REVIEW AND OUTLOOK ON ACTIVE AND PASSIVE AERODELASTIC DESIGN CONCEPTS FOR FUTURE AIRCRAFT

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Abstract

This paper presents an overview of past, on-going, and planned European research and development activities in aeroelastic design, where the main objective is an adaptive change of the elastic shape of the airplane by active deformation of the structure. A detailed overview will be given on experiences in Russia, as well as a current European research project. One very new type of active aeroelastic concept, based on an adaptive stiffness attachment of all-movable aerodynamic surfaces, will also be discussed. Some results from preliminary analytical and experimental studies in the UK and in Germany will be given.

The paper concentrates on static aeroelastic effects. It is intended to ask some critical questions about these concepts and give some answers in order to identify directions for future developments. Unfortunately, there are many more questions than answers at the moment.

1 Introduction

Revolutionary, totally new aircraft design concepts are proposed today. The expression “Morphing Aircraft” is used to describe concepts intended to smoothly adapt the external shape of an aircraft to changing mission requirements. These concepts are mainly based on the believe that new, “smart” materials will soon offer the required characteristics to create such aircraft structure that, as an example, are able to change the wing aspect ratio by 200%, or the wing area by 50% [1].

No matter how realistic such ideas are, for example with respect to the inherent stiffness that an aircraft structure needs from strength requirements, advanced materials properties, and physical laws for light weight structural design, the new aircraft designs will either suffer from aeroelastic impacts, or they can exploit them in a beneficial way.

All active aeroelastic concepts can be classified by the types of devices that initiate static-aeroelastic deformations of the structure: aerodynamic control surfaces, adaptive stiffness systems for the attachment or actuation of an aerodynamic surface, and active structural components and materials. The related group of active structures concepts concentrates mainly on the creation of large structural deformations – without special considerations about aeroelastic effects. In this case, the aeroelastic impacts from these concepts needs to be addressed.

Whereas Active Aeroelastic concepts are as old as aviation, the systematic research to exploit them on different kinds of airplanes started in Russia as early as the 1960s.

"Active Aeroelastic Aircraft Structures" (3AS) is a new RTD project, partially funded by the European Union under the Key Action Aeronautics of the "Competitive and Sustainable Growth" RTD Programme.' It is aiming at improving aircraft efficiency by means of exploiting aeroelastic deformations of the structure in a beneficial way. The project consortium consists of 15 partners from the Aeronautical industry, research establishments, and universities: ALENIA (Italy), EADS-CASA (Spain), EADS-Deutschland, GAMESA DESARROLLOS AERONÁUTICOS (Spain), Saab AB (Sweden), Centro Italiano Ricercha Aerospaziali S.C.p.A. (Italy), Deutsches Zentrum für Luft- und Raumfahrt e. V. (Germany), Instituto Nacional de Tecnica Aerospacial (Spain), Vyzkumny a zkusebni letecky ustav, a. s. (Czech Republic), Kungl Tekniska Höskolan (Sweden), Instituto Superior Técnico (Portugal), University of Manchester (United Kingdom), Politecnico di Milano (Italy), TECHNION research and development foundation Ltd. (Israel), and, as a major subcontractor, the Central Aerohydrodynamic Institute (TsAGI) from Russia. A project Internet homepage is established at: www.3AS.org.

The project started in April 2002 and it has a total duration of three years. Major wind tunnel tests are scheduled to start after 18 months. More details, about the applications of MDO concepts can be found in [1].

2 Active and Passive Aeroelastic Design Concepts in Russia

In the beginning of the sixties, the urgent need to increase stiffness of thin wings of airplanes Myasishchev M-50 and Tsybin R-020 appeared to decrease the influence of elastic structural deformations on aileron effectiveness. As it turned out, a large increase of weight was required for the solution of the aileron reversal problem, even for the case of the optimal choice of structural stiffness. Just then, after hopeless struggles with negative flexibility effects, the paradoxical decision was proposed that negative impacts from the structure must be declined, and that the flexibility must be used in a beneficial way[1]. Schematically, the proposal was, that a control surface must be located far from conventional stiffness axis of a lifting surface. In that case, the structural stiffness of the main lifting surface may be even decreased.

Special outboard ailerons were for the first time designed and tested in 1962 in the high-speed wind tunnel at TsAGI for elastically scaled models of the M-50 wing, later for the models of R-020, MiG-25, Yak-28. They require an outboard launcher, as indicated in the model of Figure 1 for the M-50, nevertheless they entirely confirmed the effectiveness of the concept. Moreover, flight tests demonstrated the use of structural elasticity of the Yak-28 wing by means of the outboard aileron to solve reversal problems for new aircraft with increased range of flight speeds (Figure 2).

