Aeroelastic considerations and technology drivers in the design of the rear fuselage and tails of commercial aircraft

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Abstract

The main functions of the empennage group in the classical aircraft configuration are to provide restoring aerodynamic forces in response to perturbations in the aircraft attitude (stabilising function) and to generate control forces to change the flight trajectory of the aircraft (control function).

The stabilising function requires a high lift gradient coefficient of the tail surfaces which is associated to planforms of high aspect ratio. However, the stall angle –important for the control function- and the flexible lift gradient are reduced as the aspect ratio increases. Balancing the contradicting requirements on the tail functions in order to obtain an optimum configuration requires advanced multidisciplinary analysis and optimisation methods including consideration of non-linear aerodynamics, structural weight and flexibility, aeroelastic coupling and handling qualities.

Understanding the aeroelastic behaviour of the rear fuselage and tail surfaces enables the specification and development of technologies and concepts to improve their overall efficiency. One avenue for improvement is to increase the stiffness of the rear fuselage and empennage, which can be accomplished by the use of novel materials and structural concepts, including those obtained from topology optimization. Additionally, favourable aeroelastic couplings can be obtained by the use of passive aeroelastic tailoring and by innovative empennage geometries which provide flexible lift gradients greater than those of their rigid references.

This paper formulates the general optimisation problem that needs to be solved in order to obtain the best compromise between weight and drag in the configuration of the rear fuselage and empennage of commercial aircraft when considering the aeroelastic effects of structural deformation in the stability and control characteristics of tail surfaces. Attention is also given to key technologies and concepts to improve the overall efficiency of the rear fuselage and empennage.

1. EMPENNAGE FUNCTIONS AND DESIGN DRIVERS

In a functional breakdown of the major components of a conventional transport aircraft, the stability and control function is performed generally by the empennage, usually comprising a horizontal tailplane with an elevator and a vertical tailplane with a rudder.

The empennage of conventional transport aircraft accounts for between 4% to 7% of the weight and drag of the complete aircraft. The potential contribution of the tail surfaces to the overall optimization of the aircraft is thus relatively small but still relevant. The opportunities for reduction of the size of the empennage arise from the possibility to improve the relevant aerodynamic characteristics which contribute to the stability and control function, from the introduction of active control systems and from less obvious improvements in the aeroelastic behavior of the rear fuselage and tail surfaces.

The concept of stability refers to the ability of the aircraft to return to an attitude of equilibrium after a perturbation. A simple example of a stable system is a weathercock which will align itself with the local wind due to the lift generated by its aerodynamic surface, located aft of the pivot point. The position of equilibrium corresponds to a zero net yawing moment. This system exhibits "natural" stability; it is the aerodynamic configuration which provides the restoring yawing moment in a passive way. If the weathercock had a classical control surface connected to a stability augmentation system with feedback on the yaw rate, the system could converge to the stable configuration in a much shorter time after the perturbation. With a proper design of the active control system and control surface, even a naturally unstable weathercock (for instance, one with the pivot point located aft of the aerodynamic neutral point of the surface) could be made stable. This would be an example of artificial stability relying on an active control.

The control function is responsible for effecting changes or maintaining the attitude of the aircraft in response to pilot –or autopilot- demands. To take the aircraft away from its stable attitude, a destabilizing moment needs to be generated and this is normally produced by the deflection of the control surfaces of the wing or empennage, located as far as practically possible from the center of gravity of the aircraft.

The following discussion on the stability and control of the aircraft will be restricted to its pitching degree of freedom but most of the devices and conclusions presented are general.

The condition for natural static stability in the pitch axis is that the derivative of the pitching moment with respect to the angle of attack –or pitch stiffness- be negative, i.e., a perturbation resulting in an increase in angle of attack generates a negative (nose-down) pitching moment. This pitch stiffness depends on the geometric and aerodynamic parameters of the aircraft as follows;

$$C_{m,\alpha} \equiv \frac{\partial C_m}{\partial \alpha} = -\frac{l_w}{c_w} C_{L_w,\alpha} - \frac{S_h l_h}{S_w c_w} \eta_h C_{L_h,\alpha} (1 - \varepsilon_{d,\alpha}) < 0 \qquad (1)$$

Where C_m is the pitching moment coefficient, α is the angle of attack of the aircraft, l_w and l_h are respectively the distances between the wing and horizontal tailplane aerodynamic centers and the center of gravity of the aircraft, c_w is the wing mean aerodynamic chord, S_w and S_h are respectively the wing and tail reference areas, $C_{Lw,\alpha}$ is the wing lift gradient, $C_{Lh,\alpha}$ the tail lift gradient, η_h the ratio of local dynamic pressure to free flight dynamic pressure at the tail surface and $\varepsilon_{d,\alpha}$ is the variation of downwash angle with angle of attack.

From the previous equation it becomes apparent that increasing the tail surface, the tail lever arm (l_h) or the tail lift gradient will make the pitch stiffness more negative and therefore the aircraft more stable.

Tail size –reference area- is well correlated to empennage weight, drag and cost and therefore is the most direct but least effective means to achieve the required level of stability.

1.1 EFFECT OF LEVER ARM

Increasing the tail lever arm generally requires lengthening the rear fuselage. This enables to maintain the same pitch stiffness reducing the tail surface but the weight and drag penalty introduced by the additional fuselage structure and wetted area must be smaller than the corresponding improvements in the empennage to make this option attractive. Additionally, as the flexibility of a beam increases significantly with its length, increasing the lever arm of the tail by means of a dedicated boom may lead to an important reduction in lift gradient of the tail due to the elastic deformation of the fuselage.

