AEROELASTIC MULTIDISCIPLINARY ANALYSIS OF THE FIN WITH INNOVATIVE ADAPTIVE CONTROL

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Abstract

This paper describes possibility of fin-box chord increase and fin structural weight reduction due to use of so called spoiler-rudder low-chord innovative control.

Chord of contemporary multiengine transport airplane traditional yaw rudder equal not less than 30% for one-link rudder and 40% – for double-link rudder.

That is necessary for achieving of high effectiveness of yaw control in case of engine failure (malfunction) and for side force gust alleviation.

It is not simple technical task to solve effectively structural weight problem taking into account flutter, static aeroelastic and strain-stress, fatigue problems due to structural limitations for fin box chord.

Such kind fin structural weight problem can be solved on the base of suggested aerodynamic tool.

The main objective of the investigation is to show the ways to realize more efficient fin's airframe structure with improved strength, reduced weight, higher effectiveness of yaw control and improved aeroelastic stability properties on the base of use of multidisciplinary approach to design of innovative adaptive controls – combination of low-chord rudder and spoiler (so called combination "spoil-rudder").

This combination includes ordinary hinged low-chord rudder with two additional spoilers. Spoilers are placed near to leading edge of rudder, on left and right side of the fin box. One attractive opportunity is using of an adaptive "smart" structure (hingless flexible skin) of the spoiler.

Aeroelastic analysis in present paper based on results of TsAGI wind tunnel investigations of "spoiler-rudder" yaw effectiveness in comparison with ordinary rudders, using elastically- and dynamically scaled models of various airplanes.

Another base of fulfilled investigations is experience of development and operating TsAGI ARGON code for multidisciplinary structural strength/aerodynamics/active control system (load alleviation etc) analysis and design.

1 Introduction

One of the basic problems of static aeroelasticity is decrease in efficiency of controls because of adverse structural deformations.

First of all it touches a lateral control. In 1960th years in a Central aerohydrodynamic institute (TsAGI, Russia) in connection with an aggravation of a problem of aileron reversal first multidisciplinary theoretical and experimental investigations of new aerodynamic controls (offset ailerons, forwardailerons) have been begun [1, 2].

Their main feature was much smaller, than at ailerons dependence on dynamic pressure, or elastic deformation. It is caused by an arrangement of these controls ahead of a wing axis. Pressure redistribution at their deflection allowed not only to cope with adverse elastic deformations of a wing structure, but even to use these deformations in the blessing.

So the concept widely known nowadays as the concept of an active aeroelastic wing, or active aeroelasticity [3] was born.

In 1970th years one more type of the aerodynamic controls using elastic deformations of a wing, so-called spoilers-ailerons (spoilerons) have been offered and investigated [4, 5].

Their valuable feature is high efficiency in a wide range of Mach numbers and dynamic pressure. It allows to bring an attention to the question on a rejection from the traditional spoilers complicating of a wing structure and worsening quality of its upper lifting surface on the bulk of wing span and its area.

The solution of this question becomes complicated an important universal purpose of traditional spoilers.

Besides the essential relation of a spoilerons effectiveness from an angle of attack is detected.

Recently the great attention is given to possibility of using of spoilers in a combination to yaw rudders.

This capability is especially attractive in connection with rather small range of change of angles of slip (in comparison with a range of change of angles of attack) and concerning the big chord of traditional yaw rudders and (appropriately) a small chord of a torsion box of a fin.

Research of observed problems is possible, naturally, only on the basis of the multidisciplinary approach, taking into account demands of aerodynamics, strength, and flight dynamics.

In this paper the capability of increase in a chord of a fin torsion box and decrease in its weight thanks to analogues of spoilerons – spoilrudders, or combinations of rudders of a small chord and the spoilers located before them is presented.

2 Results of investigation of effectiveness of a spoiler-rudder at subsonic speeds

The chord of yaw rudders modern (especially multiengine transport) airplanes is equal not less than 30 % of a chord of a fin for single-link rudders and attains 40 % – for double-link rudders.

It is called by necessity of achievement of high effectiveness of yaw control in case of engine trust failure or necessity of lateral gust alleviation.

At the restricted chord of traditional torsion boxes of fins it is rather difficult to solve a problem of effective weight reduction of a fin structure taking into account problems of a flutter, static aeroelasticity, fatigue.

Overall objective of represented research is demonstrating of ways of implementation of designs of a fin, more effective taking into account conditions of strength, fin boxes primary structures weight, high effectiveness of yaw control and favorable characteristics of aeroelasticity.

This purpose on the basis of the multidisciplinary approach to designing innovative (including with adaptive elements) controls – systems of a yaw rudder with a small chord and a spoiler – spoilrudder is achieved.

The combination a spoiler-rudder is shown on figs. 2, 3. It includes a traditional, hinged yaw rudder of a small chord (small square) and connected with it kinematically a spoiler.

The spoiler about the same span, as a rudder, places near to a rudder leading edge.

In retractable variant it places in the slot between a torsion box of a fin and a rudder leading edge, and in variant of a deflected spoiler it places on the left and right surfaces of a fin and close the slot between a fin torsion box and a rudder.

