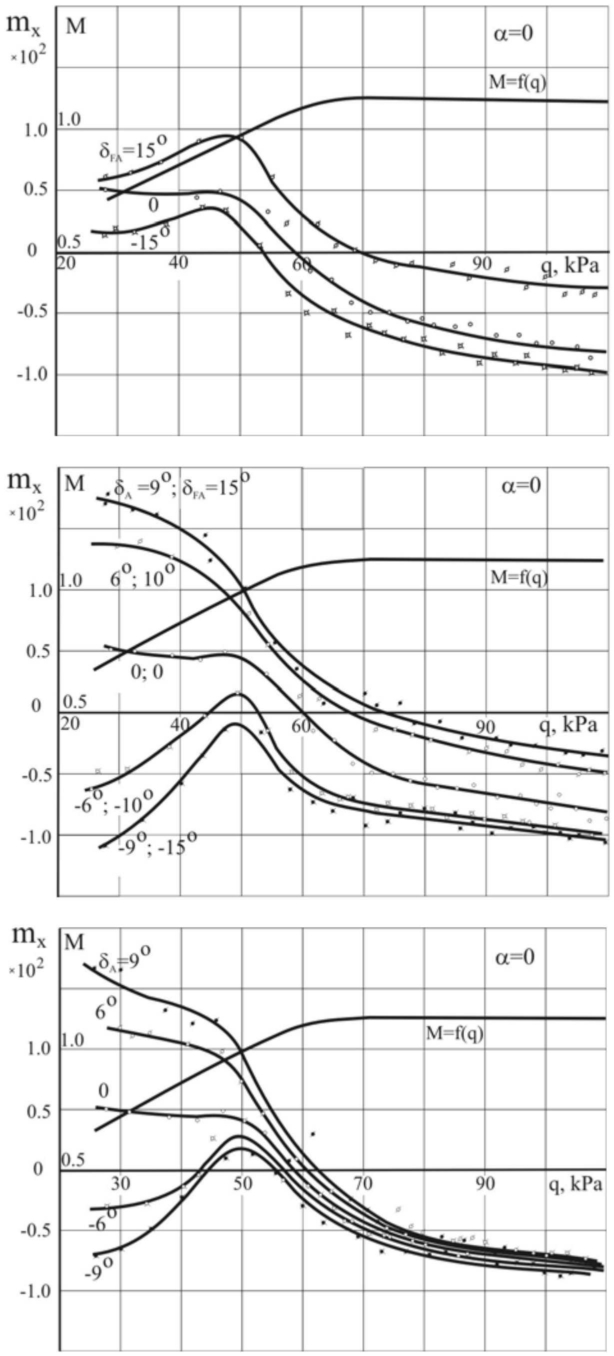


Fig. 6. Roll control effectiveness of aileron and foraileron; angle of attack of elastically scaled halfmodel $\alpha=0$

Last conclusion is valid for more great angles of attack: as subsonic wind tunnel tests of the same ESM show, – till to values $\alpha=30^o$ and flow speed V=50m/sec. But according another test results, influence of angle of attack, beginning from angles of attack $\alpha\approx10^o$, can be unfavorable both for deflection of foraileron up and down.