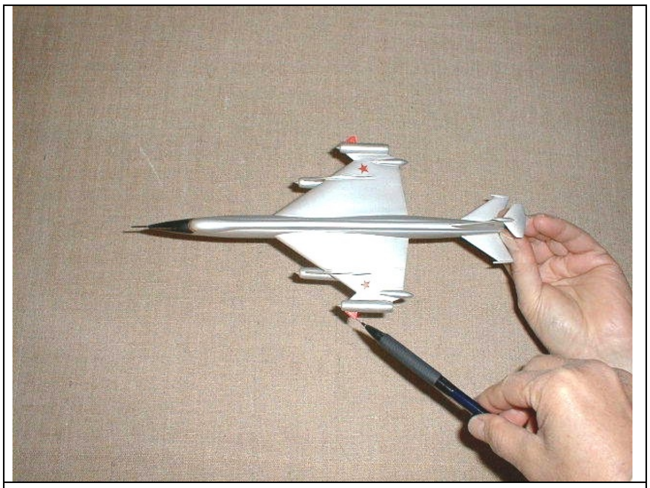

Figure 1: Additional roll control surfaces on wing tip launcher for M-50

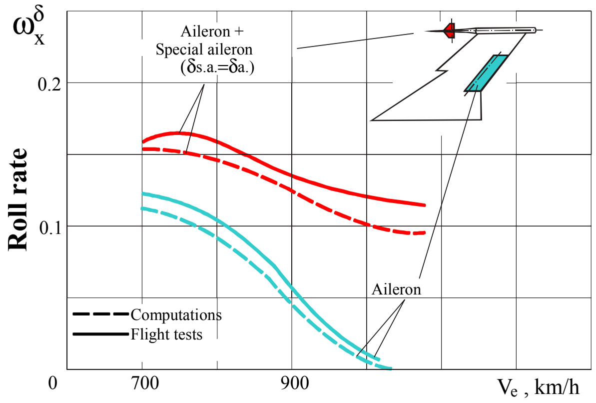

Figure 2: Flight test results for roll rate improvement with leading edge device (for Yak-28)

The traditional approach caused an augmentation of skin thickness at the wing root of more than 10 mm. Application of outboard ailerons gave possibility to even decrease the skin thickness.

In 1963 research on other control surfaces (differentially deflectable leading edges) started [2]. They also use structural flexibility but they need no outboard launcher. They were named for brevity as the fore-aileron (for the wing in Figure 3) and fore-rudder (for the vertical tail) and they did not change the wing and the tail planform. Three elastically scaled models of different aspect ratio wings were tested in wind tunnel TsAGI (Figure 3).

A characteristic peculiarity of each of the three tested models was a low critical reversal dynamic pressure. Direct WT tests have shown that with dynamic pressure increasing the effectiveness of the fore-ailerons increased too for all three models, whereas the effectiveness of the trailing edge ailerons decreased considerably, as indicated in Figure 3.

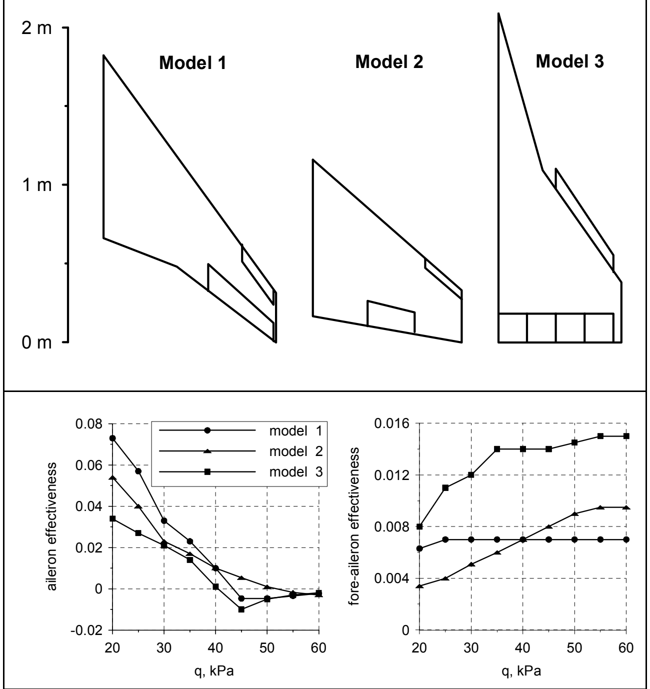

Figure 3: Three elastically scaled models. Roll effectiveness for the trailing (left) and leading edge surface (right)

In the next example, active aeroelastic concepts for design of a supersonic transport aircraft (SST) is considered. Theoretical analysis was carried out using the software package ARGON, which was developed by TsAGI for the practical realization of multidisciplinary design optimization problems. The knowledge of aeroelastic characteristics for the SST design is even more important than for conventional aircraft. The complexity of the problem is mainly characterized by very thin airfoils, needs for: a high weight effectiveness, two cruise flight regimes (subsonic and supersonic), and the structural heating. It is important to understand the peculiarity of the aeroelastic behavior of the structure during the very early design stages. Only this will give the possibility to analyze different ways for solving arising problems.

Analyses showed that the range of high subsonic speeds is critical from the viewpoint of aeroelasticity. The SST model has low flutter and reversal critical dynamic pressures. For the airplane with fuel on board, the main trouble is bending-bending flutter mode. Such flutter mode can be called a cupola-type mode, i.e. the fuselage and the wing oscillate almost in phase. The second mode is a bending-torsion flutter of the wing. For the empty airplane, one more mode of bending-bending flutter appears to be critical. This mode was called a saddle-type mode, as the fuselage and the wing oscillate in the contra-phase.

To increase the flutter stability, several different measures are required. As it was expected, the engine movement forward resulted in the increase of the flutter boundary of the cupola-type mode. At the same time, as can be seen in Figure 4, the dynamic pressure values of the two other flutter modes do not practically depend on the engine location.

