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Morphed Vertical Tailplane Assessment for Certification Requirements

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Abstract: The successful development of new high performance materials and actuators enable the controlled deformation of aerodynamic profiles for wing like type of structures. This paper presents the studies and conclusions of incorporating a novel morphing rudder for a commercial transport aircraft from the certification conditions perspective. This study provides the static directional-lateral stability evaluation of a two jet engined wing podded commercial transport aircraft when changing its conventional rudder configuration to a more aerodynamic efficient morphing configuration. The lateral force at morphed rudder deflection is set to increase 15% in relation to conventional configuration. The analysis is focused on the engine-out condition at take off which is critical for certification purposes. The analysis concludes the new configuration control surfaces trimming and slippage angle from static directional- lateral stability for this critical load case. The increment on heading moment available is also estimated for the new configuration. This augmentation is translated into minimum control speed requirements and its benefits are assessed.

Key words: Morphing, fin, rudder, engine-out, flight dynamics, certification.

1. Introduction

There is an actual trend to increase the research for better aircraft configurations in terms of structural weight and drag reduction. This trend, in fact, has been a constant challenge for aeronautics, but lately, due to the combination of higher fuel prices and bigger social concern on emissions, together with the fact of the continuous civil aircraft transport world fleet increment, have intensified the attention on the research inside the aeronautics community.

This study focuses on the research of a new morphed rudder to be incorporated on a vertical stabilizer. The modern transport aircraft fin is mainly sized by static loading stiffness and strength requirements. There are two static load cases that size most of the vertical empennage, fix and movable control rudder surface, the lateral gust during approach and landing, and the engine out during takeoff. The later load case is even more critical than the lateral gust due to the trend to increase engine thrust for higher capacities on twin engines under the wing configurations. This platform is the preferred choice for big transport commercial aircraft due to its higher fuel efficiency and the reduction of maintenance costs in relation to four-engined one. The focus of this study aims to increase rudder aerodynamic efficiency based on a morphing solution and, in consequence, enable its size reduction, not only because of the potential weight and drag reductions, but also because there are operational benefits on static and dynamic stability which can be achieved. In particular, the studies on this paper focus on lateral directional static stability effects of morphing rudder implementation on such a transport aircraft 100 passengers size.

The current developments on EU Clean Sky and Clean Sky 2 are going to enable the incorporation of different technologies up to flight demonstration, [1-14]. It is relevant, for the purpose of this study, the efforts to develop natural and laminar flow technologies up to flight demonstration. In the case of Clean Sky FP7 Smart Fixed Wing Aircraft, it is planned to flight demonstrate Natural Laminar Flow

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external wings on an A340 Flight Test Platform. For Clean Sky 2 the plan is to develop Hybrid Laminar Flow on a Vertical Tail Plane of a transport aircraft flight test bed. The smoother aerodynamic pressure distributions originated by morphing the control surface, as concluded in previous studies [15], may constitute a relevant result for future laminar flow configurations. The dynamics of the morphing wing have been addressed also in previous studies [16]. The aerodynamic improvements of a morphing wing tip have also been concluded [17].

As a matter of fact, and in parallel, NASA & Boeing have made public recently, April 2015[1], the completion of flight testing of Active Flow Control system on a 757 Vertical Tail. This system is based on 31 tiny sweeping jet actuators installed at rudder leading edge chord position. The results from these tests suggest that the vertical tail plane for this type and size of commercial transport airplane can be reduced 17% with an effect of 0.5% of fuel usage. The use of these jet actuators provide a similar effect in terms of smoothing the aerodynamic pressure distribution, as the morphing rudder can provide.

In summary, as concluded in previous published work, the aerodynamic improvement assessment of non conventional curved rudder has proved to bring potential increment of 15% on lateral force when deflected [15]. The aerodynamic pressure distribution for morphed rudder is smoother than the resulting for a conventional one. Similar use of aerodynamic profile morphing to delay the boundary layer transition from laminar to turbulent has been previously analyzed with SMA actuators [18, 19].

The new unconventional rudder can curve chord-wise, while maintaining straight lines span-wise. The new rudder deflection angle is measured as the one that forms the line connecting the hinge line with the aft trailing edge point. Therefore the only difference between the new and the conventional rudder for a given deflection angle, is that the unconventional one presents a curvature that is the base of the aerodynamic improvement. The development of an airworthy structural solution for such a rudder is the objective of previous works [20, 21] (Fig. 1).