The topic of loss of lift gradient or aerodynamic control effectiveness due to flexible effects is central to the ideas presented in this paper and will be illustrated with its most visible case, namely, the bending of the fuselage.

The pitching moment generated by the empennage is produced by the aerodynamic lift on the tail surface. This force acts at the tip of a beam which is the rear fuselage, building up bending moment up to the center of gravity of the aircraft, where the pitching moment of the tail is applied. The ensuing deformation of the aft fuselage reduces the effective angle of attack of the tail surface, reducing thus the lift (Fig. 1).

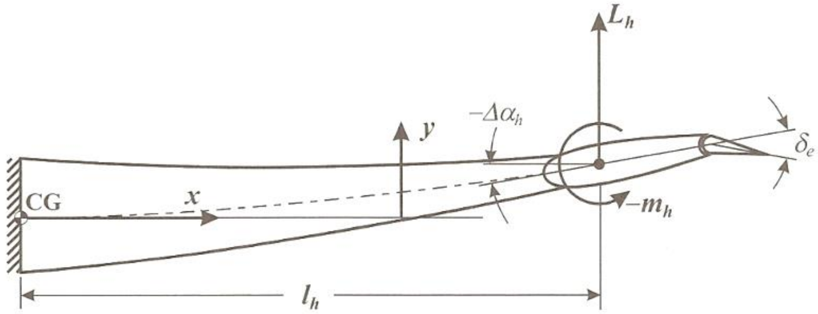

Fig. 1 Deflection of the aft fuselage as a result of aerodynamic loads on the tail (Ref [7])

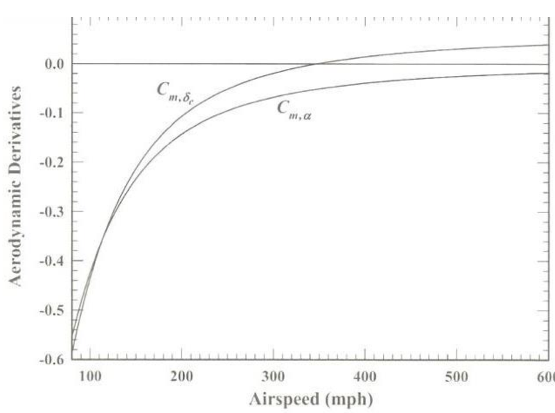

Fig. 2 Loss of aerodynamic pitch stiffness (Cm, α) and control efficiency(Cm,de) due to flexible effects when increasing the flight speed (Ref [7])

A point of equilibrium where the aerodynamic force is in balance with the elastic force is reached for every flight speed and angle of attack. The elastic deformation increases with the dynamic pressure and therefore the lift gradient, i.e., the ratio of increase of lift force with flight angle of attack, is reduced for higher flight speeds (Fig. 2).

When considering the stability of the aircraft at any flight speed, the effective lift gradient (including flexible effects) must be considered. It is clear that if the rear fuselage is very flexible, it may not be possible to stabilize the aircraft at high speeds even by increasing the tail size, as this will in turn increase the structural deformation.

Starting from the governing equation of the elastic deflection of a beam: $\frac{d^2y}{dx^2} = \frac{M_b}{EI}$ (2)

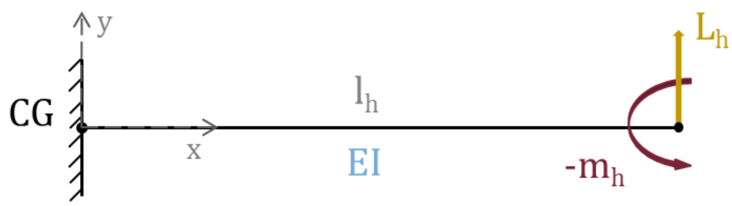

Fig. 3 Beam-like idealisation of a rear fuselage under aerodynamic empennage loads

In terms of lift and pitching moment: $\frac{d^2y}{dx^2} = \frac{L_h\,(l_h - x) - m_h}{EI}$ (3)

Where L_h is the horizontal tailplane (hereafter referred to as HTP) lift, m_h the tailplane pitching moment and EI is the rear fuselage bending stiffness.

The change of angle of attack $\Delta\alpha_h$ due to flexibility is found by integrating from the aircraft center of gravity to the center of pressure of the tail surface:

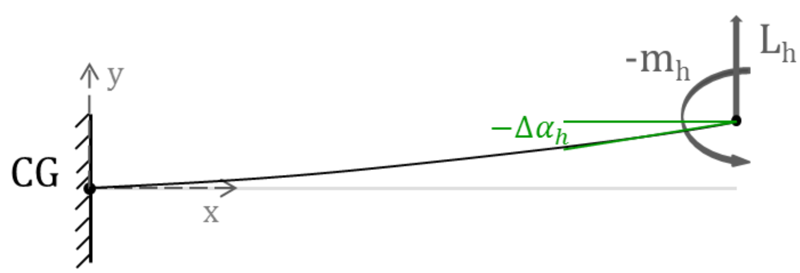

Fig. 4 Deflections of a beam-like rear fuselage under aerodynamic empennage loads

$$\Delta\alpha_h = \left.\frac{dy}{dx}\right]_{x=l_h} = m_h \int_{x=0}^{l_h} \frac{1}{EI}\,dx - L_h \int_{x=0}^{l_h} \frac{l_h - x}{EI}\,dx \quad (4)$$