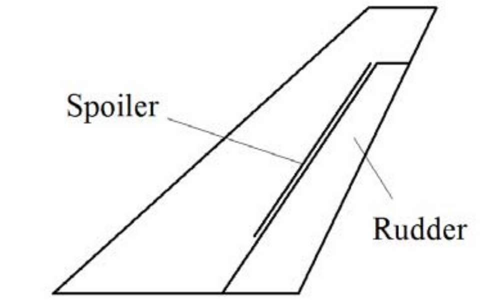
In the latter case possibility of using of an adaptive "smart" structure of a spoiler – with a hingeless flexible composite skin is attractive.

The analysis of characteristics of aeroelasticity in represented paper is based first of all on results of investigations of effectiveness of a yaw control of a combination "spoiler-rudder" in comparison with the usual rudders. These investigations are fulfilled in TsAGI wind tunnels on elastically-dynamically-scaled models of various airplanes.

As an example on figs.1, 2 results of tests in the subsonic wind tunnel of multi-purpose elastically-dynamically-scaled model of the passenger airplane with a fin (investigated in the European 3-AS project) are presented [6, 7].

On fig. 1 dependence of yaw moment from a slip angle at a deflection separately a yaw rudder (on an angle 6^o), a spoiler (on an angle 90^o), and also combination of spoiler and a rudder (spoilrudder) on indicated angles is shown.

As can be seen, effectiveness of a yaw control essentially depends on fin elastic deformations (that, from flow velocity), and also from a slip angle.



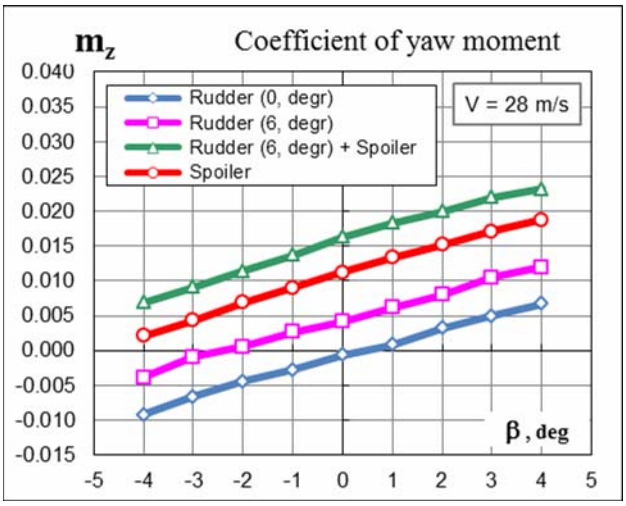


Fig. 1 Effectiveness (yaw moment coefficient) of different controls deflected on fixed angles as a function of slip angle at constant wind tunnel flow speed

Derivative of the total yaw moment due to an angle of rudder deflection equal:

$$m_{y_\Sigma}^{\delta_r} = m_y^{\delta_r} + k_s\, m_y^{\delta_{sp}},$$

where

$m_y^{\delta_r}, m_y^{\delta_{sp}}$ – derivatives of the yaw moment due to an angle of rudder and spoiler deflection respectively,

$k_s = \dfrac{\delta_{sp}}{\delta_r}$ – ratio of an angle of spoiler to an angle of rudder deflection.

According to the presented on fig. 2 dependence of a derivative of the yaw moment due to an angle of rudder deflection (at zero slip angle) with respect to the wind tunnel flow velocity effectiveness of a rudder considerably decreases in view of structural flexibility.

Slightly less effectiveness of a spoiler and even less – effectiveness a spoiler-rudder system drops. Apparently, effectiveness a spoiler-rudder system essentially above effectiveness of separately taken rudder and a spoiler. But it less than their simple sum.

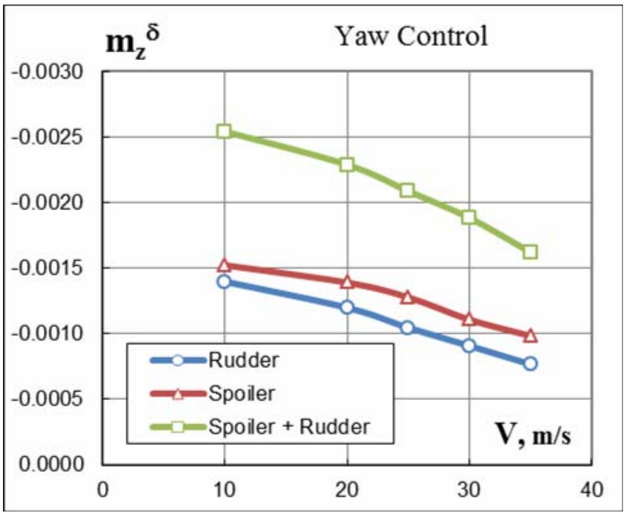


Fig. 2 Effectiveness (derivative of yaw moment coefficient to angle of deflection) of different controls as a function of wind tunnel flow speed

In regard to influence of an angle of slip it practically is absent over the range of small angles (from -4° to +4°), and at the big angles has the following feature: it is significant for a yaw rudder and is almost hardly noticeable for a spoiler, and also a combination a spoiler-rudder.