Studies like this one, that partially cover the airworthiness requirements of a morphing rudder, from static stability point of view, are required prior to flight clearance of the flight demonstrators. This article studies the lateral directional static stability of a transport aircraft in which the rudder has been reconfigured to provide a constant 15% more lateral load during deployment. The aircraft is under 1 g stationary load cruise condition.

Several solutions for control surface morphing are under development currently. SARISTU EU FP7 R&T Project partners are developing a wing control surface that can provide the required curvature when activated [22]. There are other studies to provide different morphing solutions for flapped airfoils for noise reduction [23]. The study of shape-morphing adaptive control surface of an airfoil, has provided a significant number of research in compliant mechanisms for aircraft [24, 25], wind energy [26-28], and other UAVs, Unmanned Aerial Vehicles [29-31].

There are no previous publications on the new adaptive lateral control surfaces static stability effects specifically. The more similar recent studies have been developed on morphing tailless configuration aircraft flight control from different perspectives, as aeroelastic improvements [32]; the use of distributed shape-change effectors arrays in a flight control system [33, 34]. Again, the study of new UAV configurations, has resulted on a relevant number of publications on lateral stability analysis and control [35].

2. Lateral Directional Flight Qualities and Static Analysis Matlab Modelling

The lateral-directional flight qualities must be investigated under conditions of balanced and

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[1] http://www.hngn.com/articles/86064/20150421/nasa-boeing-flight-experiments-ecodemonstrator-757-more-tests-technology.htm.

