Development of a Rudderless Aeroelastic Fin Technology

M. Trapani, S. Guo
Aircraft Design Centre, Department of Aerospace Engineering, School of Engineering
Cranfield University, Bedfordshire, MK43 0AL, UK

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Abstract

This project aims at developing a gapless and rudderless aeroelastic fin technology (GRAF) for the lateral directional control of air vehicles.
The objective of the study is to design a light weight hinge-less and gapless fin structure that will achieve the same stability and control authority characteristics of conventional configurations, i.e. those comprising a hinged rudder.
The current paper presents the details of a GRAF development including conceptual and structural design and performance analysis. Unlike a conventional stiff fin with a rigid hinged rudder, the GRAF empennage is designed as a unitized piece of "flexible" structure integrated with a compliant TE section acting as a morphing control surface. The aeroelastic fin operates essentially through span-wise twisting; this is achieved by initiating a rotation of the main beam and cambering the TE fin sections via a new actuation concept, denoted as "L Shaped Stringer" (LSS), which is here presented in detail. Consequently the twist will increase the torque due to aeroelastic coupling.
The design guidelines and operation principles of a GRAF device are presented and discussed.
It is here demonstrated that a proper aeroelastic tailoring of the control surface provides benefits both in terms of directional stability and control; nevertheless in order to exploit those advantages the aeroelastic control surfaces must be significantly more compliant than traditional empennages. This implies that the flutter and divergence margins associated to the GRAF are much tighter than in conventionally designed empennages.

1. Introduction

Traditionally hinged control surfaces have been designed and employed to generate and vary aerodynamic forces required to sustain flight and manoeuvre.
However, looking back to the beginning of the aviation history, alternative configurations for horizontal and vertical tails have been considered: for example all movable tails were applied on the first monoplanes, but they also appear on last generation stealth aircrafts. A warping wing surface was employed on the first manned powered aircraft, i.e. Wright brothers' Flyer I of in 1903 [17]. This concept was again exploited almost eighty years later, in the NASA Active Aeroelastic Wing programme (AAW) [1,4].
All-movable designs have been more successful than those based on warping, i.e. elastically deformable, structures. A warping wing/empennage presents additional challenges in terms of design and control with respect to conventionally hinged or even all movable configurations. As mentioned above, although the control technology based on elastic warping was actually the first to be exploited in flight, just very few applications followed the Wright's early attempts. NASA AAW demonstrated the possibility that a warping based, i.e. elastic morphing design, can improve the flight performances, but this required a huge technology leap.

The majority of commercial airplanes adopt hinged command surfaces and in some cases all movable horizontal tails, with hinged tabs for trimming; military aircrafts operating from medium subsonic to high supersonic speeds usually rely upon all movable horizontal tails; in same cases all movable vertical empennages have been successfully employed e.g. in the BAC TSR2, Lockheed SR-71 and F-117. This solution has been applied for avoiding the loss in aerodynamic surface effectiveness in high velocity cruise, while retaining an adequate control authority over the entire speed range.
NASA initially investigated the application of adaptive and aeroelastic wings on the F-111; the idea was to vary the wing camber in order to meet different flight conditions.
This original concept was the successfully developed leading to the last AAW prototype, i.e. an F/A-18 aircraft designed with improved rolling performances [4].
Amprikidis *et al.* [5] investigated the possibility of developing an adaptive root damper/spring for all movable vertical tails; this was meant to maximize the passive aeroelastic effect as a function of different flight speeds, thus enhancing the directional stability characteristics. Divergence and flutter at high flight speed were suppressed by increasing the spring stiffness and damping.
Allegri *et al.* [12] proposed an aeroservoelastic fin design essentially based on the belt-rib concept originally proposed by Sachau and Campanile [11]; also in this case the fin was assumed to be installed on an adaptive torsional spring/damper.
The GRAF development aims partially at replicating the research carried out by NASA for exploiting aeroelastic surfaces; at this stage the technology is applied to small UAVs flying at low subsonic speeds. On their F/A-18 aeroelastic wing prototype NASA used LE and TE devices to initiate a reversal condition on conventional ailerons, thus exciting the wing to twist.
The GRAF design instead aims at exploiting the side force acting on the fin to trigger the onset of a controlled divergence; this increases the effective angle of incidence at the vertical tail, thus improving the empennage effectiveness.