Interesting results are obtained at tests in the subsonic wind tunnel of elastically scaled model of the Il-114 airplane, presented on the fig. 3

The fin and rudder form are distinctive, and effect of an angle of slip has appeared stronger.

Effectiveness of a yaw rudder with flow velocity growth in the investigated range of flow velocity (V=10-40 m/s) at the fixed angle of attack α=1°41' decreases at all values of an angle of slip approximately for 30 %.

Effectiveness of separately deflected spoilers with flow velocity growth practically does not decrease, and (unlike a combination a spoiler-rudder) it does not depend almost on a slip angle.

At negative angle of slip effectiveness of a spoiler at low wind tunnel flow speeds (V=10 m/s) it is almost only insignificant (on 10-15 %) less than effectiveness of a combination a spoiler-rudder while at positive angles of slip it is less on 30-40 %.

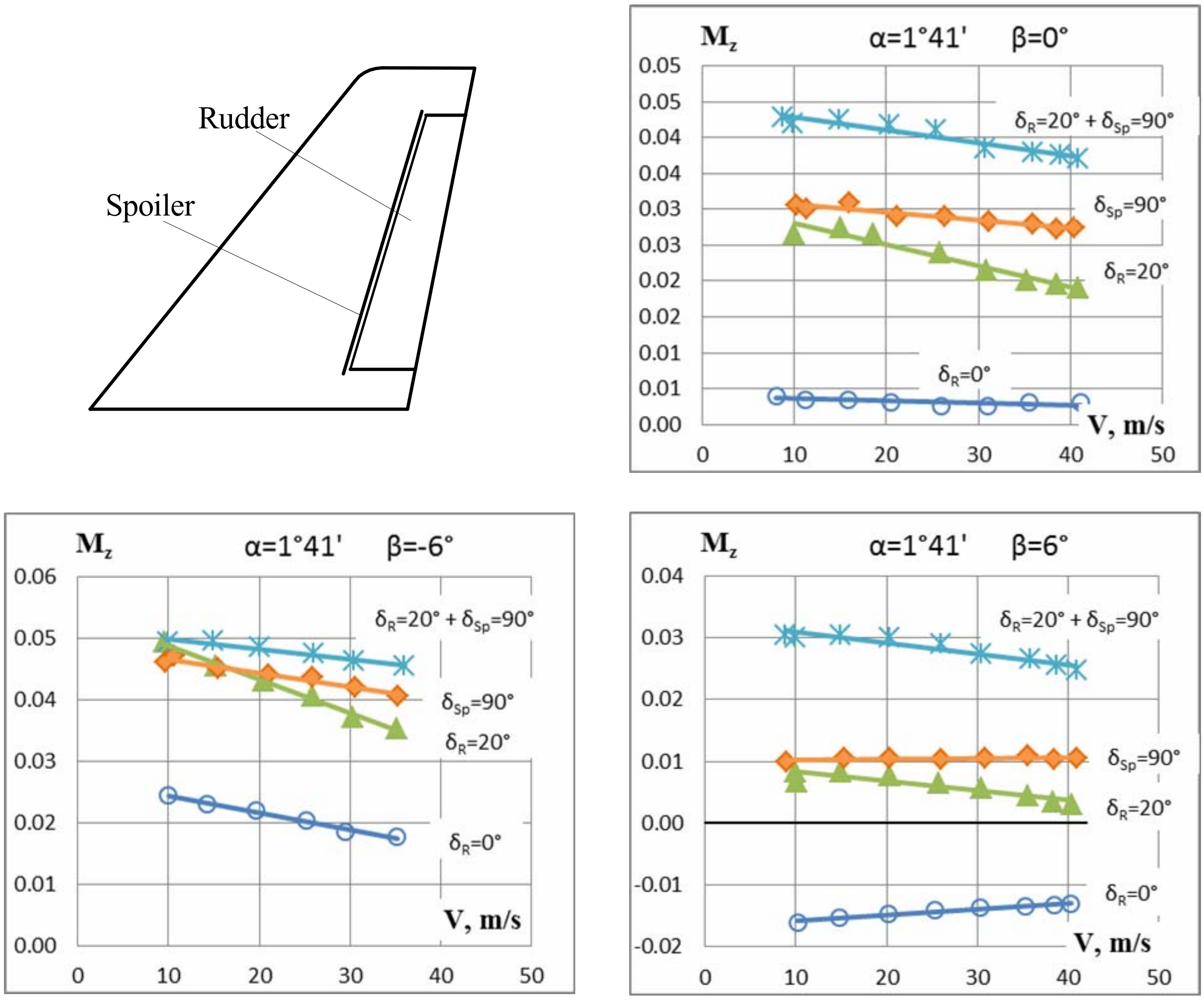


Fig. 3 Effectiveness (yaw moment) of different controls deflected on fixed angles as a function of wind tunnel flow speed at constant slip angle and angle of attack

3 Results of investigation of effectiveness of a spoiler-rudder at transonic speeds

Influence of air compressibility (or Mach number) on aerodynamic characteristics of a combination the spoiler-rudder could be inferred by the results on fig.