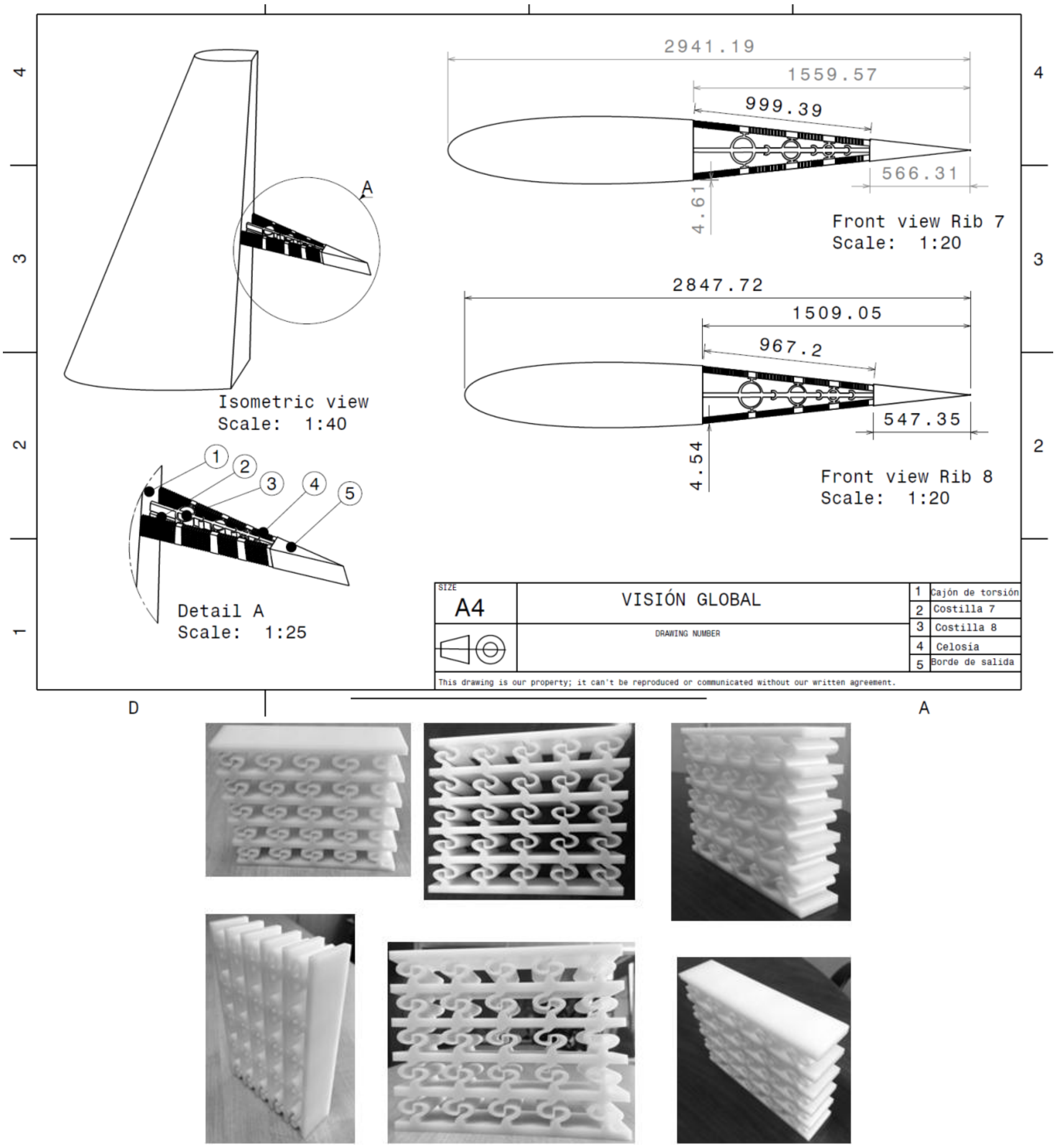

Fig. 1 Morphing rudder structural architecture and 3D printed detail.

unbalanced flight. Under equilibrated and balanced flight conditions, the three static lateral directional flight characteristics to investigate in a steady flight, are:

- Static directional stability: the variation of directional control forces and the positions of the rudder as slip angle changes;
- Static lateral stability: the variation of forces and positions of the ailerons when modifying the slip angle;
- Lateral force characteristics: the variation of roll angle when the yaw angle changes.

Then, under non-equilibrium, or dynamic, conditions, to complete the research is required to study the characteristics of the three lateral directional eigen-modes: the rolling mode, the spiral mode and the Dutch roll.

This work is centered on providing the lateral-directional static analysis. Further studies are required and are currently under development in the field of dynamic stability. The rudder modification does not affect the characteristic dynamic matrix, but it does on the control matrix, called [A] and [B] in the literature [36, 37]. In consequence, the rudder improvement affects the dynamics margins of stability and the effects can be evaluated.

Moreover, the improvement in the effectiveness of the morphed rudder in relation to the conventional one is investigated and studied, to characterize the influence of the change in the lateral/directional static stability and control of the aircraft. In the following paragraphs it is summarized the studies on the effect of the introduction of non-conventional rudder from static stability conditions of the target plane in case of engine failure on takeoff at sea level. The improved aerodynamics of the new rudder is translated into a new static equilibrium. The case study is engine-out at sea level due to its criticism on aircraft design and the implications of certification requirements.

The reference aircraft is a commercial transport 100 passengers, two engines-low wing podded. As a first step, the aerodynamic influence coefficients, or simply aerodynamic coefficients, for this reference airplane are derived, due to the lack of published lateral stability derivatives data for this type of aircraft. There are references in the literature, to obtain stability derivatives with CFD methods [38], or FEM methods [39]. In this study the method used has been well documented in the literature [40], contrasted with data published as DATCOM [41]. The aircraft key parameters are included in Table 1. This set of data has been obtained partially from reference [42].

The engine-out condition is considered at critical take off speed, an aircraft velocity 85 m/s that corresponds to the critical one for engine-out take off, air density at sea level, dry air 1.237 kg/m^3. The lateral-directional aerodynamic coefficients are derived based on the previous included aircraft data and a Matlab code that computes the different values according to literature [43]. The results for conventional rudder configuration are included in Table 2.

Table 1 Reference aircraft key parameters.

Reference aircraft parameters	Value
Wing dihedral angle (deg)	5.0
Wing reference height (m)	1.3
Wing reference surface (m^2)	72.7
HTP reference height (m)	5.3
VTP chord length at root (m)	4.7
VTP chord length at tip (m)	1.4
VTP sweep angle at ¼ chord (deg)	35.0
VTP span (m)	3.5
VTP reference height (m)	3.1
VTP reference surface (m^2)	9.8
Wing span (m)	25.1
Wing sweep angle at 1/2 chord (deg)	23.5
Wing-VTP aerodynamic lift coefficient	1.1
HTP span (m)	9.8
HTP sweep angle at 1/2 chord (deg)	30.2
Fuselage diameter (m)	3.2
Fuselage Length (m)	23.9

Table 2 Lateral directional aerodynamic coefficients (rad^{-1}).

Coefficient	Value	Coefficient	Value
cy_{beta}	-1.27	cn_{da}	-0.02
cl_{beta}	-0.30	cy_{dr}	0.36
cn_{beta}	0.26	cl_{dr}	0.02
cy_{da}	0	cn_{dr}	-0.20
cl_{da}	0.14		

3. Morphing Rudder Case Study Results

The steady flight after one engine-out event, is characterized by rudder deflection that generates aircraft lateral force and heading moment that compensates thrust asymmetry. The consequent slippage angle requires ailerons asymmetrical deflection to end the required aircraft force and moment equilibrium.