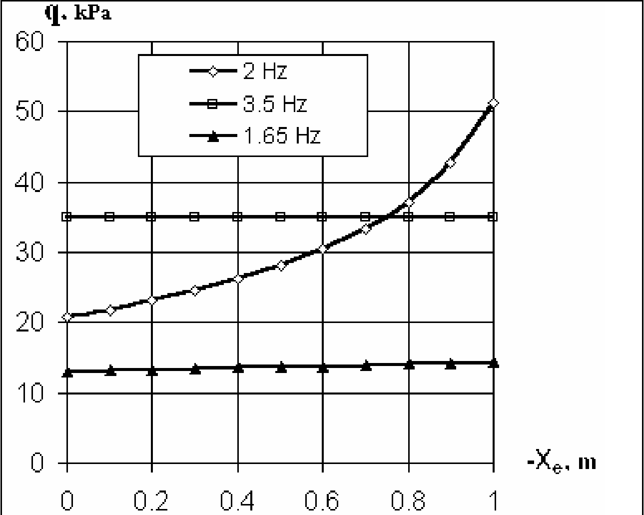

Figure 4: Flutter boundary as a function of engines location for first three symmetric flutter modes

To increase the dynamic pressure of the bending-torsion mode it is sufficient to add on the leading edge tip a small balance mass of 60kg. In this case however, the dynamic pressure of the saddle-type mode decreases even more, as it results in a smaller wing bending frequency and it brings the fuselage and the wing bending frequencies closer to each other. For the saddle- type mode, the most effective means for flutter improvement is the determination of the optimal fuselage stiffness (Figure 5). The above processes are attractive, mostly because they do not require additional structural weight, except a little balance mass on the wing tip.

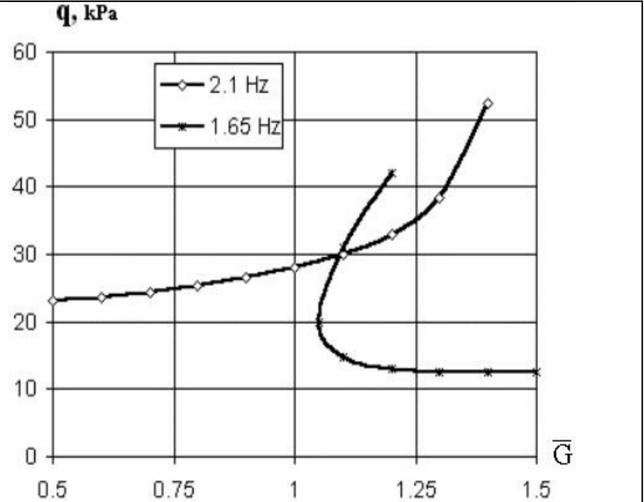

Figure 5: Flutter dynamic pressure as a function of relative fuselage stiffness

The comprehension of the nature of dynamic instabilities for each flutter mode allows effective and original solutions to be obtained using the optimization method as well as guidance from engineering experience. Furthermore, there are various ways to increase flutter characteristic speeds. The most perspective approaches amongst the various ones considered are those that can improve simultaneously both dynamic and static aeroelastic characteristics. Proceeding with such a requirement, two types of wing tip control surfaces were proposed: a wing tip aileron and an additional outboard aileron located out of the wing. In the first case the ordinary wing tip (3 meters span) was replaced by an elastic control surface. Four variants are represented in Figure 6, three new variants of the leading edge sweep angle χ_0 (**a, b, c:** -40°, -18°, 0°) are considered together with the initial variant **d**: χ_0= +51° for the case of clamped wing.

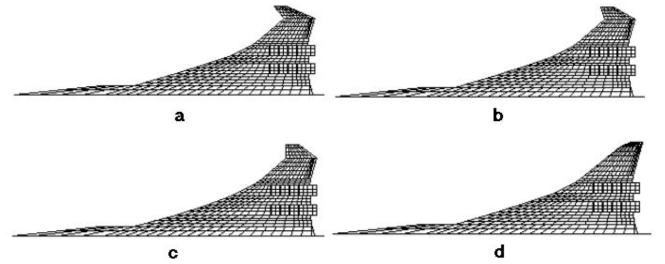

Figure 6: Four variants of wing tip control surfaces

Figure 7 shows the value of the critical flutter dynamic pressure with respect to leading edge sweep angle. It was obtained from numerical research that the application of the straight (χ_0=0°) leading edge wing tip gives the highest flutter dynamic pressure in comparison with the other variants.