They were obtained in the supersonic aerodynamic wind tunnel on elastically scaled model of a fin of aerospace airplane "Buran".

Range of investigated Mach numbers M=0.6-1.1 and relation to Mach number of dynamic pressure q=f (M) are shown on fig. 4.

Apparently, effectiveness of a yaw rudder with dynamic pressure and Mach number growth essentially decreases.

Side force and rolling moment increments at rudder deflection on 5° at M=1.1 and the maximum investigated value of dynamic pressure q are equal to zero, and the yaw moment increment decreases in the investigated range of q and M approximately in 3 times.

In this case the spoiler has been installed only spanwise the lower section of rudder (fig. 4).

Nevertheless, it has given an essential increase to effectiveness of a rudder. At Mach

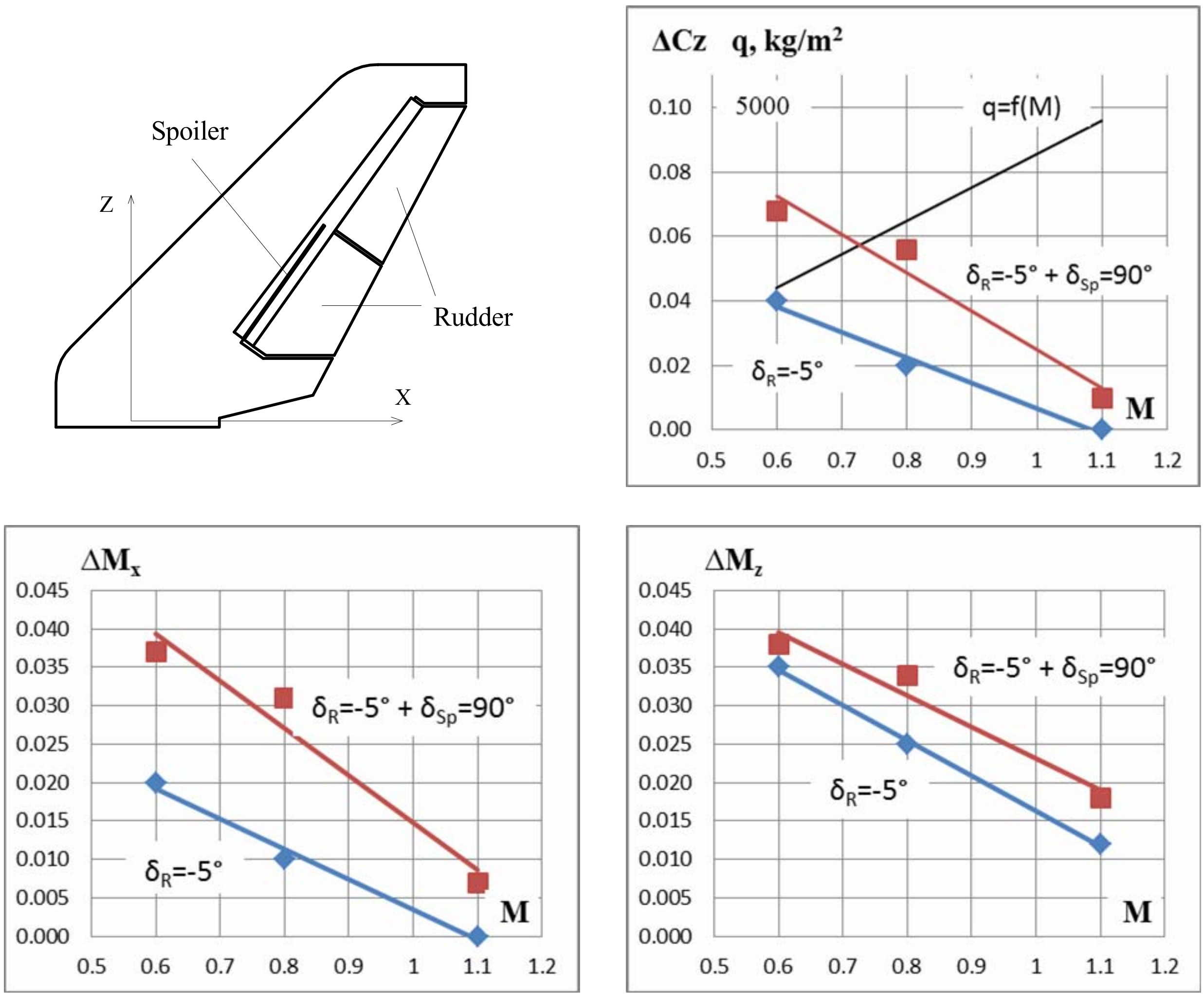


Fig. 4 Effectiveness (side force, yaw and roll moment) of rudder and spoiler-rudder system at constant angles of deflection increment) versus Mach number

number M=1.1 and the maximum investigated value of dynamic pressure this increase (on the yaw moment M_y) equal approximately 35 %.

