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Aerodynamic guidelines in the design and optimization of new regional turboprop aircraft

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ABSTRACT

This paper aims to provide some guidelines in the aerodynamic design and optimization of future regional turboprop aircraft with about 90 passengers. Currently there are no configurations on the market of this type, thus a typical 70 passengers turboprop aircraft is taken as reference starting point. The most critical aircraft components in terms of aerodynamic drag contribution and possible improvement are highlighted and an automatic procedure manageable trough MATLab® is described. This interfacing procedure allows importing and modifying geometries using interpolating curves and surfaces via NURBS. Within the optimization loop, any new geometry is analyzed trough the panel code solver until optimized shapes are found. Wing–fuselage junction (also called "Karman"), undercarriage pod, fuselage nose and wing-tip device have been investigated and estimation of performance advantages has been computed. Design of the winglet is presented highlighting performance improvements during the entire mission profile. Finally two different turboprop configurations are proposed: the first with a 4-abreast fuselage arrangement and the second with 5-abreast, highlighting pros and cons of each configuration.

1. Introduction

Nowadays the increase in oil price, the huge growth of air transport traffic and the increasing attention to the aircraft environmental footprint led to considerable interest of specialists in new configurations of regional transport aircraft. As highlighted by the ATR Senior Vice President of Operations, Luigi Lombardi, during EWADE 2011 conference, the airlines will need about 3000 new turboprops in the next 20 years [22]. The 42% of the new turboprop deliveries expected to be 70 seats. The new 90+ seat segment is a strong percentage of the total, i.e. the 39% as shown in Fig. 1. Also Bombardier Commercial Aircraft Vice President Marketing, Philippe Poutissou, has expressed optimism about the future and he sees strong demand for this size aircraft in the market in the next two decades [45]. In particular, in its latest forecast of new aircraft deliveries in the 20–149 seat market segment over the next 20 years, Bombardier forecasts that 5800 aircraft will be delivered in the 60–99 seat segment and 6300 (only 500 more) in the 100–149 seat category [45,6]. This work aims to provide some guidelines in the aerodynamic design of future regional turboprop aircraft with about 90 or more passengers.

The aerodynamic design of an airplane has been constantly improved since its introduction in the 1920s. The design of a new flight vehicle was soon accompanied by theoretical research and wind tunnel testing. These new design techniques required not only sophisticated design tools, but also high capabilities to realize the designed geometries and to sustain the costs. Past research activities on aircraft design aimed to drag reduction and usually they were focused on wing and lifting surface design, and especially on airfoil design. However, especially at high speed conditions (low lift coefficient and then low induced drag), an accurate fuselage design is crucial to reduce the total drag of an aircraft and improve flight performance.

One of the most important items on the fuselage aerodynamic design is the junction between wing and body. With the junction term is identified the connection of bodies with different aircraft components, in this special case the wing and the free-form shaped body of the aircraft. In particular, this junction induces interactions between the components, especially the combined boundary layers causes a flow phenomenon very difficult to describe and simulate as well explained in Simpson [43], Hoerner [18] and Schlichting and Truckenbrodt [39].

Simpson shows that the flow around a junction is characterized by a three-dimensional separation with horseshoe vortices

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Nomenclature

α	angle of attack	M	Mach number
β	angle of sideslip	OEI	one engine inoperative
η_p	propeller efficiency	RC	rate of climb
θ	boundary layer momentum thickness	Re	Reynolds number
AEO	all engine operative	S	wing surface
AR	wing aspect ratio	S_{ref}	reference area in the Squire–Young formula
C_D	drag coefficient	SHP	shaft horsepower
C_{D0}	zero lift drag coefficient	U_e	inviscid external velocity in the Squire–Young formula
$C_{\mathscr{L}}$	rolling moment coefficient	W_{TO}	maximum take-off weight
$C_{\mathscr{N}}$	yawing moment coefficient	b	wing span
$D_{MAX,f}$	maximum fuselage diameter	d_{eq}	fuselage equivalent diameter
H	boundary layer shape factor	e	Oswald's factor
L_f	fuselage length	r	radius in the Squire–Young formula

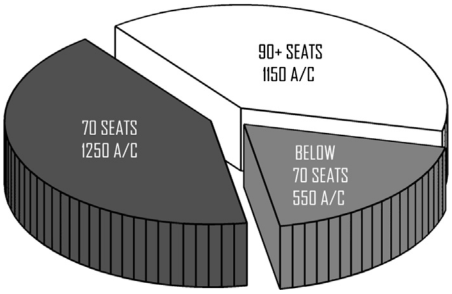

Fig. 1. Long term demand for Large Turboprop, ATR Forecast, March 2010 [22].

