Aerodynamic design of advanced rear end for large passenger aircraft

Salvatore Corcione[1,a*], Vincenzo Cusati[1,b] and Fabrizio Nicolosi[1,c]

[1] Industrial Engineering Department, University of Naples Federico II, Via Claudio 21, 80125, Naples, Italy

[a]salvatore.corcione@unina.it, [b]vincenzo.cusati@unina.it, [c]fabrnico@unina.it

Keywords: Aircraft Design, Forward Swept Tailplane, Leading Edge eXtension, Aerodynamics

Abstract. This paper focuses on the aerodynamic design of an advanced rear end concept for a large passenger aircraft, such as the Airbus A320. The aim was to reduce the size of the horizontal tailplane to minimize the aerodynamic drawbacks related to longitudinal stability and control requirements. This reduction would lead to improved aircraft performance by reducing fuel burn and rear-end weight. Assuming the same position of the aerodynamic center of the horizontal tailplane of a conventional aircraft, the results of this investigation showed that the required stabilizing performance of the tail could be achieved with a smaller tail surface. A reduction of 6% in tail planform area was achieved by leveraging the unique aerodynamic characteristics of a forward-swept tail, combined with the implementation of a leading-edge extension device. The reduced wetted area and the lower weight of the horizontal empennage could result in fuel savings of 100 to 120 kg of fuel per 1,000 km. This is equivalent to approximately 1.0 to 1.2% for the specific aircraft category being considered.

Introduction

Advancements in design and improvements in empennage efficiency and effectiveness have the potential to enhance aircraft performance by reducing fuel burn and weight through reductions in tail-plane size. The penalties associated with meeting both longitudinal and directional stability and control requirements constitute a significant portion of the total aircraft drag. Loads acting on aircraft tails contribute to the overall induced drag, compressibility, profile drag, structural weight, and maximum lift capability of the aircraft. The empennage of a typical Large Passenger Aircraft accounts for one-fifth to one-fourth of the total lifting surface and 3% up to 6% of the maximum take-off weight. It contributes 5% to 8% to the total trimmed drag in cruise conditions [1].

The simplest unconventional solution is represented by the Vee-tail [2,3]. This solution is sometimes used in remotely piloted aircraft and has also been implemented in mass-produced manned aircraft, such as the Beechcraft Bonanza M35. However, the results of the NEFA [4] project concluded that although a Vee-tail configuration offered performance improvements due to its reduced wetted area, the added complexity and additional system did not result in any weight or cost benefits over a conventional empennage. A comprehensive study on advanced rear-end configurations was recently conducted in the EU-funded project NACRE [5] demonstrated that these configurations could offer advantages in terms of reducing empennage drag, but not in terms of weight.

To further advance the implementation of rear-end concepts that effectively reduce drag and weight, the utilization of a forward-swept horizontal tailplane could represent a viable way.

The adoption of a forward-swept tailplane enables a structural configuration in which the connection of the horizontal tail to the rear end does not require a structural opening in a region of the fuselage that is heavily affected by structural loads [6]. By removing the structural opening at the rear end, the weight of the fuselage can be reduced. This solution also reduces fuselage deformations, resulting in a more efficient horizontal stabilizer surface [6].

Transonic aircraft wings typically have a positive sweepback. The main reason is linked to the aircraft encountering a vertical gust during its flight. In the case of positive sweepback, the bending deformation decreases the local angle of attack, resulting in a natural reduction of aerodynamic loads. In the case of a wing with a negative sweep angle, the effect is reversed. As a result, static divergence may occur, leading to structural failure. Forward-swept wings are capable of withstanding significantly higher gust loads compared to wings with positive sweepback, making them heavier. Despite this drawback, several studies have explored the potential of utilizing the aerodynamic advantages of a forward-swept wing [7,8] propose a solution to mitigate the coupling between flexional and torsional deformation by using aeroelastic tailoring techniques. In terms of structural sizing, aeroelasticity is less demanding for wings with a relatively low aspect ratio. Thus, in the case of horizontal tails, introducing negative sweep angles could be a viable solution to improve the performance of the rear-end and empennage.

Forward-swept lifting surfaces offer several aerodynamic advantages over conventional sweepback designs. For a given leading edge sweep angle, forward-swept wings exhibit a shock-sweep angle that is five degrees higher than that of aft-swept wings [9]. Therefore, the implementation of a forward-swept design requires a smaller leading edge sweep angle compared to a positively swept-back configuration with an equivalent sweep angle at the quarter chord line. Moreover, in a forward-swept wing, the airflow moves from the root to the tip, resulting in higher stall angles [10], increasing the maximum aerodynamic forces or reducing the tailplane area can yield the same maximum force, potentially leading to a decrease in drag and weight.

This paper deals with the aerodynamic design of an advanced rear-end configuration carried out within the EU-funded project named IMPACT [11]. The aim is to optimize the rear-end of the fuselage and empennage of large passenger aircraft to reduce drag, weight, and fuel burn. The investigation focuses on minimizing the surface area of the horizontal tailplane by utilizing the unique characteristics of a forward-swept lifting surface, which is further enhanced by passive leading edge extension devices.