The lift and pitching moment can be written as functions of the lift coefficient and pitching moment coefficients as:

$$L_h = \frac{1}{2}\rho V^2 S_h \bar{c}_h \cdot C_{L_h,\alpha} \cdot [i_h + \Delta\alpha_h - \varepsilon_{d\alpha} + \eta_e \delta_e] \quad (5)$$

$$m_h = \frac{1}{2}\rho V^2 S_h \bar{c}_h \cdot C_{m_h,\delta_e} \cdot \delta_e \quad (6)$$

Where δ_e is the elevator deflection angle, η_e is the elevator efficiency, i.e. $\eta_e = \frac{C_{L_h,\delta_e}}{C_{L_h,\alpha}}$

Replacing the above in eq. (4), we obtain:

$$\Delta\alpha_h = -K_L \cdot C_{L_h,\alpha} \cdot [i_h + \Delta\alpha_h + \eta_e \cdot \delta_e] + K_m \cdot C_{m_h,\delta_e} \cdot \delta_e \quad (7)$$

Solving for $\Delta\alpha_h$:

$$\Delta\alpha_h = -\frac{K_L \cdot C_{L_h,\alpha} \cdot [i_h + \eta_e \cdot \delta_e] - K_m \cdot C_{m_h,\delta_e} \cdot \delta_e}{1 + K_L \cdot C_{L_h,\alpha}} \quad (8)$$

Where:

$$K_L = \frac{1}{2}\rho V^2 S_h \int_{x=0}^{l_h} \frac{l_h - x}{EI} dx \quad (9)$$

$$K_m = \frac{1}{2}\rho V^2 S_h \bar{c}_h \int_{x=0}^{l_h} \frac{1}{EI} dx \quad (10)$$

The K_L and K_m coefficients are thus representative of the flexibility of the fuselage and are reduced as the bending stiffness, EI, increases or the fuselage length decreases.

The pitching moment contribution of the HTP is given by:

$$(m_{CG})_h = m_h - l_h L_h \quad (11)$$

Which can be re-written in non-dimensional form as:

$$(C_m)_h = \frac{S_h \bar{c}_h}{S_w \bar{c}_w} \cdot C_{m_h \delta_e} \cdot \delta_e - \frac{S_h l_h}{S_w \bar{c}_w} \cdot C_{L_h,\alpha} \cdot [i_h + \Delta\alpha_h + \eta_e \delta_e] \quad (12)$$

The variation of pitching moment coefficient with respect to elevator deflection is obtained by differentiating with respect to δ_e:

$$(C_{m,\delta_e})_h \equiv \frac{\partial C_m}{\partial \delta_e} = \frac{S_h \bar{c}_h}{S_w \bar{c}_w} \cdot C_{m_h \delta_e} - \frac{S_h l_h}{S_w \bar{c}_w} \cdot C_{L_h,\alpha} \cdot [\eta_e + \frac{\partial \Delta\alpha_h}{\partial \delta_e}] \quad (13)$$

Likewise to obtain the variation of pitching moment with respect to trim angle, we differentiate with respect to i_h:

$$(C_{m,i_h})_h \equiv \frac{\partial C_m}{\partial i_h} = -\frac{S_h l_h}{S_w \bar{c}_w} \cdot C_{L_h,\alpha} \cdot [1 + \frac{\partial \Delta\alpha_h}{\partial i_h}] \quad (14)$$

From which we obtain:

$$(C_m)_h = (\Delta C_{m,\delta_e})_h \cdot \delta_e + \left(\Delta C_{m,i_h}\right)_h \cdot i_h \quad (15)$$

$$= \frac{S_h \bar{c}_h}{S_w \bar{c}_w} \cdot C_{m_h \delta_e} \cdot \delta_e - \frac{S_h l_h}{S_w \bar{c}_w} \cdot C_{L_h,\alpha} \cdot \underbrace{\left[\eta_e + \frac{\partial \Delta\alpha_h}{\partial \delta_e}\right]}_{\boldsymbol{\eta_{e_{flexible}}}} \cdot \delta_e - \frac{S_h l_h}{S_w \bar{c}_w} \cdot C_{L_h,\alpha} \cdot \underbrace{\left[1 + \frac{\partial \Delta\alpha_h}{\partial\, i_h}\right]}_{\boldsymbol{\eta_{ih_{flexible}}}} \cdot i_h \quad (16)$$

We can now define a flexible elevator efficiency and a flexible trim efficiency which affect the corresponding rigid terms in the equation for the elastic variation of the pitching moment coefficient (15).

$$\eta_{e_{flexible}} = \frac{C_{L_h,\delta_e}}{C_{L_h,\alpha}} - \frac{K_L \cdot C_{L_h,\delta_e} - K_m \cdot C_{m_h,\delta_e}}{1 + K_L \cdot C_{L_h,\alpha}} \quad (17)$$

$$\eta_{ih_{flexible}} = \frac{1}{1 + K_L \cdot C_{L_h,\alpha}} \quad (18)$$

When performing the configuration optimization of the rear fuselage length and empennage size, the flexible pitching moment coefficient $(C_m)_h$ shall be treated as a constraint, taking the constant value as that which satisfies the stability handling qualities for a given location of the centre of gravity and trim and elevator deflections.

$$(C_m)_h = (C_m)_{h,baseline} = \text{Constant} \quad (19)$$

For the theoretical rigid situation, C_m conservation is simple as it is equivalent to preserving the product of lever arm times tail area (assuming homothetic variations of the planform and ignoring variations of dynamic pressure ratios and downwash gradients). Therefore when displacing the tail planes aft, and therefore increasing lever arm, tail areas are reduced in direct proportion.