Although the concept is applied to a fin, the application can be directly translated in terms of wing design.
The GRAF design does not rely upon the usage of smart materials to provide actuation; only standard fibre-reinforced composites and aluminium alloys are employed for building the fin. Avoiding smart materials makes obtaining large deformation of the empennage more difficult; nevertheless smart actuation typically requires high voltage power and this implies a significant weight penalty. The GRAF concept presented here has power demands in line with those of conventional electro-mechanic servos; this is largely due to the adoption of the LSS layout.
The weight savings which can be achieved adopting the GRAF concept are primarily due to the thinner skin and lighter spar design; moreover the number of secondary components, e.g. fasteners and hinges, can be drastically reduced. Additional benefits are sought when improving the fin effectiveness; this implies that the empennage can be made smaller, thus leading to further weight reductions.
Regarding aerodynamic benefits, a sealed gap increase the performance of an airfoil section and, in turns, that of the aerodynamic surface it belongs to. Fig. 1-2 present the results of experimental tests performed on flapped NACA airfoils back in 1941 [13]; sealing the flap gap increases the sectional lift and reduces the drag.
The exploitation of the aeroelastic effect to enhance aerodynamic performance has been extensively investigated from a theoretical and conceptual point of view; Phillips [10] examined how an aeroelastic tailored wing may be twisted to achieve an elliptic lift distribution in different flight conditions, thus minimizing the induced drag associated to the lifting surface.

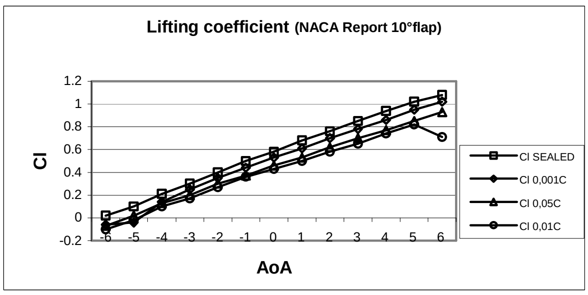


Fig.1 NACA 0009 Lifting Coefficient with sealed gap[13]

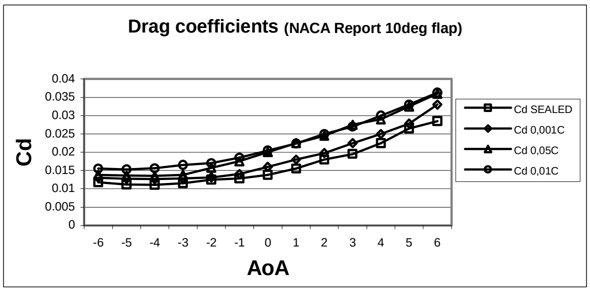


Fig.2 NACA 0009 Drag Coefficient with sealed gap [13]

Nevertheless no traditional control surface can be operated on a gapless, i.e. hinge-less, empennage; in this case the only way of generating control forces is through overall elastic deformations, i.e. overall warping or elastic morphing of the lifting surface.
The GRAF/LSS system has been designed to accomplish the control task by warping fin. Whereas in a traditional empennage configuration hinges transform the actuation torque in a rotation of command surfaces, the LSS concept allows performing the same task without opening gaps in the fin skin to accommodate the rudder hinge.
The objective of the design effort presented here is to exploit all the possible beneficial effects which a unitized, i.e. gapless and hinge-less, lifting surface configuration can offer.
The authors have developed and compared several GRAF concepts during the past years. This paper is focussed on the latest design, denoted as MT4; as mentioned above, this vertical tail is meant to be applied on small UAV platforms. The main design driver is to develop GRAF configuration which offers the same stability characteristics and control authority of a traditional vertical empennage. Nonetheless the GRAF design offers additional advantages; first of all the aerodynamic efficiency is improved because the proposed configuration is gapless. Secondly the overall empennage weight is reduced if compared to a traditional hinged rudder design.