It can be explained so: due to deflection of spoilers pressure distribution change on a fin chord leads to more favorable (rather than – at deflection of a yaw rudder) torsional fin deformations.

Essential decrease of traditional yaw controls effectiveness is linked with sweep and with rather small chord of a fin box caused, in return, the big chord of rudder.

It is natural, that rather smaller size of a fin box chord is characteristic for planes with double-link rudders, as shown, for example on fig. 5 for An-72 airplane.

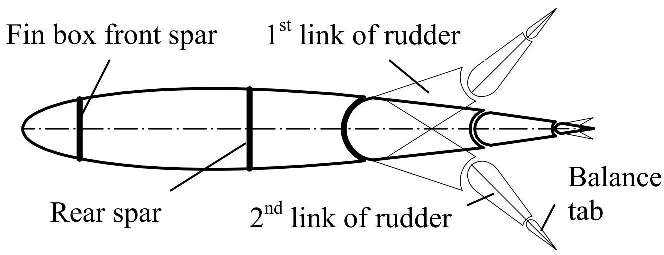


Fig. 5 An-72 fin with double-link rudder cross-section

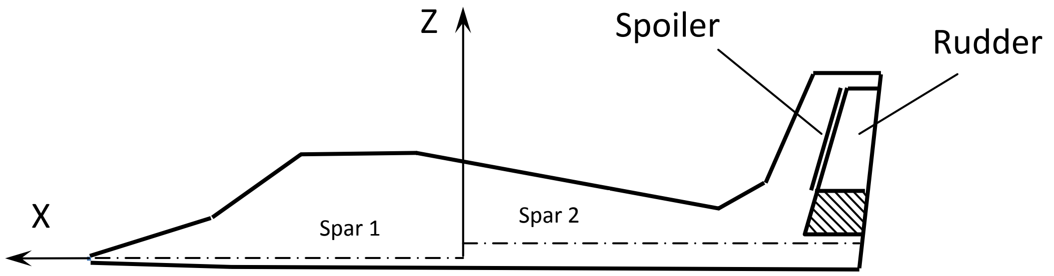
4 About improvement of flutter characteristics

Insufficient stiffness of the fin can become the reason of origin of problems with a flutter (fig. 6). Experience of design of the training aircraft which scheme is displayed on fig. 7 testifies to it.

Necessary increase of the fin stiffness can achieve two ways: 1) increase of a fin box chord at the expense due to decrease of a yaw rudder chord and 2) due to rejection of the lower (shaded) section of a yaw rudder and increase for this score of fin stiffness on this area.

In both cases because of reduction of the area of a rudder there are problems with insufficient efficiency of yaw control. To solve them that is possible, besides, by means of the spoilers working together with rudder of a smaller chord and smaller span (fig. 6), i.e. spoilrudder system.

Apparently, change of yaw angles in the investigated range from -5° to +5° practically does not affect effectiveness spoilrudder system.



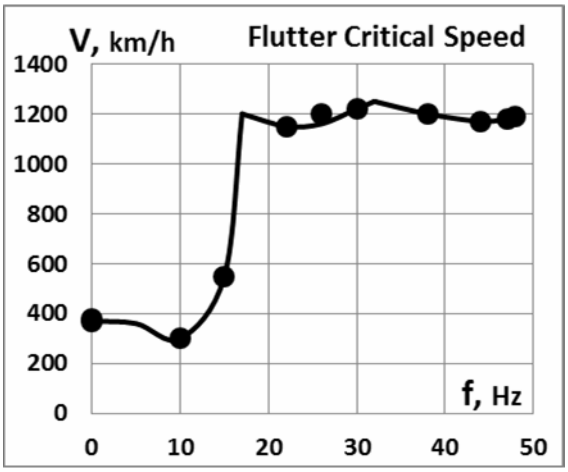


Fig. 6 Flutter critical speed versus yaw rudder frequency

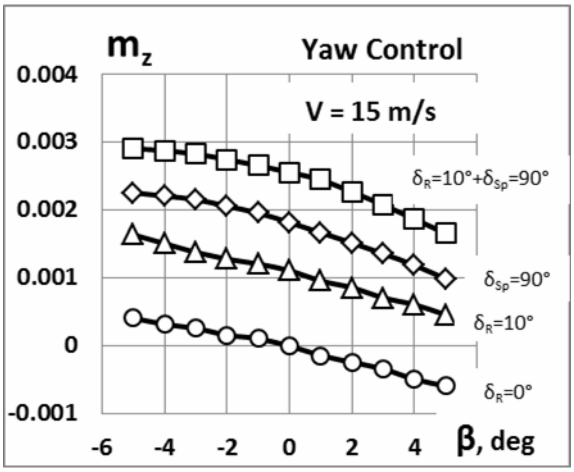


Fig. 7 Effectiveness (yaw moment) of rudder, spoiler and spoiler-rudder system deflected on fixed angles as a function of slip angle at constant wind tunnel flow speed

The analysis of dependence of the yaw moment from a yaw angle m_z=f(β) at fixed wind tunnel flow speed V=15 m/s testifies that spoilers (as deflected separately, and together with a rudder) give an essential increase (to 30-40 %) to efficiency of rudders.