Adding flexible effects makes the relation not directly proportional as the stiffness effects come into play. A numerical target solver is necessary to iterate and find the tail area to maintain $(\boldsymbol{C_m})_{\boldsymbol{h}}$

The optimum trade-off between rear fuselage length and empennage size is not trivial to be obtained as drag considerations need also to be considered which exhibit a complex relationship with the slenderness and shape of the aft fuselage and the structural stiffness is also a function of the materials and design principles used, which are also to be traded as part of the overall cost. The previous discussion illustrates the key physical effects that influence the aeroelastic performance of the empennage as a function of the stiffness of the rear fuselage.

1.2 SWEEP EFFECT

Aircraft flying at high speeds, where compressibility effects cannot be ignored, usually have swept lifting surfaces and empennages.

The aerodynamic advantage of the sweep lies in the fact that the adverse effects of compressibility, produced by the overspeed of the airflow around the aerodynamic surface, which increases with the relative thickness of its profile, are related to the component approximately perpendicular to the line of 50% of the chord. Therefore, for a given airspeed, an aerodynamic surface with a given sweep will be subject to compressibility effects equivalent to those of a profile with no sweep but with a relative thickness ratio equal to the cosine of the sweep angle.

A greater relative profile thickness will result in lower structural weight of the surface as the internal loads produced by the aerodynamic loads are reduced due to the increased girder of the structure.

The effects of the sweep angle on lifting surfaces and empennages are beneficial for high-speed flight in terms of compressible drag, as described above. However, the effect of the sweep angle on the lift gradient is not beneficial for the stability of the aircraft as increasing the sweep angle decreases the rigid lift gradient.

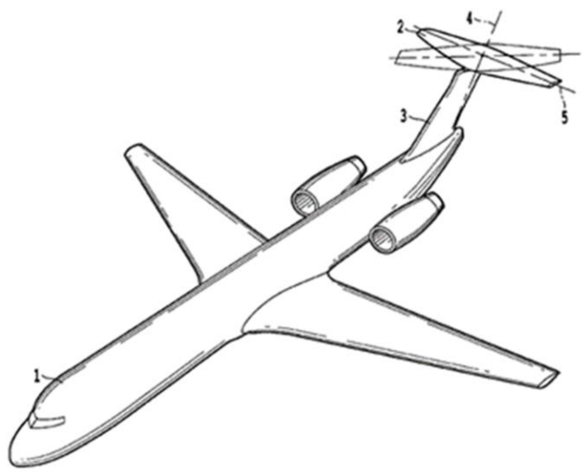

Fig. 5 Pivoting horizontal tailplane concept aimed at tailoring the tail lift gradient and maximum lift coefficient (Ref [3])

A conceptually simple, although rather exotic, way to tailor the lift gradient of a tail surface is to modify its sweep angle. Variable sweep wings have been used in many aircraft –although for different reasons-, and a similar mechanism could be used on the empennage, albeit at a large cost. A pivoting tail (Fig. 5) offers the same function with a significantly simpler mechanism (although, admittedly, still complex (Ref [3])

The sweep angle of a lifting surface has also an effect on its aeroelastic behavior. In the case of a surface with aft-sweep, a bending deformation generates a reduction of angle of attack at the tip, $\Delta\alpha$, given by the following equation (Ref. [6]);

$$\Delta\alpha = \tan^{-1}(\tan\theta \sin\Lambda) \tag{20}$$

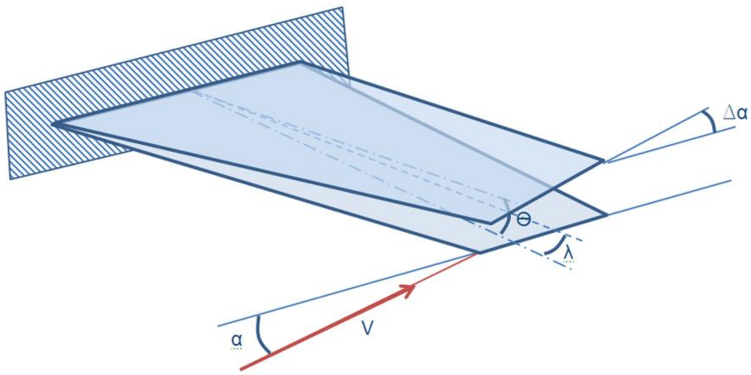

Fig. 6 Elastic deformation of a swept-back lifting surface due to bend-twist coupling

Where λ is the structural sweep angle and Θ the equivalent bending angle. As is the case for the elastic deformation of the fuselage, the bend-twist coupling in a swept-back lifting surface reduces the lift gradient, and this effect is greater as the flight speed increases. Surfaces with high aft-sweep angle and high aspect ratio –producing larger bending deformations- are particularly prone to this loss of elastic lift gradient.