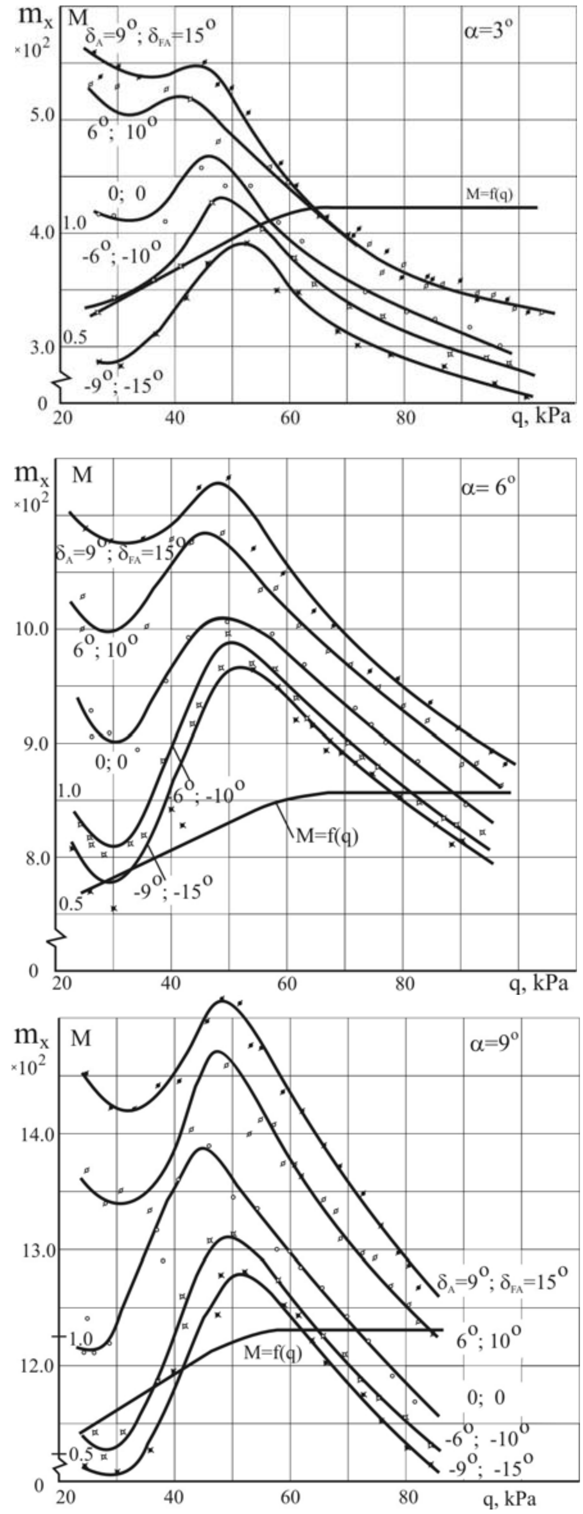


Fig. 7. Roll control effectiveness of aileron and foraileron; angles of attack $\alpha=3°, 6°, 9°$

The decision of such kind problem may be different for different aircrafts. For ones most attractive possibility is using of great surface of foraileron and small angles of their deflection (less than 10°). For another more effective decision is disconnection of foraileron at small dynamic pressure value q (α>10÷15°). Most radical decision is the development of rational control law for aileron and foraileron sections deflection in dependence from dynamic pressure, Mach number, angle of attack, angle of possible initial symmetrical deflection of leading edge sections. Of course similar approach is advantageous also for using of different sections of trailing edge independently from leading edge sections deflection.

3.3 Differential leading edge as pitch and yaw control

Wind tunnel tests of supersonic transport (SST) small aspect ratio wing's ESM showed that all previous main conclusions about using of differential leading edge are valid also for such kind aircraft. It was shown, that effectiveness of forward elevons (forelevons) as roll and pitch control (in contrast with elevons, which effectiveness significantly drops with dynamic pressure increasing) at least didn't decreased in investigated transonic diapason of Mach number M.

It was shown also, that most advantageous is using of outer section of forelevon with as possible great chord. Positive essentialities of forelevons are more noticeable when they are used for roll (but not for pitch) control. It was find, that effectiveness of forelevons (only their down deflection was investigated) practically didn't decreased with angle of attack increasing up to α=8°.

Using of differential leading edges, for example, of vertical tails has one additional prospective area – for effective yaw control. According to supersonic wind tunnel tests of ESM of maneuvering aircraft with two fins (fig. 8, 9) at high value of dynamic pressure q (M=1.1) most noticeable increasing of yaw control effectiveness is achieved when mutual deflection of rudder (δ_{rud}=15°) and forward rudder (forrudder) (δ_{forrud} =15°) used. This increasing is not less than 15-20% in comparison with independent rudder deflection.