To characterize the flight, the maximum rudder deflection is set to 30º for conventional and new morphed rudder. The deflection angle for the new morphed rudder is convey to be the one between non deflected position and the line that joints rudder leading edge height middle point with the aft trailing edge point.

To sustain equilibrated flight after engine out, the aircraft presents slip angle that can be derived based on the equation that provides the lateral force, Y_{ext}:

$$C_{y_{\delta_a}}\delta_a + C_{y_{\delta_r}}\delta_r + C_{y_\beta}\beta + C_L sen\,\Phi = -\frac{Y_{ext}}{qS_{ref}}$$

As the external lateral forces are null, and $C_{y_{\delta_a}}$ is also considered negligible for the purpose of this analysis, then:

$$\beta = -\frac{C_{y_{\delta_r}}\delta_r + C_L sen\,\Phi}{C_{y_\beta}}$$

For the reference airplane, in order to provide enough clearance between engines and wing tips with the ground, the limitation of the roll angle, Φ, is set to 5º. In consequence, the maximum rudder deflection is set to 30º, the ailerons to 28º and the aircraft bank angle to 5º, for both configurations. The engine-out stable flight aircraft required slippage angle, β, for the original and the morphed configurations are obtained by means of the aforementioned Matlab code and the results included on Table 3.

This confirms that the new rudder has an associated increase in slip angle between 5 and 10% in relation to the conventional configuration.

Finally the maximum available yaw moment can be calculated using the equilibrium equation.

$$C_{n_{avail}} = C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r + C_{n_\beta}\beta$$

As for both configurations, $C_{n_{\delta_a}}$= 0.0179 and C_{n_β}= 0.595, then the value of $C_{n_{avail}}$ is derived as shown in Table 4.

The new rudder has an associated increase in the maximum yaw moment available around 7.7% compared to the conventional configuration. This result implies that the aircraft configuration with the new rudder present a potential decrease, corresponding to the square root of improved yaw moment available, of 3.8% of the minimum lateral control speed VMC, on ground VMCG and in flight VMCA, as defined by certification authorities as airworthiness requirements [44], paragraph CS 25.149.

This is a significant improvement to complete flight qualities assessment for one of the sizing rudder cases. Decreasing 3.8% minimum control speed on the ground and in flight has an associated greater margin of controllability of the airplane relative to the rate of loss control commands (stick shaker). This is an issue that deserves further investigation, because of the potential benefits on configuration decisions for large transport aircraft design. Currently there is a tendency to enlarge transports aircrafts based on smaller platforms capacity, A350 XWB 1000 in relation to version 900 and Boeing 777X in relation to the basic versions 777-300. The diminishing effect on the minimum control speed is very relevant to avoid the undesirable situation of higher minimum control speed that stick shaker warnings when enlarging the capacity of already certified airplanes.

Table 3 Engine out stable flight angles.

Configuration	cy_{dr}	cy_{beta}	beta (deg)
Conventional	0.36	-1.27	7,0º
Morphed rudder	0.42	-1.27	7.5º
Difference	15.0%		7.8%

Table 4 Effect on the available yaw moment of the introduction of new rudder in relation to the conventional configuration, in the case of engine failure at takeoff.

Configuration	δ_a (deg)	$C_{n_{\delta_r}}$	$C_{n_{avail}}$
Conventional	26,1	-0,1084	4,1
New rudder	27,9	-0,1247	4,4
Increment	6,6%	15 %	7,7%

4. Conclusions

Consequently, the results of modifying the aircraft configuration with the new unconventional rudder for lateral directional control in level flight status after engine out during take-off, are as follows:

- The change on the derivative coefficients of directional stability for slippage and aileron deflection of lateral force, balance and yaw moments, is negligible;
- The lateral directional stability force coefficients for rudder deflection increase 15% due to increased efficiency of the nee morphed rudder.

Regarding the attitude of the aircraft after engine failure on takeoff and the restore balanced flight with the new morphed rudder and in relation to the conventional one, the following conclusions apply:

- There is an increase in the angle of slippage due to the greater effectiveness of the rudder, around 8%;
- The available yawing moment rises 7.7% and consequently the minimum lateral control speed is decreased around 4%.

These findings can be considered validly from a relative point of view since they are the result of comparing conventional rudder configurations and unconventional one. The absolute validity cannot be inferred due to the lack of robust aerodynamic data coefficients, resulting from flight tests, as they have been analytically estimated.

Further studies regarding the effect of the new morphing rudder from lateral directional dynamics stability are required in order to completely assess the certification requirements.

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