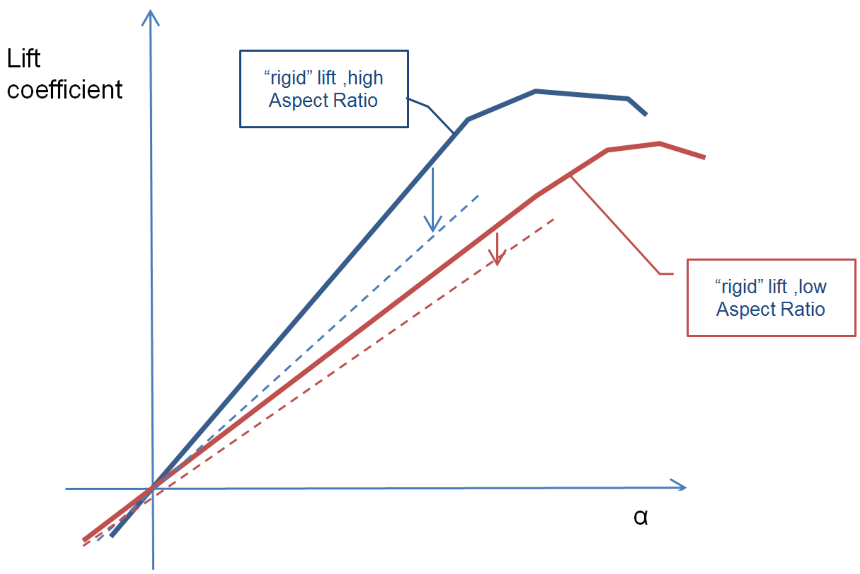

Fig. 7 Rigid and elastic (dotted lines) lift on a swept-back lifting surface due to bend-twist coupling

The proportionally larger loss of flexible efficiency on surfaces of higher aspect ratio is depicted in Fig. 7. Note that as the aspect ratio increases so does the rigid lift gradient, but for a significant sweep angle the flexible effects may end up negating the overall benefit.

Other adverse aeroelastic phenomena like flutter must be taken into consideration and, in general, it can be stated that an efficient stability and control function benefits from a stiff structural chain (rear fuselage plus tail surfaces).

1.3 FORWARD SWEPT TAILS

The same geometric coupling affecting aft-swept lifting surfaces applies to surfaces with "negative" or forward sweep but in this case the angle of attack variation due to bending generates a positive elastic feed-back on the lift.

On a forward swept wing, the aeroelastic deformation tends to increase the structural loads and, therefore, the structural weight; moreover, the increased lift gradient of the wing results in a more dynamic response of the airplane to turbulence and to vertical gusts and, therefore, in less comfort for the passengers.

However, in the case of a horizontal stabilizing surface of negative sweepback, this greater aerodynamic response to disturbances makes the stabilizer surface more efficient in its function of recovering the attitude of the airplane in the event that it encounters turbulence or vertical gusts during flight and, therefore, this aeroelastic coupling can be considered advantageous.

There are additional particular advantages associated to forward-swept lifting surfaces which can be summarized as follows:

- For tapered lifting surfaces with the same sweep angle of the line of 25% of the chord, a smaller sweep angle of the leading edge of the surface with negative sweepback results in a smaller crossflow in the direction of the wingspan, with a resulting reduction of the coefficient of friction in the boundary layer and, therefore, less aerodynamic drag. Even more importantly, reducing the cross-flow is one of the enablers for natural or hybrid laminar flow.

- The cross-flow and general spanwise motion of the air is from tip to root in the case of a surface with negative sweepback, which results in the possibility of achieving larger stall angles than in the case of positive sweptback surfaces, where the cross-flow drags the boundary layer towards the marginal tip, decreasing the energy of the boundary layer in that zone.

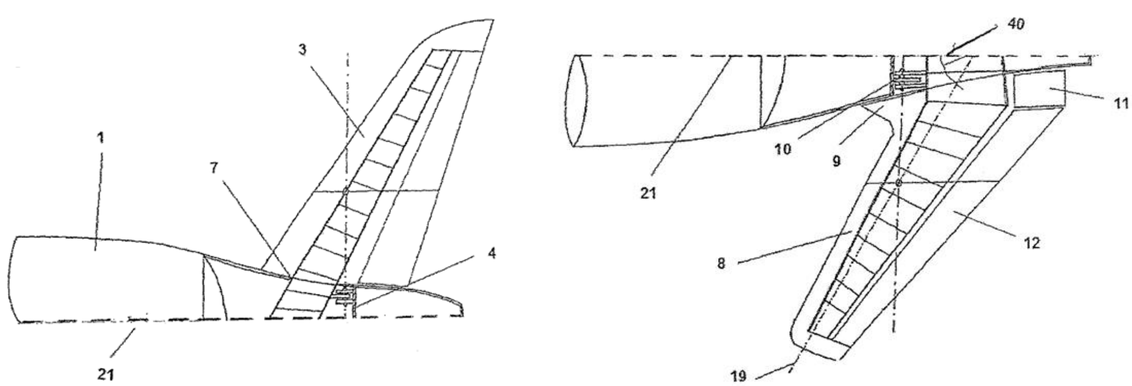

Fig. 8 Conventional aft-swept horizontal tailplane(left) and forward-swept tailplane (right) (Ref [5])