2. Design Constraint, Objectives and Methodology

The development of a feasible GRAF configuration is based on a multidisciplinary design activity, which involves pure aerodynamics, flight mechanics and aeroelasticity.
Generally speaking, whenever significantly compliant structures are considered, then great care must be exercised in dealing with instability phenomena. Thus the assessments of buckling, divergence and flutter conditions are critical for the GRAF design, together with the application of usual structural integrity criteria based on strength.
The skin thickness is a key design variable; the fin skin needs to be compliant, i.e. thin enough, to allow the overall fin torsion, and at the same time sufficiently stiff to avoid local buckling and resist the aerodynamic pressure.
Achieving a sufficient directional control authority has been the most challenging objective in this project; this is due to the fact that large deformations are needed to generate adequate control forces during the low speed flying phases, e.g. take off, approach and landing with lateral winds.
The Eclipse UAV demonstrator, shown in Fig.3, has been chosen as a design case for the GRAF integration on a flying platform.
The Eclipse is the first prototype UAV designed in the framework of the FLAVIIR research programme [15], whose main intent is developing new technologies for maintenance free, low cost UAVs without unconventional control surfaces.

Fig.3 Eclipse vehicle [15]

The vehicle has a take-off weight of 45kg; it comprises a diamond shaped wing and a conventional vertical tail with hinged rudder, whose configuration is illustrated in Fig.4.

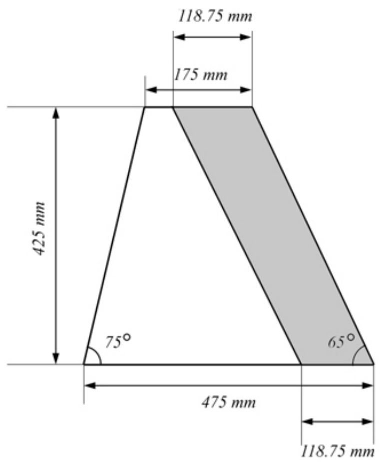


Fig. 4 Eclipse Fin Geometry

The Eclipse fin and available wind tunnel test data are taken as a reference case for a comparative analysis to assess the overall performance of the GRAF concept and match those of the conventional fin within the boundaries dictated by strength and stability criteria applied to the warping configuration. In the analysis the following methods/tools have been or will be applied:

Aerodynamics and Flight Mechanics:

- 2D/3D inviscid modelling using the Vortex/Doublet Lattice Method [6,16] ;
- 3D viscous/turbulence modelling will be carried out during the last year of the project to asses the design; this will be supported by wind tunnel testing
- MSC/PATRAN Flight Loads Tool, employed for evaluating aerodynamic derivatives, as well as flutter and divergence speeds.

Structures and Materials:

- FEM model developed in MSC/PATRAN; this comprises also composite materials, represented via the embedded laminate modeller.
- FE analyses run using MSC/NASTRAN and the associated aeroelastic solution sequences

Control system:

- the GRAF concept requires advanced control methodologies since the aeroelastic response of warping lifting surfaces is considerably different from that featuring conventional flapped empennages. This topic is beyond the scope of the present paper, but a dedicated PhD project is currently running at Cranfield University.

3. The Aeroelastic Fin Technology

To date, the morphing technology has been applied mostly on wings and horizontal tails, rather than fins. Hence there are few representative cases available for the aeroelastic tailoring of vertical empennages, most of them related to all movable configurations. The main problem in obtaining large elastic deformations for vertical fins is that vertical empennages have relatively low aspect ratios if compared to wings. This implies that, given the same actuation torque and torsion stiffness, the overall twisting deformations for fins may not be effective enough. Therefore the GRAF design is focused on obtaining sufficient amount of twist together with a deflected TE surface.
The GRAF primary structure essentially works as a large torsion box. The skin usually provides the largest contribution to the torsional stiffness. Shear and bending moments are withstood by the main spar inside the torsion box. There are two main elements of novelty in the GRAF design proposed here, namely the “slot connection” at the fin root and the LSS configuration.