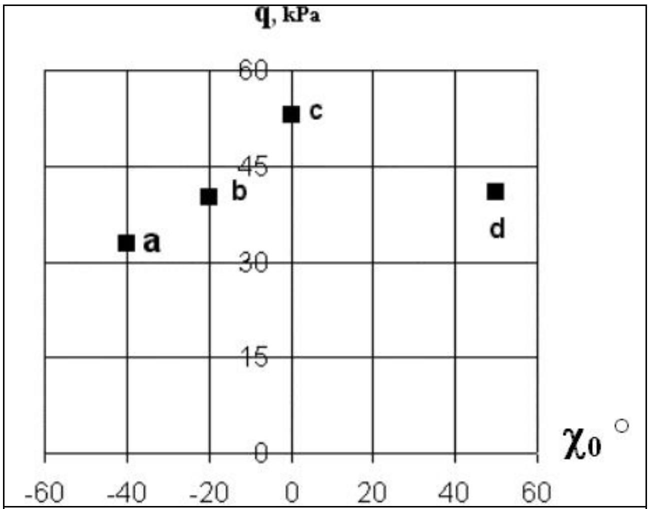

Figure 7: Flutter boundary as a function of leading edge sweep angle for four variants of wing tip control surface

In the second case the flutter of the wing with the additional outboard aileron was investigated. The aileron was clamped on the launcher, which length equals the wing tip chord. Three variants of the aileron location were considered (Figure 8): LE-variant - outboard aileron is ahead of the wing; TE-variant – outboard aileron is behind of the wing; LTE-variant – both outboard ailerons.

The area of the outboard aileron is 0.1% of the wing area, center of gravity is located ahead of the rotation axis, mass is changed from 15 kg to 30 kg. The obtained results show the influence of the outboard aileron’s eigenfrequency (“partial frequency”) on the flutter speed for LE and TE- variants (Figure 9). The heavier forward aileron is effective at small Eigenfrequencies, and the lower weight aft aileron is preferable from the viewpoint of flutter at high aileron (attachment) stiffness.

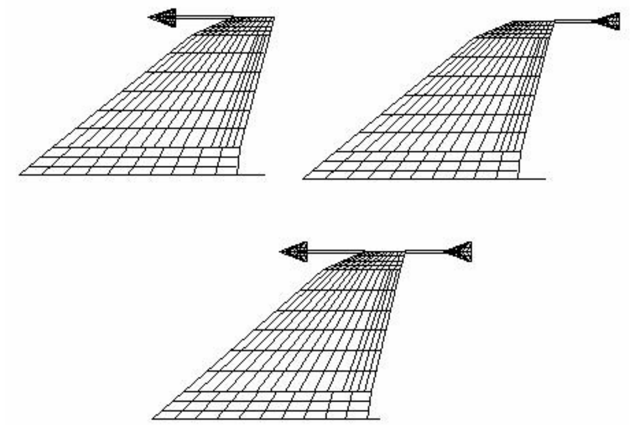

Figure8: Three variants of additional outboard aileron location: LE, TE, LTE

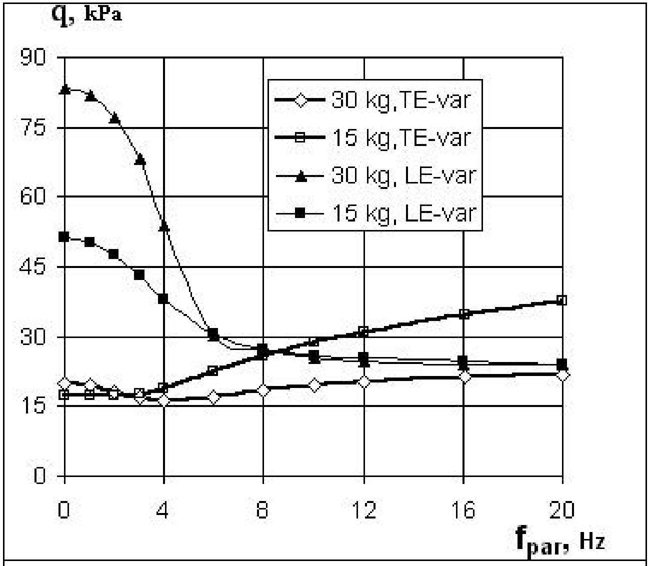

Figure 9: Flutter boundaries as a function of the Eigenfrequency of the additional outboard ailerons for LE and TE variants

Ensuring adequate static aeroelastic characteristics for the SST configuration is of similar importance. Numerical results show that the elasticity of the structure has considerable influences on the aerodynamic characteristics. These are:

- a decrease of the lift force,
- the degree of static stability (forward shift of the aerodynamic center),
- effectiveness of control surfaces, especially in roll.

As was expected for this structure there is no aeroelastic divergence tendency. The mass distribution also has essential effects on the aerodynamic derivatives for the elastic aircraft.

To increase the stiffness in this case requires unacceptable structural weight. Thus, application of additional control surfaces is more attractive for ensuring adequate characteristics of static aeroelasticity. Sweeping the wing tips allows reduction in the degradation of the lift curve slope coefficient C_L^α and to control the degree of static stability $(x_F - x_{c.m})/c_{mac} = -m_L^\alpha / C_L^\alpha$ (c_{mac} is the mean aerodynamic chord). It is illustrated in Figures 10 and 11 for high subsonic speeds. (The variants of sweep angle correspond to Figure 6).