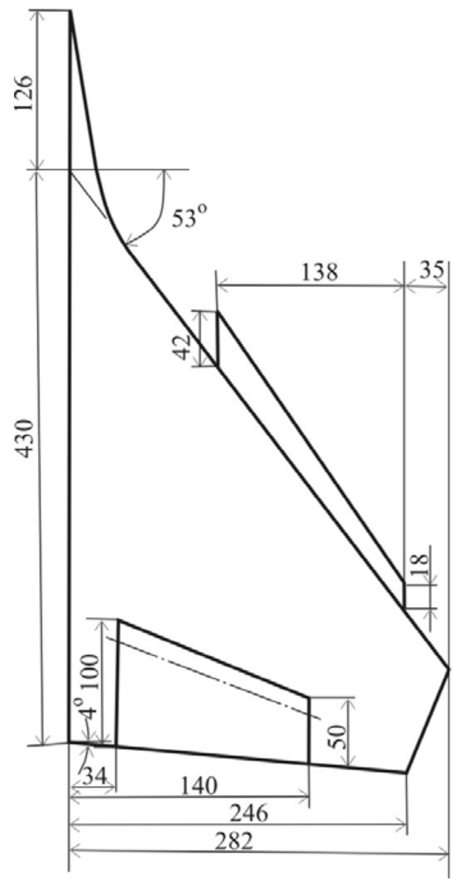


Fig. 8. Fin's ESM with rudder and forward rudder (forrudder) as yaw control

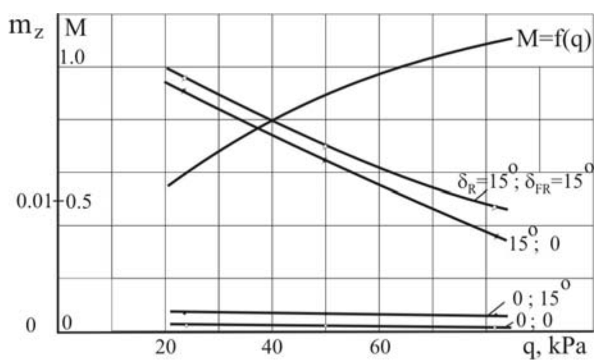
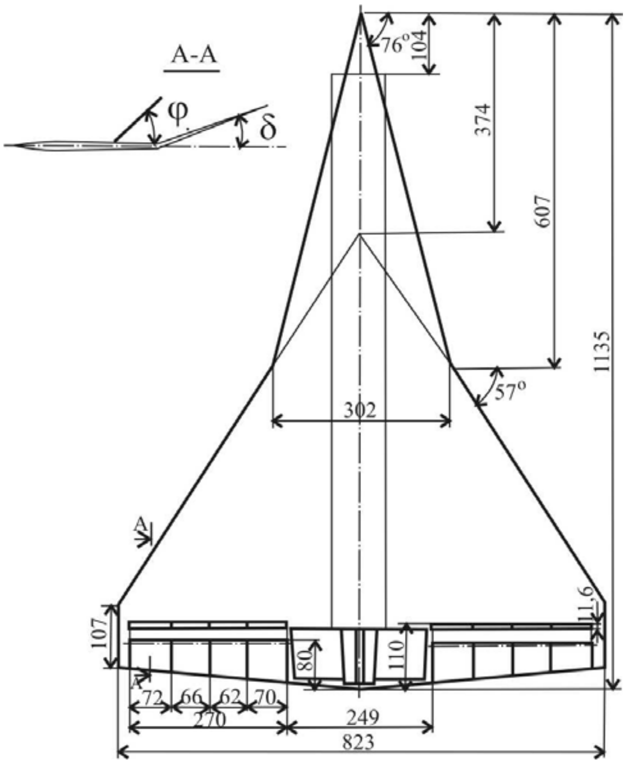


Fig. 9. Yaw control effectiveness of rudder and forrudder; fin's ESM wind tunnel test results