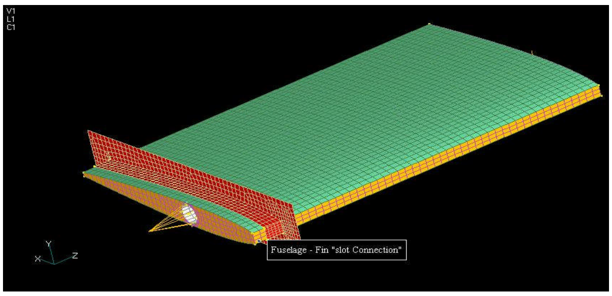


Fig. 5. Fin inserted into the “slot connection” (red).

As shown in Fig. 5 the GRAF will be inserted into a slot on the fuselage. Rather than fully clamped, such connection will restrict the fin skin from translation and rotations along both the x and y axis. However it allows a free warping hence a certain degree of freedom in twist about its single spar along vertical axis. Between the slot and fin skin a thin elastomer layer will be fitted to seal the gap to avoid a free play. Since the fin side skins are not rigidly attached at the root, they will slide vertically along the slot when the skins will be stretched or compressed in torsion to produce a greater twist angle. The bending and partly the shear force will be carried by a tubular beam acting as the fin spar. It is connected to the fin ribs and clamped at the root to a bearing mounted to the fuselage. Table.1 shows that a much larger twist deformation can be obtained by such slot-insert connection than a fixed root mounting.

Table 1: Comparison of rotation between fixed and aeroelastic fin, actuated by servos.

Aeroelastic Fin - Rectangular shape: Twist and Power			
	Flexible Slot Connection		**Fixed Root**
Twist:	9.4 deg	7.0 deg	1.4 deg
Torque:	6Nm	4.2Nm	4.2Nm
Actuation forces:	2x100N	2x70N	2x70N

As mentioned earlier, the second original feature of the GRAF concept is the “LSS”. As presented in Fig. 6, an internal actuation force is applied to the end of a LSS, the skin will be bent to form a curvature. The axial forces, coming from two small actuators placed inside the fin structure, will transfer the action via the arm of the “L” element to the skin panels.

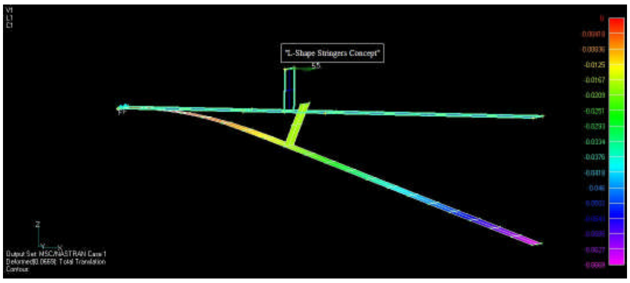


Fig. 6. Strip of TE skin with LSS system to bend the panel.

The stringer will act as a foot pressing on the skin and forcing it to bend. In this way a cambered TE, as a morphed rudder, will increase the side force contribution for a further aeroelastic effect. This action is necessary when large manoeuvring actions are requested, because twisting only the tail will not be enough to provide the control force needed.

The main actuation system includes a linear actuator installed at the base of the fin and connected to the fin tubular spar via a push/pull lever. The tubular spar is located at 40% of the fin root chord.

N ribs are mounted on the tubular spar; the first N-1 from root to tip are attached to roller bearings on the spar, therefore they are able to rotate with respect to the supporting composite tube. The N-th rib at the tip is fixed to the tubular spar. When the actuator is activated a torque is transmitted to the fin structure through the tubular spar; the N-th rib, i.e. that at the tip, rotates together with the composite spar. The remaining N-1, being free to rotate, will be dragged by the tip rib and the skin thus following the overall twisting motion.

In Fig. 7 is shown the whole fin with a partial covering only in the TE section were the LSS is lodged.

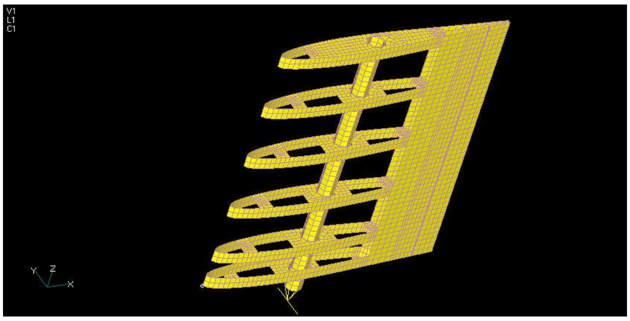
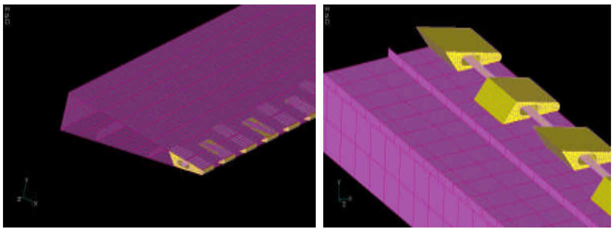