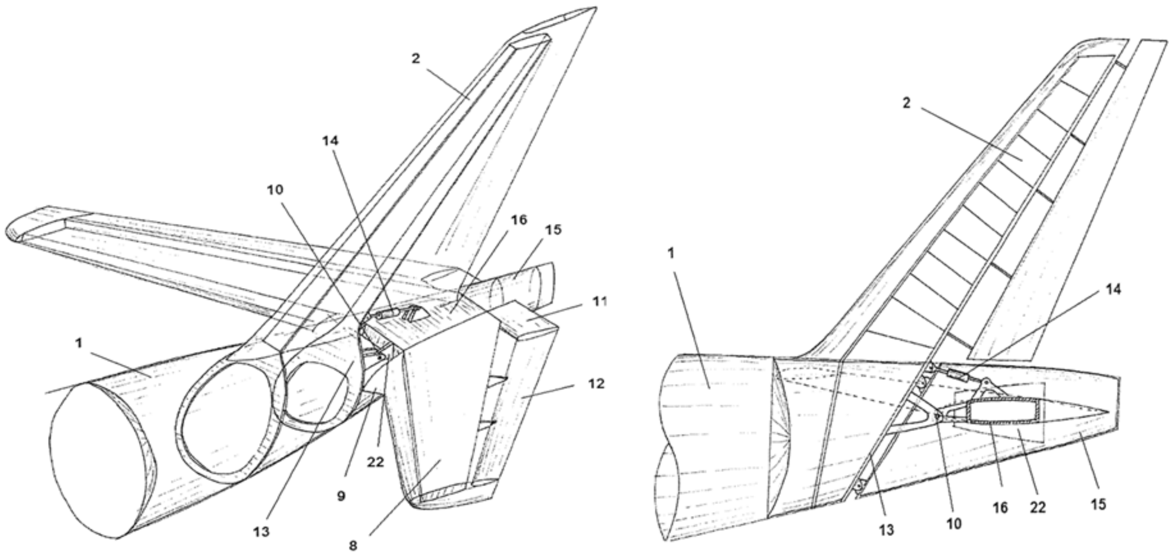

Fig. 9 Structural arrangement for a forward-swept tailplane (Ref [5])

Fig. 8 shows a possible design for a forward-swept horizontal tailplane compared with a conventional configuration. An additional benefit of this concept is that no structural “cut-out” is required on the rear fuselage, i.e., the structural box of the tailplane is attached to a closing frame of the –possibly- pressurized fuselage, increasing the overall stiffness (thus reducing flexible lift gradient losses caused by the fuselage cut-out) and increasing available payload volume.

A possible structural arrangement illustrating these points is shown in Fig. 9.

1.4 CONTROL FUNCTION

1.4.1 Maximum control power and stall

The control function requires the generation of enough pitching moment (in the case of the longitudinal motion under discussion) to change the attitude of the aircraft at the rate required by the pilot or to balance the aircraft for extreme –generally forward- locations of its center of gravity.

The physical limiting factor for the control function is the maximum lift coefficient at the stall of the surface, generally –although it depends on the handling qualities criteria used- with maximum control deflection.

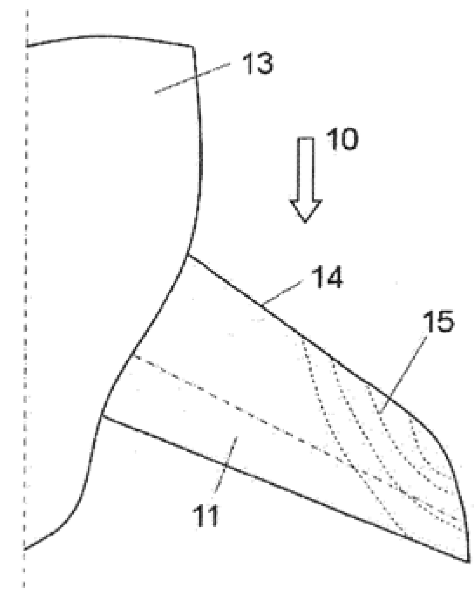

Fig. 10 Typical pattern of stall onset in a conventional, aft-swept, tail surface

Tail stall angle is a design constraint related to the safety of the aircraft flight and is determined by the sweep angle, the taper and aspect ratio of the surface as well as, among other design features, the aerofoil thickness and leading edge shape.

When an aircraft encounters a flight situation such that the wing may stall (as a consequence of severe turbulence which may upset the aircraft attitude or in the case of flight through a region of the atmosphere with icing conditions, where ice can be accrued in the wing leading edge, breaking the aerodynamic smoothness of the aerofoil), it is essential that the tail surfaces remain effective in providing sufficient aerodynamic forces to restore the aircraft attitude. An important design requirement for the aircraft tail surfaces is, therefore, that their stall angle is greater than that of the wing, even in icing conditions.

In particular, tail stall angle in icing conditions, when it is assumed that the tail leading edge has an ice form which breaks the aerofoil smoothness and thus reduces the maximum lift coefficient, is a crucial design consideration for modern commercial aircraft. There are several accidents documented where the root cause has been the stall of the tail in icing conditions and therefore the loss of control of the aircraft (Ref. 10). Fig 11 shows schematically the ice shape and its effect on promoting flow separation at the leading edge.

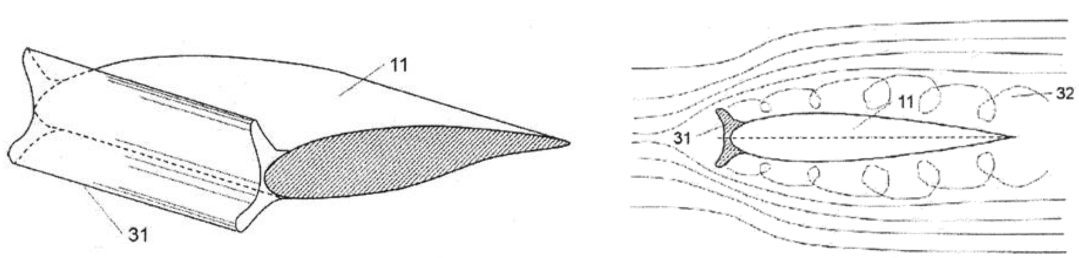

Fig. 11 Typical ice shape on a leading edge of a tail surface and flow separation inducing early stall

There are known methods to minimize ice accretion on the tail surfaces consisting on heating the leading edge or on having a flexible leading edge cover which can be inflated with the aim of preventing the formation of ice on the leading edge or breaking the ice once it has formed. The operation of these devices requires a positive action from the pilot who activates them if atmospheric icing conditions are detected. These methods not only are costly to install and maintain but carry the risk of not being operative when required, without prior indication.