Advanced Rear End Aerodynamic design

To fully catch the peculiar aerodynamic features, high-fidelity CFD RANS calculation were required. The high-fidelity analysis was performed using the commercial software STARCCM+. Details of the numerical model setup are reported Table 1, whereas Figure 1 shows a comprehensive overview of the fluid domain and the application of boundary conditions. The investigation started by comparing the reference isolated tailplane geometries: a conventional tail (HTP) and a reference forward-swept arrangement. Table 2 summarizes the main design parameters. Results clearly indicate that the isolated forward-swept tail arrangement effectively wash in the aerodynamic loads. Thanks to this peculiar behavior, the FSHTP exhibits better aerodynamic performance in terms of lift curve slope and maximum achievable negative lift coefficient, as indicated by the chart of Figure 2. This means that an aerodynamically equivalent forward-swept tail would require a smaller area to reach the same aircraft stability and control characteristics.

Since an additional component must be added, this element can be designed to enhance the lifting capacity of the tail. In this respect, the additional element would be a leading-edge extension device (LEX).

Table 1 Numerical setup and mesh characteristics for high-fidelity CFD analysis

Parameter	**Value**
Domain span	16 $b_H/2$
Domain height	30 $b_H/2$
Domain length	100 $b_H/2$
Mesh type	unstructured polyhedral
On body minimum surface size	0.0042 (m)
On body target surface size	0.035 (m)
Number of volume cells	11 183 156
Number of prism layers	25
First cell wall distance	$1e^{-6}$ (m)
Turbulence model	SST $\kappa - \omega$
Flow model	Compressible
Inflow boundary condition	Free stream
Outflow boundary condition	Pressure outlet
Number of iterations	5000
Mach number	0.2
Flight altitude	sea level

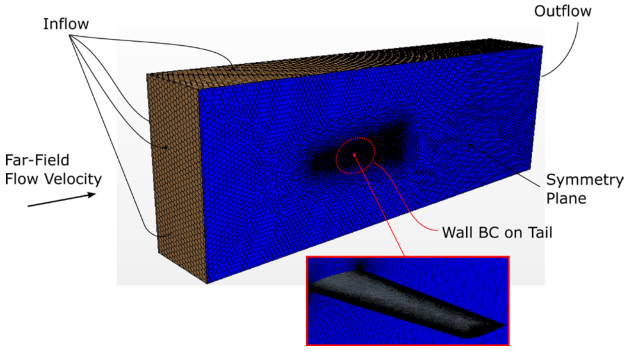

Figure 1 Fluid domain and boundary conditions using STAR-CCM+.

Table 2 Reference geometries, HTP and FSHTP.

	HTP	**FSHTP**
Sweep angle	32 deg	-15 deg
S_H	31.36 m^2	31.36 m^2
$b_H/2$	6.723 m	6.723 m
Taper Ratio	0.36	0.715
Aspect Ratio	5.765	5.765

Unfortunately, these advantages are lost when considering the fuselage-tail configuration. The forward-swept tail arrangement exhibits significant separation at the junction with the fuselage. This reflects on the lifting capabilities, as shown in Figure 3.

To design an effective advanced rear end that incorporates a forward-swept tailplane, an additional component must be introduced to prevent significant flow separation at the junction of the fuselage.

Leading Edge eXtensions (LEX) are aerodynamic features found on some aircraft, typically fighter jets. LEX refers to the forward extensions of the wing root area, usually in a triangular or trapezoidal shape. They are located at the junction between the wing and the fuselage. The primary purpose of LEX is to improve the aircraft's high angle-of-attack performance and enhance its manoeuvrability.

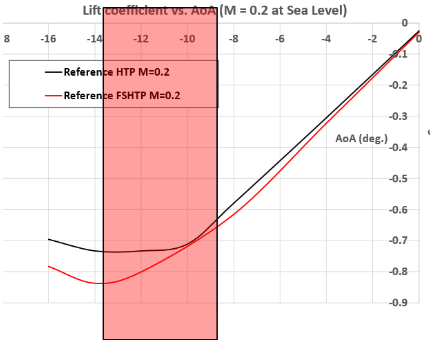

Figure 2 Comparison of the lift coefficient curves for conventional HTP and FSHTP configurations.

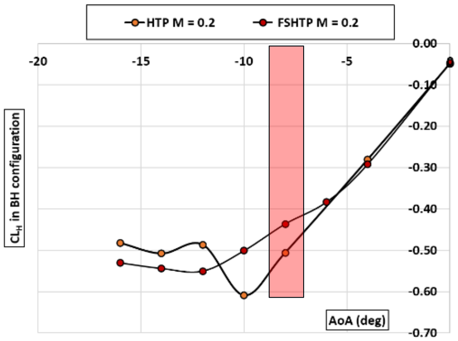

Figure 3 Comparison of the lift coefficient curves for HTP and FSHTP (body and horizontal tailplane).