Fig. 7 GRAF-MT4: Ribs, flexible TE and carrying load beam.

The torsional kinematics described above is limited by the stiffness of the TE section; this tends to produce an “S” shape for the deformed configuration, which limits the amount of lateral side-force generated by the fin. In order to avoid this behaviour it was initially considered to open the fin TE, thus reduce the torsion stiffness significantly. However the resulting structure appeared to be too compliant and prone to flutter at low flight speed. Therefore a variant of the open gap concept has been introduced in the form of the “swivel” device illustrated in fig. 8a-b. This system is similar to the one on conventional door, which may be easily bonded to the two side skins and pivoted for the closure

of the TE. From a kinematic point of view the swivel TE allows a relative rotation of the skin sides with respect to a span-wise axis, while the relative translation in a chord-wise direction is constrained.
The swivel TE is the only component of the fin device made of aluminium alloy.



8a 8b
Fig. 8a-b Swivel concept applied on the TE of the MT4.

An actuator peak torque is required to initiate the twist deformation. However even when the servo is off the fin is able to twist passively under the action of a side wind.
The actuation mechanism on the tubular spar can also provide limits to the maximum twist angle as a function of the flight speed. This can be achieved simply by limiting the stroke of the linear actuator depending on the flight conditions.
As mentioned above, the aeroservoelastic fin concepts available in literature [5,12] are based essentially on all movable configurations, those present an horizontal gap at the fin root. The GRAF concept presented here does not require a gap at the root; a seamless connection to the fuselage can be achieved. The carbon fibre ribs are made in one piece mould.
The main characteristic of the ribs, as shown in Fig. 9, is to have a 20 mm height edge along the entire airfoil section perimeter, with exception in the area where the flexible TE is located. That edge will be stiff enough to act as a support for the skin layers and, at the same time, not too much rigid to allow deformations during the twisting.

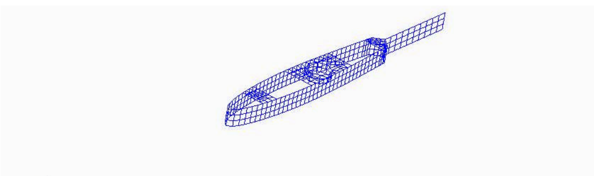


Fig. 9 Carbon Fiber Rib of the MT4 model

4. Results and Comments

The adoption of a flexible TE and gapless configuration also yields benefits in terms of aerodynamic efficiency [13].
The airfoil section chosen for the fin is the RAE104; this choice is motivated by the fact that the same profile is used on the conventional Eclipse fin.
A 2D aerodynamic potential analysis [16] of the airfoil section was conducted to assess the GRAF performance against the Eclipse fin. The influence of a whole hinged rudder on a classic fin is greater than a linear twist distribution of an aeroelastic fin for directional control. Although the maximum twist angle is attained at the tip, the twist angle at the root is virtually zero. Thus the aeroelastic fin requires a TE deflection on top of the overall twisting deformation when high values of side force coefficient are needed.
Those effects are discussed in Fig. 10, where a comparison between conventional and aeroelastic fins is presented for the case study considered here.

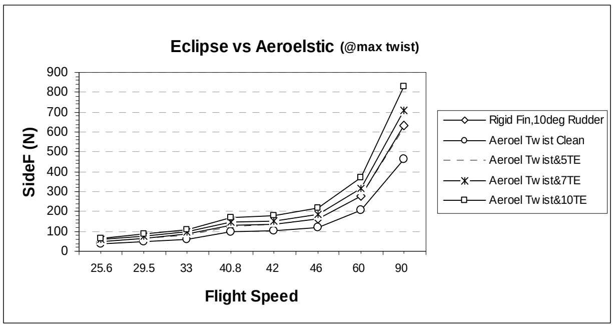


Fig. 10 Sideforce comparison between conventional and aeroelastic fin.