It is especially important if to consider relatively greater unfavorable influence of air compressibility on efficiency of rudder, in comparison with corresponding influence on efficiency of spoilers.

5 Results of some calculated investigations of spoiler-rudder system effectiveness.

As it was already marked, smaller dependence of control efficiency on elasticity of a wing structure for spoiler-aileron system in comparison with traditional aileron (or yaw rudder) is caused by more favorable pressure distribution on a chord.

It is possible to judge it by results of calculations shown on fig. 8. For known model BACT [8] (Benchmark Active Control

Technology) of the NASA Langley research center comparisons of differential pressure distribution ΔC_p on a model chord are executed for deflected aileron and spoiler - separately and together. Calculations are executed by L.Teperin with using of ANSYS CFX software; the mathematical model is agreed with experimental results from paper [8].

It is visible from drawing that at a joint deflection of aileron and a spoiler not only the total value ΔC_p is augmented, but also the pressure centre is considerably shifted forward, and it is closer to an elastic axes that favorably influences on efficiency of control, taking into account elasticity of a structure.

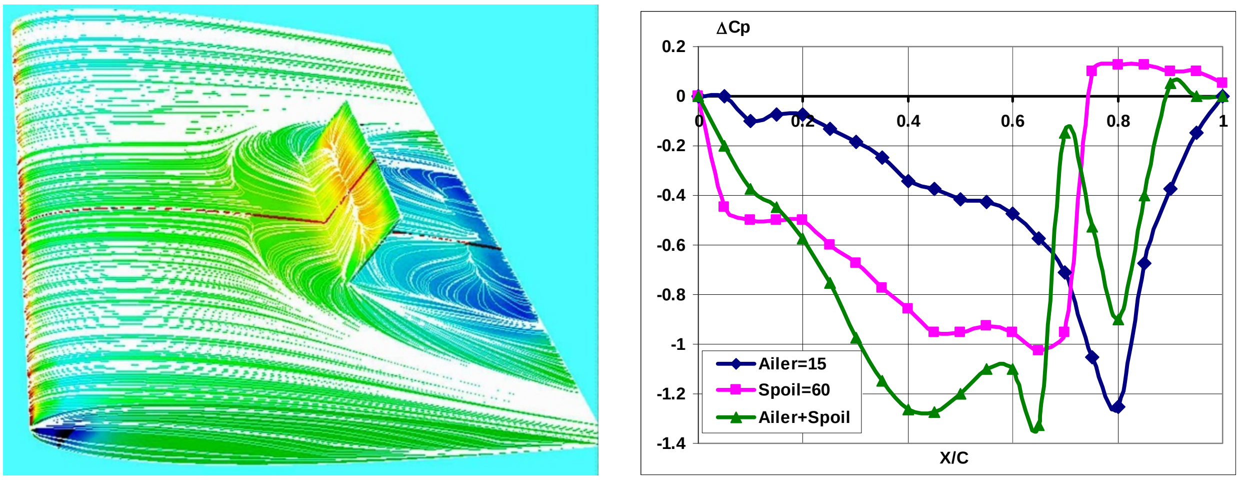


Fig. 8 Calculated flow pattern; M=0.77. Differential pressure distribution on a chord of BACT model for deflected aileron and a spoiler - separately and together

Other example of investigations of efficiency of a spoiler with aileron is shown on fig. 9. The theoretical model of long range passenger airplane with aileron in an end part of the wing and a spoiler ahead aileron on the base of a complex of programs ARGON is considered.

The spoiler chord is selected from a condition of its greatest efficiency taking into account features of the selected primary structure. Optimum there was a variant when it occupies a surface between a wing box and aileron (fig. 9).

It is supposed that there are spoilers on upper and lower surfaces. At a deflection of aileron up (down) the spoiler of the upper (lower) surface proportionally to aileron deflection is deflected: $\delta_{sp}= k_s\,\delta_{ail}$. Total spoileron system effectiveness is led to a unit aileron deflection, thus it is meant that spoilers angles of deflection essentially more than at aileron.

On fig. 9 efficiency of roll control at a separate and joint aileron and spoiler deflection at k_s=3 is shown. It is visible that such system ensures efficient roll control till to limiting high dynamic pressure; the necessary margin on a critical reversal dynamic pressure is achievable.