Thus it is clear that passive means to prevent ice accretion on the leading edge would be preferred.

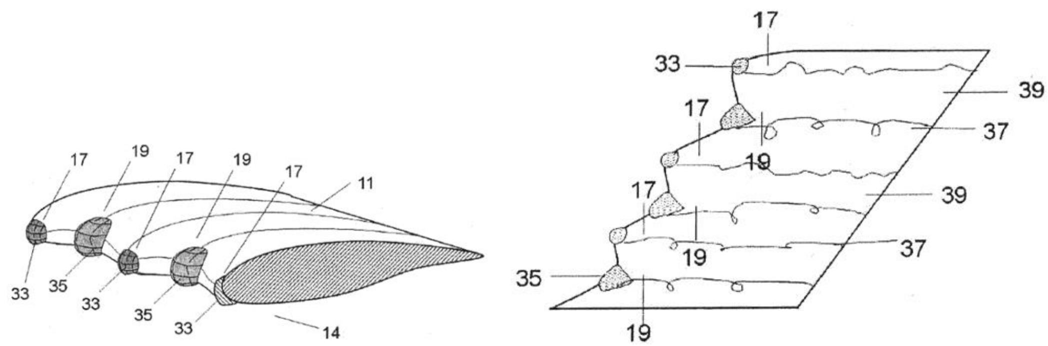

Fig. 12 Undulated leading edge concept seeking to use accreed ice as vortex generators in order to delay stall in icing conditions. Ref [1]

A potential passive means to delay stall in icing conditions is to design the leading edge of the tail surfaces with a smoothly undulated shape. The intent is that ice is formed first around the stagnation points with a shape such that would act as a vortex generator at high angles of attack. In this condition, the additional energy injected in the boundary layer, using the same mechanism as conventional fixed vortex generators or dog teeth, will delay the flow separation and, therefore, increase the angle of stall.

The shape and size of these undulations remains an interesting topic of research.

1.4.2 Rapid actuation and aeroelastic considerations of control surfaces

Reducing the size, lever arm or lift gradient of the tails will reduce the natural stability of the aircraft. Assuming that the tail control efficiency and power are sufficient, a certain degree of natural instability can be compensated by an artificial stability augmentation system, generally using pitch rate as the main feedback.

The automatic control system will deflect the control surfaces in response to pitch perturbations and the angular rate of deflection will be higher the more unstable the aircraft is. One technology enabler for artificial stability is rapid actuation of control surfaces which requires fast actuators and light and stiff control surfaces.

Many fighter aircraft are naturally unstable and their control surfaces are all movable “tailerons”. In the case of commercial aircraft, which tend to have larger empennages, conventional control surfaces are more suitable but their design should be adapted to the requirements of rapid actuation if the avenue of relaxed natural stability is explored.

The typical installation of the actuators in a control surface of a tail is between the rear spar of the main torsion box and the front spar of the control surface. The space allocation for the actuation system can be in the order of 5% to 10% of the local chord, which causes a noticeable reduction of the torsional stiffness of the tail surface and usually results in a weight increase of the structure since thicker skins and stringers are required in order to restore the desired torsional stiffness for aeroelastic and strength considerations.

Covering the separation between the rear spar of the torsion box and the leading edge of the control surface likewise requires installing relatively large and flexible aerodynamic fairings which do not contribute to the rigidity or strength of the lifting surface, in addition to introducing significant bending loads on the ribs of the torsion box at the base of the hinge fittings.

In the case of systems in which the actuators are connected directly to the control surfaces, these are usually located approximately at the centre of pressure of the control surface in order to minimize torsional deformation. In any case, the placement of the actuators within the aerodynamic surface requires providing access for inspection, which complicates the design of the aerodynamic surfaces.

One means to install actuators in a more favourable place is to use a strong and stiff torsion bar to effect the rotational movement. The actuators can be installed inside of the fuselage, thereby enabling the use of larger electromechanical actuators which are more suited for rapid actuation. This concept of actuation is typical of smaller aircraft but the key technology enablers for the application of this configuration at a scale typical of commercial aircraft are the development of structural materials and design principles to maximise the stiffness of the control surface and torsional bar to prevent loss of effectiveness associated to the deformation of the controls. Fig. 13 shows such a concept where the rudder is actuated from within the fuselage.