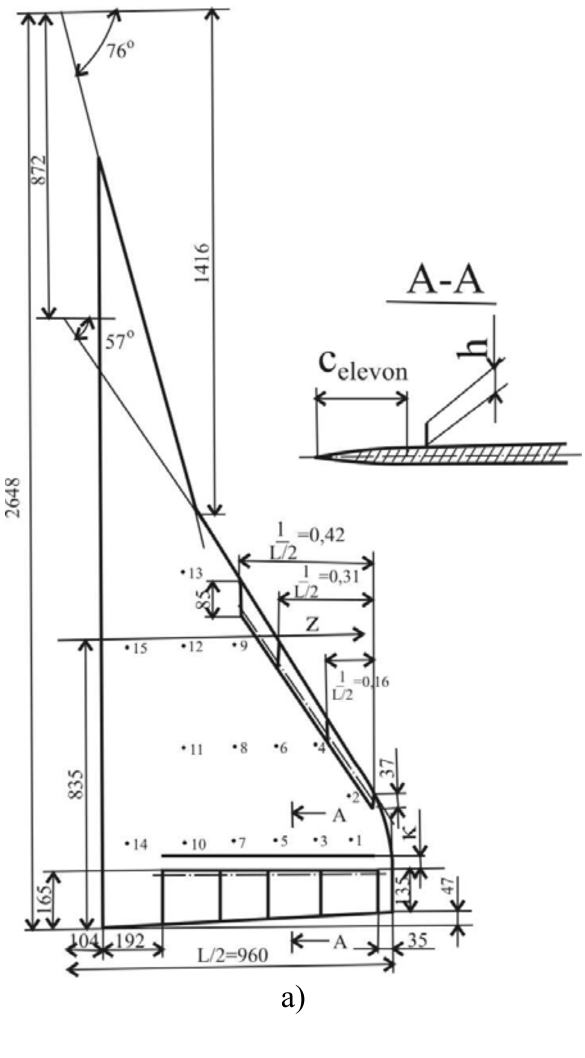
Increasing of effectiveness can also be achieved due to rational kinematical connection of rudder with forrudder, which can give mutual decreasing of hinge moments.

3.4 Combination of spoiler and aileron - spoileron

Effectiveness of SST low aspect ratio wing elevons (fig. 10a, 10b) 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 [7]. Spoiler of this combination (spoilevon) can be rotatable (fig. 10b) or extendable (in last case angle of spoiler deflection equal to 90° (fig. 10a). Height of all investigated four section of spoiler was equal to 12.5% and 20% of local elevon chord ($\bar{h} = h/c_{elevon}$=0.125 and 0.2). One additional investigated variant was for two outer sections of spoiler ($\bar{h}^*$=0.2), fig. 10a, 11, 12.



b)



a)

Fig. 10. Supersonic transport (SST) ESM with forward elevon (forelevon) and combination of spoiler-elevon (spoilevon): a) extendable, b) rotatable

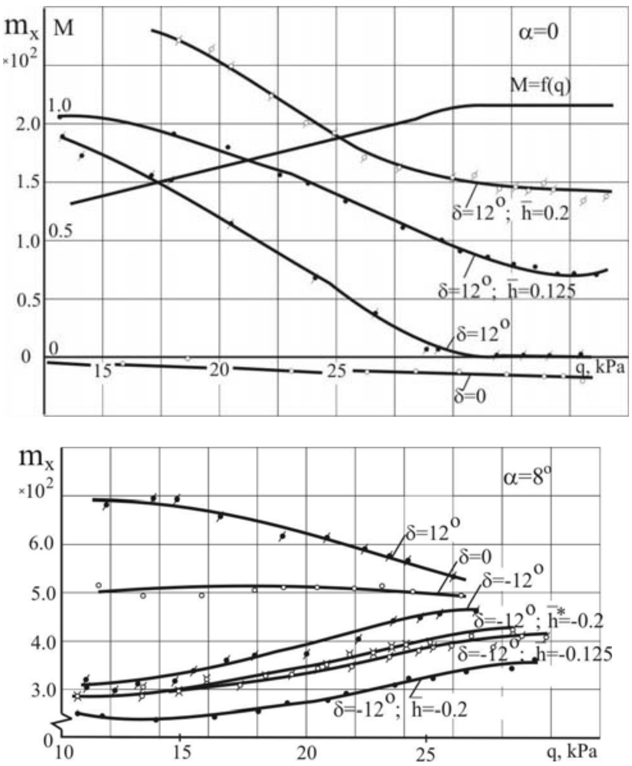


Fig.. 11. Influence of dynamic pressure and angle of attack on effectiveness of spoilevon as roll control; SST ESM wind tunnel test results

High effectiveness of spoilevon as roll (fig.11) and pitch (fig.12) control remains up to investigated angle of attack α=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 elevon. Angles of attack (or angles of sideslip) are limited in this case and it is possible to "use" torsional elastic deformations most effectively.