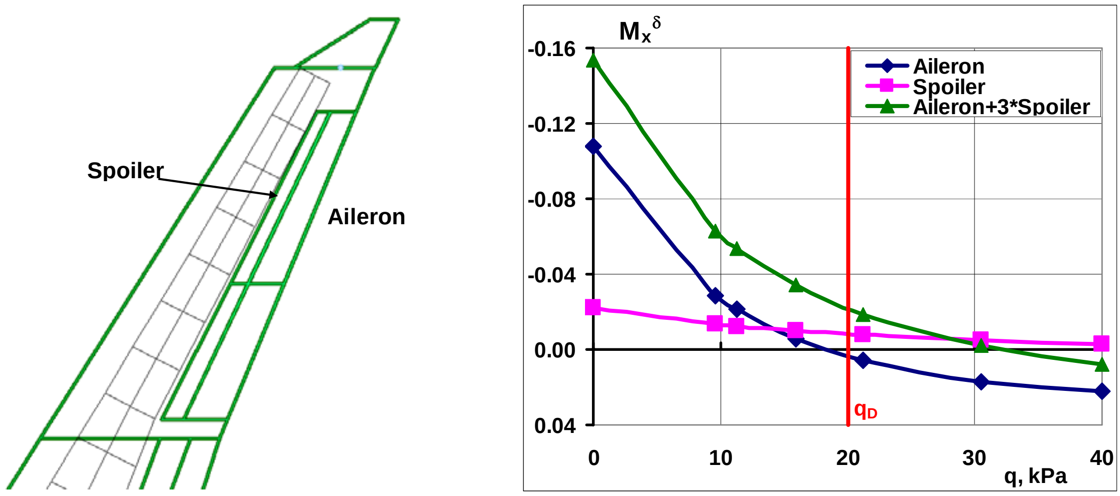


Fig. 9 Influence of elasticity on effectiveness of roll control of the long range airplane project: derivative of rolling moment to deflection of aileron and a spoiler (separately and together) as a function of dynamic pressure at constant Mach number M=0.82

6 About a capability of decrease in structural weight of a fin box

Below on two typical examples the capability of weight reduction of a fin box due to decrease of a chord of a rudder and respective increase in a chord of a fin box is observed.

Torsional stiffness of a fin box for simplicity is schematized as unichamber closed loop in which the wall is so thin on its thickness that it is possible to consider tangential stresses constant and equal to stresses on the middle of a thickness of a wall.

Direction of these stresses – on a tangent to a central line of a wall. In such statement for definition of tangential stresses the Bredt formula is used:

$$\tau = \frac{M_t}{2F\delta},$$

where

M_t – torque moment,

F – the contour area on a central line,

δ – thickness of a wall of a contour.

The torsional moment of inertia is expressed so:

$$J_t = \frac{4F^2}{\oint \frac{dS}{\delta}}, \qquad (1)$$

where

dS – differential of length of an arc of a contour on a central line.

We assume for simplicity a thickness of a wall of a contour of a constant then the torsional moment of inertia will be determined as:

$$J_t = \frac{4F^2\delta}{S}, \qquad (2)$$

where

S – contour perimeter on a central line

On the basis of (2) for NACA0010 profile, with use of characteristic relative sizes of a fin of typical medium range airplane the relation of a non-dimensional torsional moment of inertia of a fin box ($J_t = J_{tors}/J_{0.46}$) to its relative width (x/c) is determined (fig. 10).

Here

x – width of a fin box,

c – local wing chord,

J_{tors} – torsional moment of inertia,

$J_{0.46}$ – torsional moment of inertia for x/c=0.46.

The box beginning (or the position a front spar along chord) is accepted the same, as on medium range airplane. We assume a thickness of a wall of fin box constant on perimeter. We analyze a possibility of fin box stiffness increase due to increase of a fin box chord via the displacement back its rear spar.

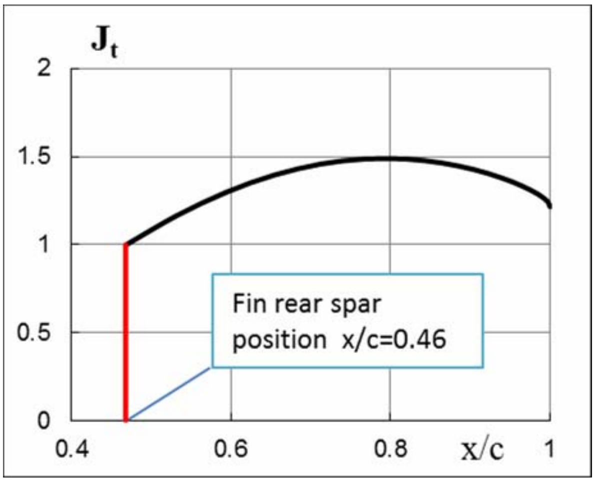


Fig. 10 Non-dimensional torsional moment of inertia of typical medium range airplane fin as a function of fin box width

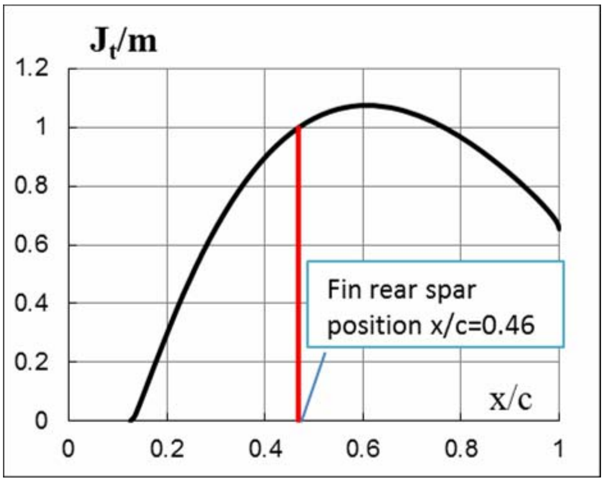


Fig. 11 Ratio of a torsional moment of inertia of typical medium range airplane fin to structural mass of a fin box as a function of fin box rear spar position

Apparently from the plot on fig. 10, at increase in width of a fin box to 0.8 the torsional stiffness of box increases in 1.5 times.