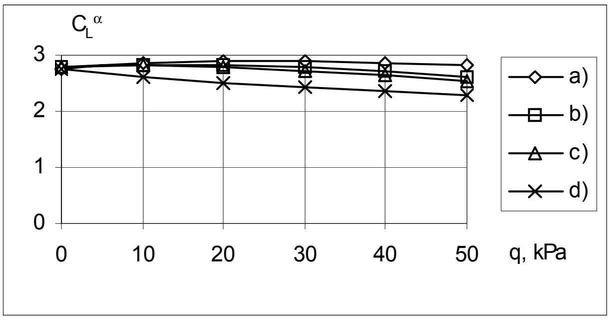

Figure 10: Lift slope coefficient of elastic SST for different sweep angles

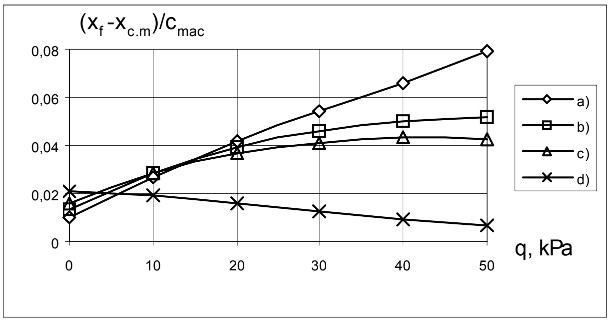

Figure 11: Influence of structural elasticity on the degree of static stability for different sweep angles

The wing tip control surface increases the roll control effectiveness for a sweep angle of --40° (variant **a**). The rolling moment coefficient derivative with respect to the tip aileron deflection angle m_x/δ_{tip} even increases due to structural elasticity (Figure 12).

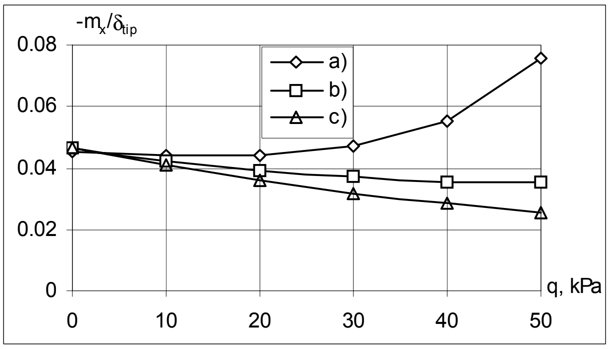

Figure 12: Influence of structural elasticity on the roll control effectiveness for different sweep angles

The effectiveness of the outboard ailerons considered above on the rigid wing is negligible in comparison with the effectiveness of the trailing edge ailerons (Figure 13). Nevertheless the outboard ailerons on the elastic wing (with acceptable control laws) improve essentially the aircraft controllability due to the additional forces arising from favorable wing twist. The effectiveness of the outer section of the trailing edge aileron (δ_2) versus dynamic pressure q is shown in Figure 13 (curve 1). The effectiveness of the outboard ailerons is also presented in this figure: curve 2 – variant LE, curve 3 – variant TE (see Figure 8). The deflection of both outboard ailerons essentially improves roll control as illustrated in Figure 13, curve 4. Here additional surfaces are deflected by law: $\delta_{LE}=2\delta_2$, $\delta_{TE}=-2\delta_2$.

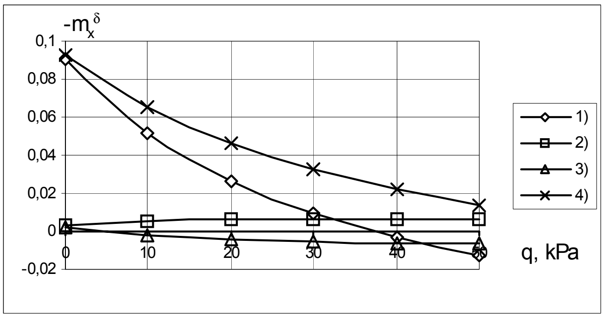

Figure 13: Influence of structural elasticity on the roll effectiveness of outboard ailerons

Fore-ailerons can be considered as tools to ensure roll control (Figure 14). It gives the possibility of using structural elasticity for increasing roll moment at critical flight regimes.

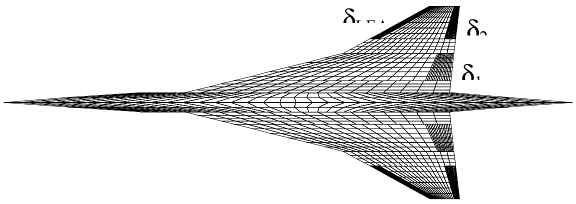

Figure 14: Location of ailerons (δ_1, δ_2) and fore-aileron (δ_{LEA})

Fore-aileron effectiveness is small at low dynamic pressure (rigid structure) but its efficiency sufficiently increases for high dynamic pressure (Figure 15).

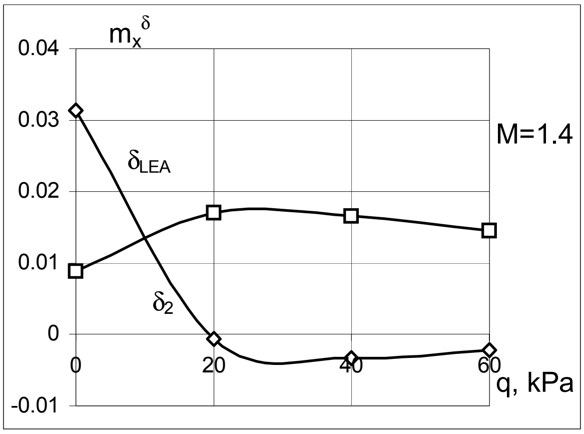

Figure 15: Roll effectiveness of outer aileron and fore-aileron

Different combinations of the trailing edge ailerons and fore-aileron deflection were investigated. Figure 16 shows roll rate at limit dynamic pressure for unit control deflection with four different control laws: 1 - δ_1; 2 - $\delta_1+\delta_2$; 3 - $\delta_1+\delta_2+\delta_{LEA}$; 4 - $\delta_1+\delta_{LEA}$. It is seen that using of the fore-aileron together with the inner aileron increases the derivative of roll rate with respect to deflection angle of the aileron ω_x^δ up to 2°/sec per degree of the aileron deflection. It is acceptable for this type of aircraft.