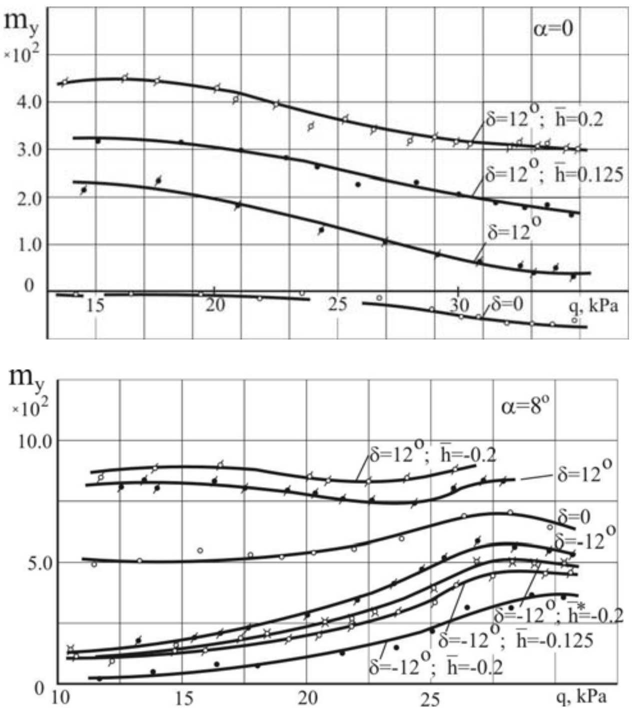


Fig. 12. Influence of dynamic pressure and angle of attack on effectiveness of spoilevon as pitch control; SST ESM wind tunnel test results

Combination of spoiler and elevon (aileron or rudder) is very 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 and pitch, but also (essentially) as yaw control.

3.5 Active aeroelastic wing

A new version of American F/A-18 fighter was the airplane, for which the prospects of innovative controls and "use of elasticity" concept were confirmed in 1980-90's [8]. The problem of higher efficiency of roll control was solved just in the same manner as it had been suggested by TsAGI for high speed manoeuvrable and other aircraft types.

The major new elements of the new "active aeroelastic wing", "the real breakthrough in control system development", as the program was also 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 roll control. Thus, the system has been realized which includes outboard forward and conventional ailerons.

The problem of providing required efficiency of roll control for the Su-27 test prototype appeared to be so complicated and important, that it became the subject of consideration for the joint commission of TsAGI and Design Bureau experts in aerodynamics, flight dynamics, control systems, strength and aeroelasticity. It was found out on the base of testing ESM in TsAGI T-109 wind tunnel and multidisciplinary analysis that to get the needed control efficiency by means of ailerons required extra weight of approximately 30% of outboard wing weight ($G_{outb.\ wing}$=1040 kg), or 35% in case of differentially deflected horizontal tail. The commission did not find it possible to use spoilers and made the following general conclusion: the most promising in terms of weight efficiency is the use of foraileron for roll control, which required extra weight not more than 10% of the wing weight.

By that time, in early 70-th, it had been shown however that foraileron efficiency was rather a complicated function of Mach number, angle of attack and dynamic pressure. Thus, use of foraileron led to more complicated control system, which was one of the reasons to reject foraileron on the Su-27 in mass production version.

First opened (nonconfidential) information about TsAGI's investigations in this area (including information about investigations of differentially leading edge – foraileron as effective roll and loads control) was published on ONERA-TsAGI Symposium [5].

US Patent on the same system was received by Northrop Corporation in 1983 [9].

Also, it was shown that foraileron can be used not only to solve the problems of static aeroelasticity, but of structural dynamics as well, and to reduce effectively airframe weight. Today this is the breakthrough in the practice of designing the newest airplanes [8-12].

Research in another proposed in the mid of 1990's in TsAGI area has been continued. This research related to the use of divergent properties of wing and empennage on the base of rational selection of their plane-forms. High efficiency and prospects of this approach were demonstrated by TsAGI and Design Bureau's experts in solving the problem of following an assigned law of angular velocity variation in time to stabilize a missile motion along its trajectory [13].

4 About multidisciplinary theoretical investigations

"Use of aeroelasticity" concept mainly connects with static aeroelasticity problems, such as: reversal of control, rational load redistribution, increasing of stability (for example, using divergence tendency of reduced fin).

But other characteristics are also very significant: aerodynamic drag, loads, strength, fatigue, aeroservoelasticity. That's why it was necessary to develop multidisciplinary investigations for approving of the "use of aeroelasticity" concept.