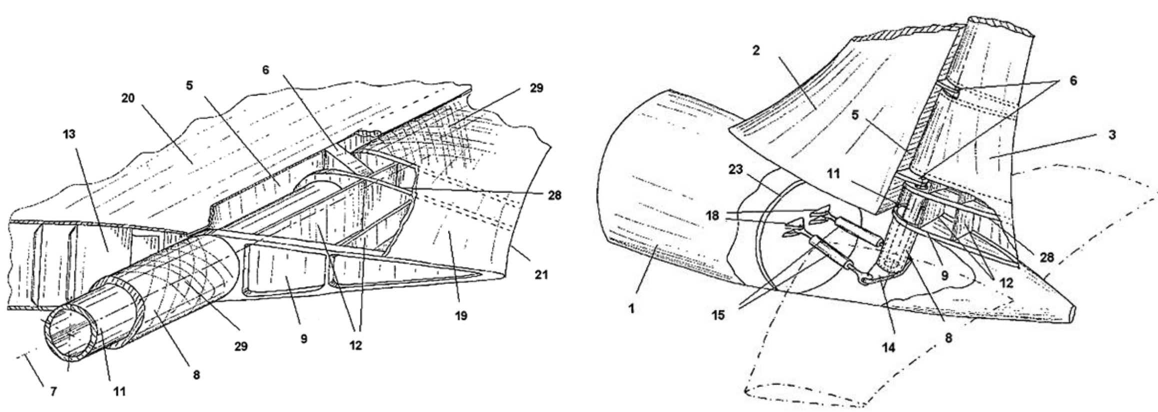

Fig. 13 Empennage control surfaces actuated from within the fuselage through a high strength and stiffness torsion bar

The “double-hinged” elevator or rudder concept, in which the control surfaces comprise two surfaces with parallel hinges, movable relative to one another and relative to the lifting surface of the aircraft and mechanically linked provides increased control efficiency, i.e., control force per degree of deflection of the primary hinge (assuming a gearing ratio greater than one in the secondary hinge). These control surfaces are usually of full-span configuration, with the control surface including the whole span of the lifting surface, i.e. the secondary control surface includes the whole span of the primary control surface. This configuration is prone to stalling under deflection of the controls due to the high local lift coefficient generated at the tip of the surface and also to problems resulting from the lack of stiffness of the secondary element of the control surface.

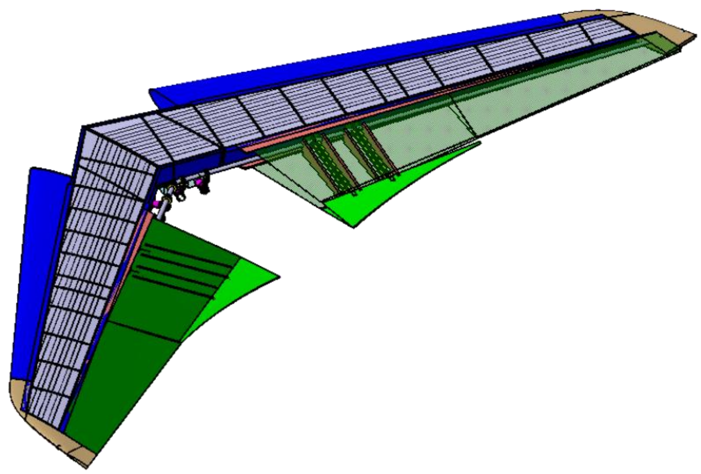

Fig. 15 Torsionally-actuated, partial span double-hinged elevator concept (Ref. [2])

One means to reduce the stiffness and control power drawbacks of full-span double-hinged control surfaces is to reduce smoothly the span of the secondary element in order to tailor the load distribution and prevent the generation of a vortex at the end of its span. Combined with a torsion bar actuation system, this configuration is well suited to the implementation of rapid actuation principles as required by less naturally stable aircraft with smaller empennages.

2. CONCLUSIONS

The continuous drive to optimise aircraft performance will call for smaller empennages in the future aircraft. A means to achieve this is to find configurations which exploit the physical drivers contributing to the stability and control functions of the empennage. The geometric optimisation of the "rear-end" (rear fuselage plus tail surfaces) requires simultaneous consideration of the weight, drag and cost of the components while including the flexibility effects in the calculation of the handling qualities of the aircraft.

Very slender rear fuselages, as found, for example, in glider aircraft, enable reducing the tail size as long as the loss of aerodynamic effectiveness due to the structural deformation does not overcome the pure geometric effect of increasing the lever arm. The effect of flexible deformation becomes more important as the size of the aircraft increases and, in order to make this configuration attractive for future aircraft concepts, research must be directed towards materials and structural design principles oriented to maximising the stiffness of the rear fuselage.

Passive means to use the aeroelastic deformation in favour of the empennage performance include the use of negative sweep tail surfaces. In this case, the flexural-bending coupling actually increases the flexible lift gradient with respect to the rigid reference. Additionally, in this configuration the large structural cut-out in the rear fuselage is removed, contributing to further reductions of the flexible efficiency losses.

In order to improve the control function of the tails, technologies, concepts and devices oriented to maximising the lift coefficient of the surfaces, particularly in icing conditions, are sought. A concept has been presented where the geometric configuration of the leading edge is such that the ice accretion is concentrated at discrete points so that, at high angles of attack the ice shapes act as vortex generators, thus increasing maximum lift coefficient.

The pursuit of a less naturally stable aircraft in order to minimise empennage sizes relies on the ability of the automatic flight control system to perform the corrections required to compensate the perturbations at high rates. The technology enablers for these concepts include actuators of high bandwith as well as control surfaces of high stiffness and low inertia, such as the concept presented in this paper.

Unlike wings, where natural flexibility is a passive means to reduce flight loads, the rear fuselage and tail surfaces benefit from high stiffness. The concepts presented in this paper are an illustration of the problems that need to be addressed and some of the research avenues that can be taken in order to improve aircraft performance though rear-end optimization.

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