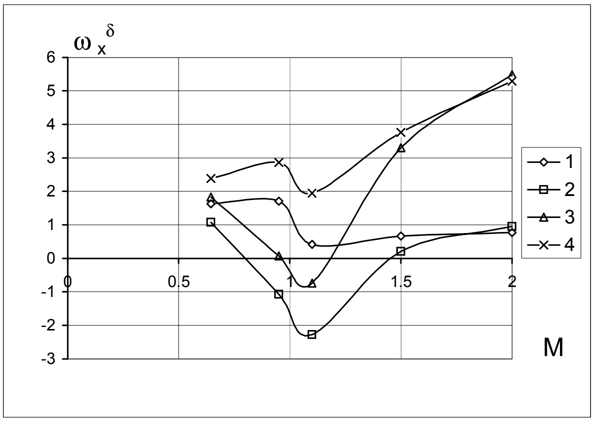

Figure 16: Roll rate for unit aileron deflection at different control laws

3 The European 3AS project

The 3AS project is aiming to cover a wide range of potential Aeroelastic Concepts. For this reason, the designs can only be analyzed and optimized in a preliminary manner, rather than investigating all aspects of all involved disciplines in depth, as would be required for a real airplane design. In order to at least look at all important design aspects, a so-called "experts panel" with members from the different disciplines will review the different concepts at important phases of the design process and for the planned tests. The following different types of airplanes will be investigated in 3AS, depicted in Figure 17:

- a long range, wide-body, 4-engine transport airplane,
- a 3-surface commuter jet,
- a high aspect ratio UAV for high altitudes,
- a small RPV.

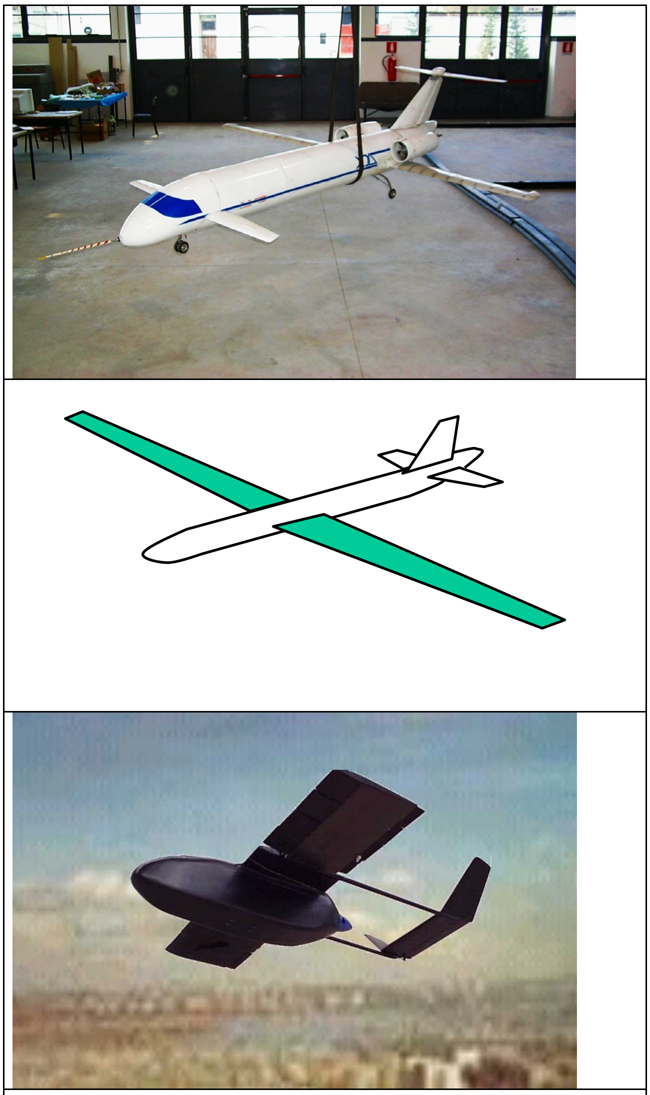

Figure 17: Configurations for the 3AS project

The long-range transport airplane is designated the "European Aeroelastic Research Wind Tunnel Model" (EuRAM). An already existing low speed wind tunnel model serves as the baseline configuration. The wind tunnel model has a length scale of 1/10, which gives a span of almost 6 meters. The velocity scale is also 1/10. Based on this design, a full size aircraft analysis model will be established. The following concepts will be applied to this model:

- new control surfaces at the wing tip, forward of the elastic axis, to adjust the flexible wing deformation to the optimum shape for minimum induced drag,
- modification of the inboard aileron by a new kind of structure that allows large deformations at small internal forces, in order to create a more continuous deformed shape, thus improve achievable control forces,
- replacement of the existing vertical tail by a smaller, all-movable surface with variable rotational attachment stiffness in order to provide large stabilizer and control forces at all speeds by means of creating higher forces in the aeroelastic deformed compared to the rigid case.