The first multidisciplinary studies based on the method of polynomials [14, 15] were undertaken to develop and substantiate the "use of elasticity" concept. These are only multidisciplinary approach and the complex research on the problems of reversal, flutter, aerodynamics and strength that made it possible to prove the validity and prospects of the concept. Later this approach, which also has its independent value, was used in TsAGI to create more powerful tool - ARGON software package for multidisciplinary studies and structural optimization [16, 17].

ARGON package is based on agreed models of two levels. The Ritz polynomial method (1-st level model) is used for aeroelasticity problems solving and loads estimation. And for strength analysis more detailed finite element method (2-nd level model) is used. Main advantages of this package are fast parametric investigations of aeroelastic characteristics and possibility of aircraft structural optimization on the base of two-level approach taking into account strength, stiffness and aeroelasticity requirements. Optimization procedure is based on using recurrence relations followed from optimum criteria for structural weight minimization with stress and displacement constraints. To take into account buckling constraints the criterion of equal stability of structural panels is used for determination of reasonable sizes of panel.

Another multidisciplinary software package, developed in TsAGI, KC-M [18], also based on Ritz polynomial method, but is mainly dedicated to solve dynamics problems, including transonic aeroelastic problems, buffeting and design of elastically,-dynamically-scaled models.

Running multidisciplinary analysis in aeromechanics started earlier by W.P. Rodden [19], though this was not related to the development of active aeroelastic wing concept.

5 About multidisciplinary experimental investigations

Important steps in implementation of multidisciplinary approach into experimental research for solving aeromechanical problems were made in TsAGI. A concept of the multi-purpose aeroelastic modular model made of composite materials was developed in 1994 [20, 21]. The model has detachable wing or tail box panel and is intended for wind tunnel tests on flutter, reversal, divergence, buffeting, total and distributed aerodynamics loads of a "rigid" and elastic airplane with the possibility to vary dynamic pressure scale of similarity and mass distribution. The advantage of the approach is its fastness, cost effectiveness, and, the main, the high accuracy it brings into experimental studies. The prospects of the idea, in which multidisciplinary analysis methods are interlinked with experimental ones, have been recognized as quite significant [22]. Born by the development of the use of elasticity concept, the approach has its own value today and is being actively developed in some countries.

6 Adaptive controllable structures

Control of elastic deformations with the aid of using composite materials for solving the problems of divergence was proposed by N. Krone in 1975 [23]. In line with this concept so called "selectively-deformable" structures were suggested [25-27].

The structures of this kind exhibit higher elasticity in one direction (e.g. tension/compression), while keeping high stiffness in others (bending, torsion, shear), with extremely wide usage.

The areas of application are: engineering and civil buildings and constructions; automotive, railway, sea shipping and pipeline transport; medical equipment; aviation and rocketry. The important part of the concept is so called adaptive controllable and "smart" structures – they can be used as significant element in development of adaptive wing structure.

7 Conclusions

The practice of last fifty years showed that actual problem of reversal of control cannot be decided by traditional means – increasing structural stiffness and weight. Nontraditional approach to solving of this "local" problem gave impulse to promising attempts to solve many other aeromechanics problems using the same instruments – innovative aerodynamic control surfaces and control system.

"Use of aeroelasticity" or Active Aeroelastic Wing concept turns aircraft lifting surface (wing or tail) elastic deformation into a net benefit by using of leading and trailing edges sections or special combination of spoiler and trailing edge activated by control system. It seems attractive to use self-teaching digital flight system on the base of renewed flight information about effectiveness of different controls as function of Mach number, dynamic pressure, angles of attack, angles of sideslip, control sections deflection etc.

In connection with last year look and information of our American colleagues [8, 28] about Active Aeroelastic Wing concept as "new level for the purpose of revolutionizing air vehicle design" it would be reasonable to present short information (previously confidential but now opened) about TsAGI's early investigations in this area.

The contemporary "use of elasticity" concept, in the meaning we put today in this term, is based on suggested in TsAGI in 1960-s innovative controls (forward aileron etc.). Related methods of multidisciplinary tests and analysis in aeromechanics have been considered as innovative areas in advanced aviation designs. We consider this concept as promising way to achieving of high safety, high weight efficiency and competitiveness of advanced airplanes.

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