Fig. 10 shows that in order to reach the same performance as the conventional configuration, the GRAF design needs to operate with at least 5 degrees of TE deflection on top of the twisting deformation.
Nevertheless the GRAF performance in terms of side-force can be further improved by 30-50% just increasing the deformation up to 7-10 degrees of TE deflection.

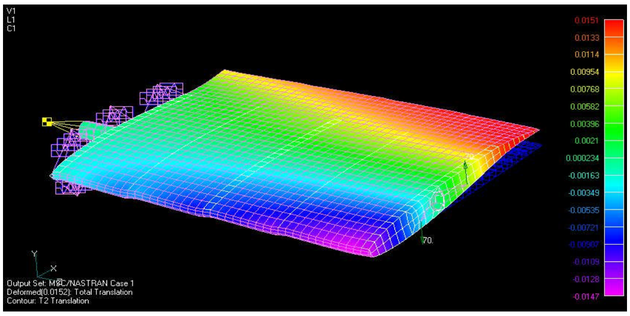


Fig. 11. Aeroelastic fin displacements under actuators action.

The data presented in Fig. 10 have been worked out for flight speeds ranging from the stall one, i.e. 25.6m/s, to a velocity 50% in excess of the design dive speed, i.e. 60 m/s for the Eclipse.

Regarding the aircraft overall static stability, the results obtained from MSC/Flight Loads analyses show satisfying improvements in the lateral/directional behavior.

In the graphs which follow data for two versions of the fin will be presented; the vertical empennage "V2" comprises an additional reinforcement on the leading edge, which the first version, i.e. "V1", misses.

During the study it has been observed that LE stiffness has a strong impact on the overall twisting stiffness of the fin, as even elementary torsion theory would suggest. This results also agrees with the fact that the swivel device largely increases the torsional stiffness of the section TE, so that the twisting is effectively restrained only by the LE.

The LE is made of rubber for both the "V1" and "V2" configurations; the thickness is 4mm along the entire fin span. The "V2" version is further strengthened with two additional layers of glass fiber.

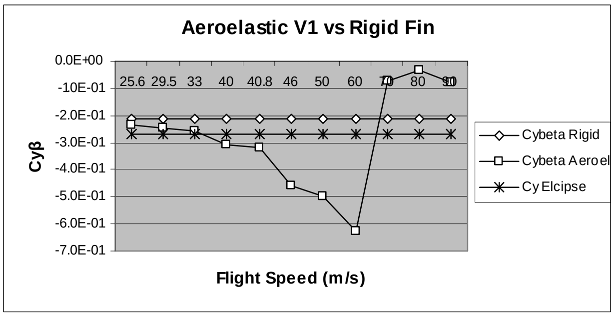


Fig. 12 Comparison of Cyβ coefficients between GRAF and conventional designs.

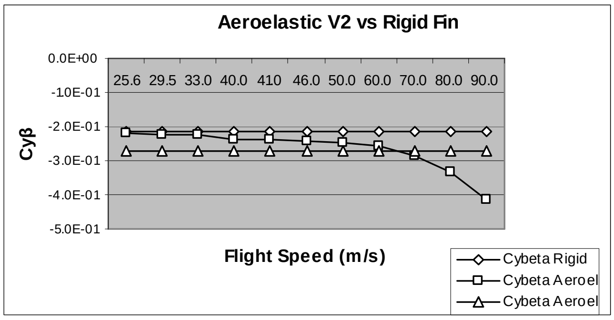


Fig. 13. Comparison of Cyβ coefficients between GRAF and conventional designs.

From Fig. 12-14 it can be observed that for the "V1" model the $C_{y\beta}$ and $C_{N\beta}$ are up to twice the values obtained for the conventional hinged rudder design of the Eclipse vertical empennage; this is true when considering a low speed range, i.e. up to the climb speed of 46m/s. On the other hand the "V2" configuration behaves better at high speeds, as shown in Fig.13-15.