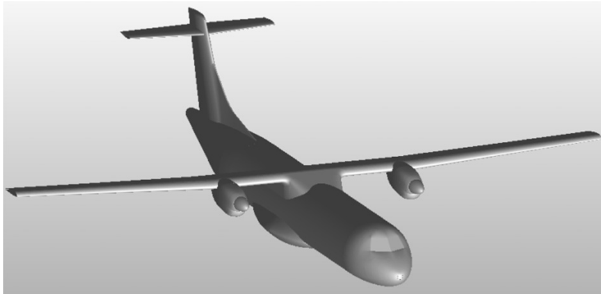

Fig. 2. Typical regional turboprop aircraft.

that wrap around the obstacle. These vortices are responsible for high turbulence intensities, high surface pressure fluctuations and increased in drag. He summarizes that the vortices intensity is related to the shape of the obstacle, its size, its blockage to the flow field and Reynolds number. These phenomena can be reduced modifying the wing body geometry or the approach flow.

As suggested by Siegel [42], in order to achieve improvements, there are several ways to manipulate the flow around the junction: (i) optimize the relative wing–body position; (ii) adapt the junction shape with fillets and fairings and (iii) manipulate the flow with active installations.

Extensive experimental research was done in the past at NACA, such as the broad investigations by Jacobs and Ward [21] on the relative wing–body position and fillet-specific investigation by Muttray [24]. The drag characteristics of wing–body junctions were summarized by Hoerner [18] and Schlichting and Truckenbrodt [39]. Subsequently improvements of measurement systems and numerical simulations made it possible to focus on the flow phenomena itself. Remarkable investigations were made by Fleming et al. [15]; extensive measurements can be obtained from Oelcmen and Simpson [30] and a detailed summary is given by Simpson [43]. More in detail the influence on lift and drag of the wing–body relative position was extensively investigated by Jacobs and Ward [21].

The main results of this work were (i) drag coefficient gradient $CD\alpha$ increases greatly for high-wing configuration, especially as the wing bottom surface is tangent to the fuselage surface; (ii) short lengthwise position of the wing to the fuselage nose has a small positive effect in reducing parasite drag. However it was also shown in Ref. [21] that, in order to achieve a fitting curvature of the intersection lines, fairings, fillets and fuselage design at these positions provide the chance to reduce drag to acceptable magnitudes similar to middle or far outer wing mount position. Especially sharp angles between body and wing cause early separation, thereby wider join angles reduce drag. An interesting approach for these wider join angles in combination with cambered high-mounted sailplane wings was done by Boermans et al. in Refs. [4,5].

Perhaps the most useful approach to reduce fuselage drag is the adoption of fillets and fairings between wing and body, and an accurate fuselage design, so-called stream-line fitted body-shaping as described in Ref. [5].

Haines [17] advises a fairing designer to do the following: (a) eliminate flow separations, including those that lead to standoff vortices, (b) reduce cross-flows in boundary layers, (c) merge different streams smoothly, and (d) avoid the development of thick boundary layers.

White did extensive research [49] on a 1929 low-wing motor plane wing–body junction and measured a greatly reduced separation and drag reduction. Also leading edge and trailing edge fillets were investigated in Refs. [49,23,47] showing that an accurate design of these parts can reduce drag. In particular they focused on the junction vortices highlighting both experimentally [49,23] and numerically [47] how smooth fillets and streamlined fairings can reduce flow separations thus reduce aerodynamic drag.

In this research work particular attention has been posed to the wing–body junction, wing–body fairing, undercarriage vane and on the fuselage nose. As a matter of fact, in these zones several geometry discontinuities or abrupt change in curvatures can occur especially for typical turboprop aircraft as shown in Refs. [12,13].

The present work aims to provide aerodynamic guidelines putting in evidence critical turboprop aircraft components which can negatively affect drag coefficient.

To better highlight the most critical areas in terms of aerodynamic behavior, a typical 70 passengers turboprop aircraft is taken as reference starting point. This configuration has the wing in the high position for propeller clearance, T-tail and under wing engines as shown in Fig. 2.

An aerodynamic analysis of the reference geometry has been performed trough a panel code deeply tested and used by the au-