By performing a Design of Experiment about several forward-swept tailplanes and LEX designs, see Figure 4, the best solution has been identified. As shown by the results of Figure 5, the maximum lift capabilities of the horizontal empennage can significantly be improved by introducing a forward-swept tailplane enhanced by a LEX device. The optimum solution (see the solid grey line in Figure 5), provides for a tailplane area which is 6% lower than the reference tails (see Table 3) giving a maximum negative lift coefficient which is approximatively 20% higher than the reference conventional tailplane.

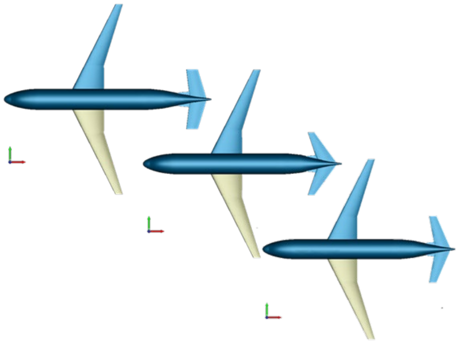

Figure 4 Some configurations investigated in the DoE execution.

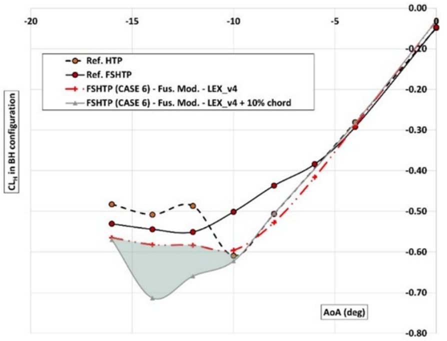

Figure 5 Lift coefficient curves for reference HTP, FSHTP and best FSHTP enhanced by a LEX device (in body and horizontal tailplane arrangement).

Table 3 Geometric parameters, reference HTP, FSHTP and Optimised FSHTP and LEX.

	HTP	**FSHTP**	**Optimised FSHTP+LEX**
Sweep angle	32 deg	-15 deg	-10 deg
S_H	31.36 m^2	31.36 m^2	29.45 m^2
$b_H/2$	6.723 m	6.723 m	6.723 m
Taper Ratio	0.36	0.715	0.620
Aspect Ratio	5.765	5.765	6.103
$(C_{LEX}+C_{rootH})/C_{rootH}$	---	---	1.804
b_{LEX}/b_H	---	---	0.217

References

[1] Anderson, J.D., Aircraft Performance and Design, WCB McGraw-Hill, Boston, MA, USA, 1999

[2] Sánchez-Carmona, A. and Cuerno-Rejado, C. and García-Hernández, L., Unconventional tail configurations for transport aircraft, Progress in Flight Physics 9 (2017) 127-148. https://doi.org/10.1051/eucass/2016090127

[3] Sánchez-Carmona, A. and Cuerno-Rejado, C., Vee-tail conceptual design criteria for commercial transport aeroplanes, Chinese Journal of Aeronautics 32 (2019) 595-610. Chinese Journal of Aeronautics. https://doi.org/10.1016/j.cja.2018.06.012

[4] CleanSky, New empennage for aircraft (NEFA), https://cordis.europa.eu/project/id/G4RD-CT-2002-00864

[5] Frota, J. and Nicholls, K. and Müller, M. and Gall, P.E. and Loerke, J. and Macgregor, K. and Schmollgruber, P. and Russell, J. and Hepperle, M. and Dron, S. and Plötner, K. and Gallant, G., Final Activity Report. New Aircraft Concept Research (NACRE), NACRE Consortium: Blagnac, France (2010). https://cordis.europa.eu/project/id/516068/reporting

[6] Llamas Sandin, R.C. and Luque Buzo, M., Aircraft Horizontal Stabilizer Surface, Google Patents (2010) US 2010/0148000 A1. https://patents.google.com/patent/US20100148000A1/en

[7] Seitz, A. and Kruse, M. and Wunderlich, T. and Bold, J. and Heinrich, L., The DLR Project LamAiR: Design of a NLF Forward Swept Wing for Short and Medium Range Transport Application, 29th AIAA Applied Aerodynamics Conference (2012). https://doi.org/10.2514/6.2011-3526

[8] Seitz, A. and Hübner, A. and Risse, K., The DLR TuLam project: design of a short and medium range transport aircraft with forward swept NLF wing, CEAS Aeronautical Journal 11 (2020) 449-459. https://doi.org/10.2514/6.2011-3526

[9] Roskam, J. and Lan, C.T.E., Airplane Aerodynamics and Performance, DARcorporation, Lawrence, Kansas 66044, USA, 1999

[10] Bertin, J.J. and Cummings, R.M., Aerodynamics for Engineers, Pearson Education International, Upper Saddle River, NJ, 2009

[11] AIcraft advanced rear end and eMpennage oPtimisaAtion enhanced by anti-iCe coaTings and devices (IMPACT), GA no. 885052. https://www.impact-cleansky-project.eu/