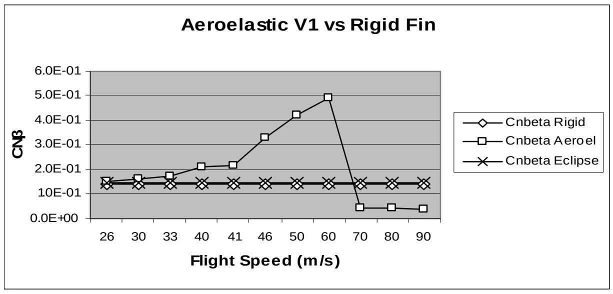


Fig. 14. Comparison of Cyβ coefficients between GRAF and conventional designs.

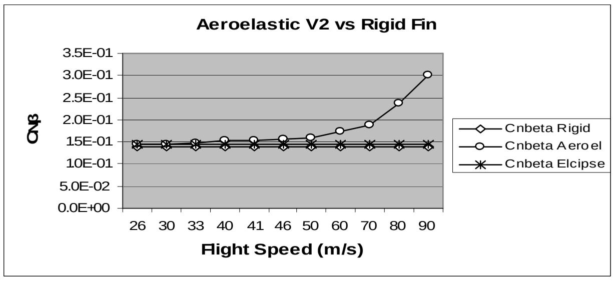


Fig. 15. Comparison of CNβ coefficients between GRAF and conventional designs.

The main objective of this study is to design a light weight aeroelastic fin. Although the "V2" configuration provides a good performance in terms of stability, the actuation force requires to deform the fin is in this almost twice the amount required for "V1". This would require doubling

the number of servos, thus increasing the weight.
Considering the "V1" model, the overall design is lighter than the eclipse fin:

- the structural weight of the Eclipse's fin with actuator (0.95Nm torque) is: 0.613kg
- the aeroelastic fin weight with actuators (2x2.7Nm torque) is: 0.541kg

However considering the "V1" model there is a limit on the flutter speed, which is of 83 m/s as shown in Fig. 16; . It is worth of noticing that this is well beyond 20% of the Eclipse design dive speed of 60 m/s.

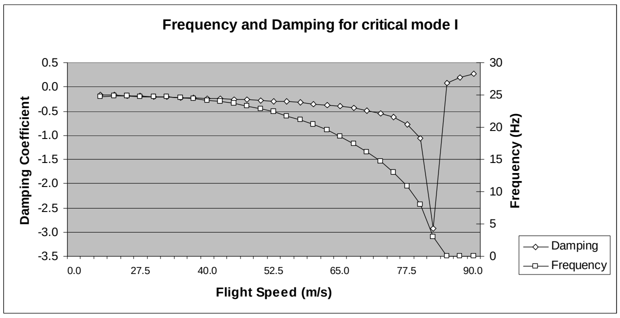


Fig. 16 Frequency and damping coefficients vs flight speeds.

5. Conclusions and future works

The GRAF as proposed here has the potential of being employed on next generation aircrafts. This kind of morphing structure provides a feasible alternative for the application when performance, aerodynamics and stealth capabilities are required against the conventional fin design.
The key advantages of GRAF configurations are the weight savings, the improved stability characteristics and control authority. Despite the design difficulties that must be faced especially when dealing with vertical tails having very low aspect ratio, this conceptual study has lead to positive results.
The slot connection of GRAF together with the twisting shaft and the LSS design played a key role in this successful design. The LSS helps the fin to camber its shape without hinges. The tubular shaft initiates the twist in only a small part of the fin and leads to the aeroelastic effect to enlarge the deformation and aerodynamic force. Finally, the slot-connection presenting a smart and novel design, allows the fin warping to obtain an increased twist, compared to a fixed root design.
Since the GRAF concept leads to an improved stability and control characteristics, the gross fin area can be reduced with respect to a conventional configuration. This will lead to a further reduction in aerodynamic drag, radar visibility and weight for the aeroservoelastic vertical empennage.
The next "V3" GRAF model will be based on an inverted trapezoidal geometry intending to reduce the portion of root chord in contact with the fuselage. In the meantime a prototype of the "V1" fin will be built and tested in the wind tunnel in order to validate the theoretical assessment of the GRAF design.

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