The winglet configuration offers the advantage to incorporate an additional control surface at the wingtip more easily, and additional aerodynamic advantages seem to be possible. The initial design efforts will concentrate on finding the proper size and shape of the wing tip surface, which allows adjustment of the wing deformation for minimum induced drag. This requires also a look at the rigid aerodynamic impacts of this additional surface, if it is positioned outside of the wing geometry. This requires a trade-off between the additional friction drag, gains in the induced drag, if the span of the baseline wing is increased by this surface, and interference effects between the additional surface and the winglet.

The "Selective Deformable Structure" (SDS) concept is based on a patent from TsAGI [Ref 5]. The principle is shown in Figure 18. The design and application to the EuRAM configuration will mainly be investigated by TsAGI, while GAMESA will concentrate on the design and full-scale static test applied to the wing and aileron for a commuter jet.

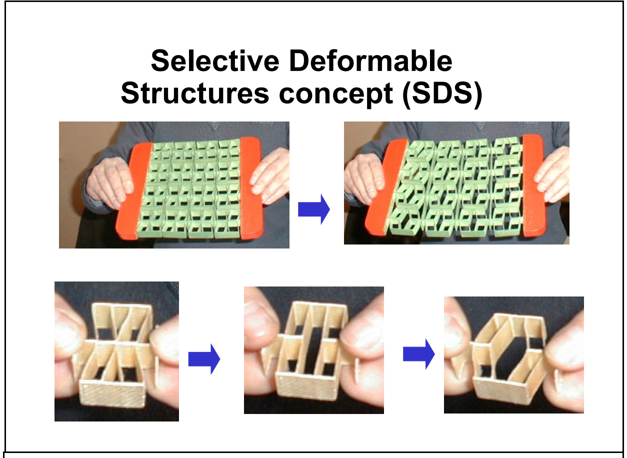

Figure 18: SDS concept

Partner INTA will investigate the potential aerodynamic benefits. This concept will need special attention in the structural description at the macro-level as well as at the micro-level. Several active structures and materials concepts will be applied to the other configurations.

4 All-Movable Stabilizer Surface with Adaptive Rotational Stiffness

The two key functions of an aircraft's vertical tail and rudder have to provide are lateral stability and manoeuvrability about the yaw axis. Traditional designs have large surface areas, with heavy, stiff internal structures. In order to design a reduced size vertical tail, high aeroelastic effectiveness has to be provided at high and low speed. This goal can be achieved by an integrated design approach, where a smaller size, all-movable vertical tail is fitted with a root attachment. The rotational axis is located behind the elastic axis, as indicated in Figure 19, and the torsional stiffness can be adjusted to the flight condition: low for low speed, and high for high speed.

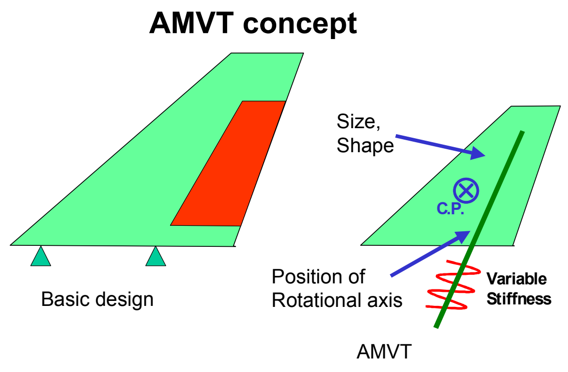

Figure 19: Active All-Movable Vertical Tail concept

Compared to other Aeroelastic design concepts that exploit aeroelastic benefits only at high speeds, this concept exploits aeroelastic effects throughout the whole flight envelope, as indicated in Figure 20. The reduced size will result in lower structural weight for the tail, reduced bending moments due to the smaller span, and reduced friction drag from the smaller surface.

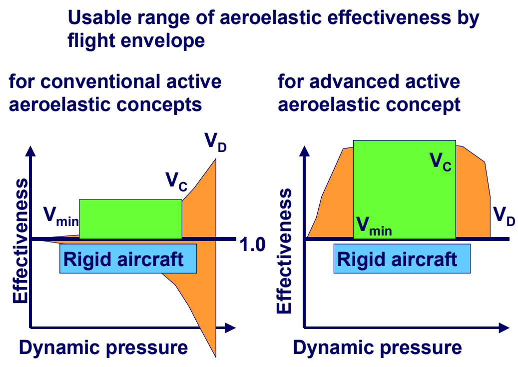

Figure 20: Advantage of AMVT concept compared to fixed-root surface concepts

Figures 21 and 22 show example fin efficiencies that were obtained for a typical all-moving vertical tail with varying stiffness. Note that in the first case the attachment point is forwards, and the resulting efficiencies are less than one. In the latter figure, the attachment is further aft, and this results in efficiences greater than one.