On fig. 11 the ratio of a torsional moment of inertia to structural mass of a fin box ($J_t/m=(J_{tors}/m)/(J_{tors}/m)_{0.46}$) is shown. It can be seen that the increase in width of box till 0.75 is advantageous also on structural mass.

Essentially big capabilities on torsional stiffness increase are observed by consideration of a fin of airplane An-72 with double-link rudders. The typical cross-section of a fin, normal its elastic axes is schematically shown on fig. 5.

The change of a non-dimensional torsional moment of inertia of a fin box ($J_t=J_{tors}/J_{0.4}$) depending on its width is presented on fig. 12.

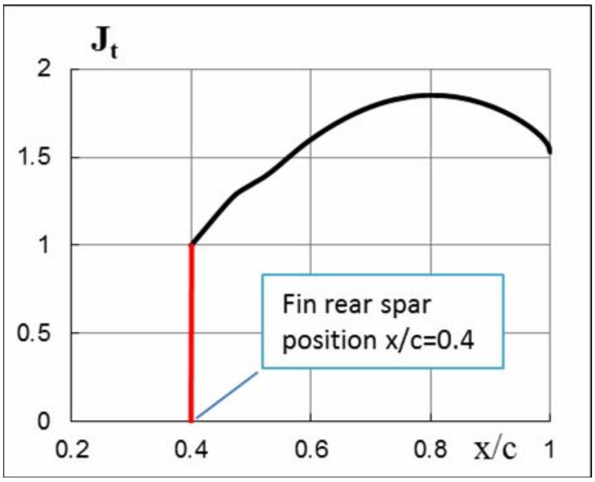


Fig. 12 Non-dimensional torsional moment of inertia of An-72 airplane fin as a function of fin box chord size

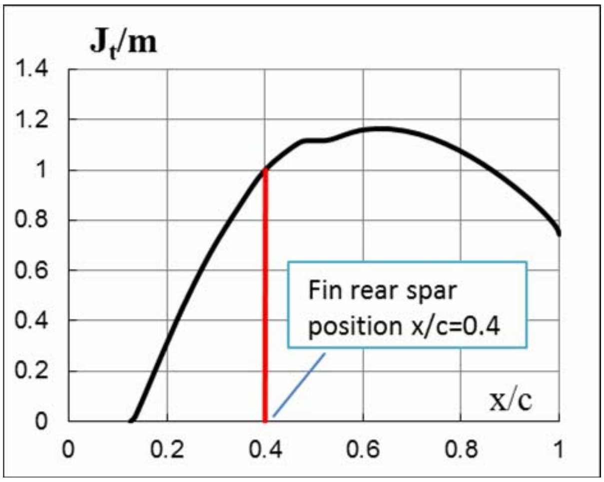


Fig. 13 Ratio of a torsional moment of inertia of An-72 airplane fin to structural mass of a fin box as a function of fin box rear spar placement

That is, torsional stiffness can be increased more, than in 1.8 times, in comparison with stiffness of fin box of An-72.

The structural mass of a fin box thus grows more slowly than torsional stiffness (fig. 13). Thus, on an example of fins of medium range airplane and An-72 is shown that the increase in a fin box width gives essential increase in torsional stiffness with high mass efficiency.

7 Conclusion

The analyzed spoiler-rudder system is development of the active aeroelasticity concept (or active aeroelastic wing).

The central idea of this concept offered in a TsAGI in the beginning of 1960, - application of the specific controls creating at the deviation such of pressure redistribution on a lifting surface at which effect of elastic deformations becomes negative in the minimum extent, or even positive.

It is obvious that such kind investigations, which are include first of all the analysis of aerodynamic characteristics, and also aeroelasticity and strength characteristics, it is necessary to base on the complex multidisciplinary theoretical approach and also to use aerodynamic wind tunnel tests of multi-purpose elastic-dynamically-scaled models.

The presented investigations are based on experience of tests of multipurpose aeroelastic models in various aerodynamic wind tunnels of TsAGI, and also on use of the calculation complex developed in a TsAGI the ARGON of joint theoretical investigations of problems of strength, aerodynamics, systems of active control (systems of decrease in loadings) modern airplanes, and also at the solution of problems of static and dynamic aeroelasticity in a broad range of dynamic pressure and Mach numbers.

It has allowed to show that use of system a spoiler-rudder (including with adaptive elements of a spoiler) opens a potential of increase in a chord of a fin box not less, than on 15 %, appreciable increase in stiffness and weight reduction of a fin structural weight.

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