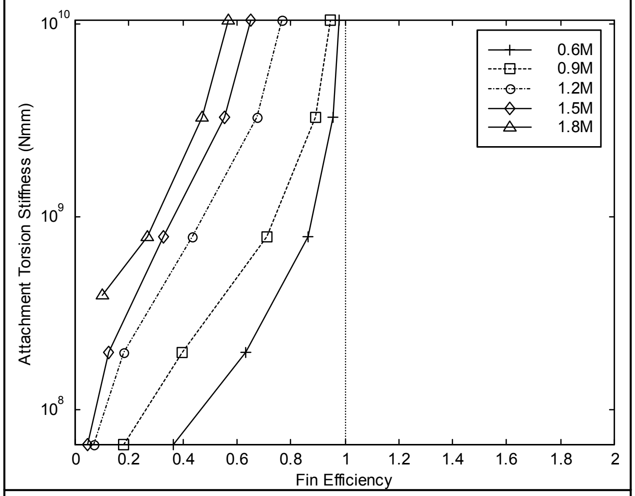

Figure 21: Fin Efficiency VS Torsional Stiffness for 1500mm Attachment Point

The 3AS project will develop "Adaptive Stiffness Attachments" and consider this concept in terms of global designs using MDO [6,7]. A number of preliminary analytical and wind tunnel tests have been performed, using the model shown in figure 23. Reasonable agreement has been found, as shown in figure 24.

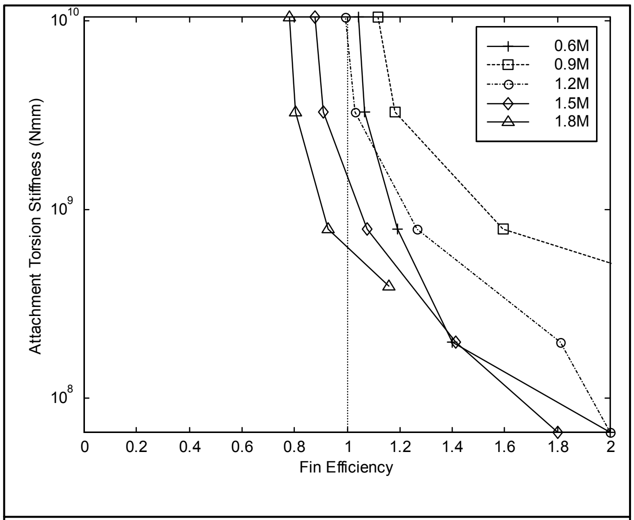

Figure 22 Fin Efficiency VS Torsional Stiffness for 2300mm Attachment Point

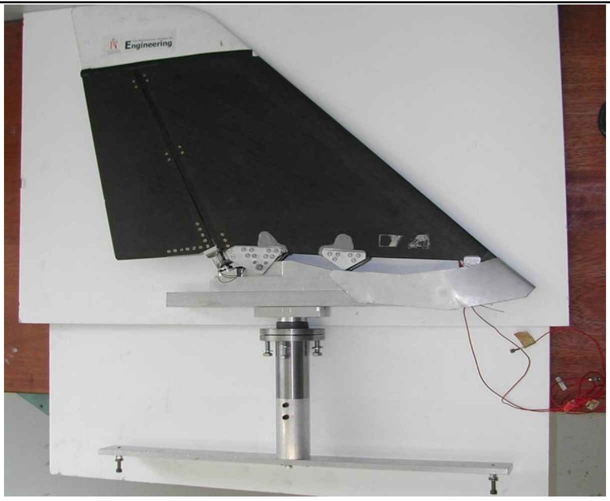

Figure 23. Wind Tunnel Model with Adjustable Attachment Position and Stiffness

5 Conclusions

Some aspects of active aeroelastic concept had been already proposed in the 1960s. Nevertheless, even nowadays, the knowledge in this area has not been systematically categorized. In this paper, an attempt has been made to analyse the active aeroelastic concept in the relation to multidisciplinary design. The use of a variety of different concepts have been considered. The results obtained are promising, however, for their practical implementation, the development of methods, algorithms, software, analytical and experimental investigations should be carried out. Therefore it is advisable to unite the effort of skilled specialists from different aeroelastic schools in order to obtain more knowledge and experience for practical design implementation.

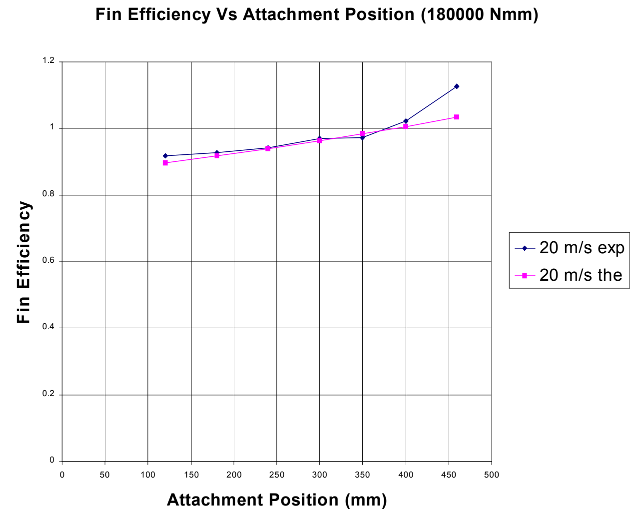

Figure 24. Comparison of Experimental and Theoretical Fin Efficiencies

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