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An investigation on vertical tailplane contribution to aircraft sideforce

Fabrizio Nicolosi [1], Pierluigi Della Vecchia [*,2], Danilo Ciliberti [3]

University of Naples "Federico II", Via Claudio 21, 80125 Naples, Italy

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ABSTRACT

The paper presents a deep investigation on the aerodynamics of the vertical tailplane and the correct estimation of its contribution to aircraft directional stability and control, especially during the preliminary design phase. Nowadays the most used methodologies in preliminary design to estimate the contribution of vertical tailplane on aircraft directional stability and control are (i) the classical method proposed by USAF DATCOM (also presented in several aeronautics textbooks) and (ii) the method presented in ESDU reports. Both methodologies derive from NACA World War II reports of the first half of the '900, based on obsolete geometries that do not represent the typical shape of a transport aircraft. The other limit is that these methods give quite different results for certain configurations, e.g. in the case of horizontal stabilizer mounted in fuselage. As shown in literature, the main effects on the sideforce coefficient of the vertical tail are due to the interactions among the aircraft components. In order to better highlight these effects, a different approach using the RANS equations has been adopted. Several CFD calculations have been performed on some test cases (used as experimental database) described in NACA reports to verify the compliance of CFD results with available experimental data. The CFD calculations (performed through the use of a parallel supercomputing platform) have shown a good agreement between numerical and experimental data. Subsequently the above mentioned effects have been deeply investigated on a new set of aircraft configurations. The configurations that have been prepared differ among them for wing aspect ratio, wing–fuselage relative position (high-wing/low-wing), vertical tailplane aspect ratio (vertical tail span versus fuselage height) and horizontal tailplane position respect to the vertical tailplane (with the aim of investigating the effect of fin-mounted T configuration, typical of regional turboprop transport aircraft). All the CFD analyses have been carefully post-processed and have been useful to obtain new curves to predict the above mentioned effects and thus to have a more accurate estimation of vertical tailplane contribution to aircraft directional stability and control.

1. Introduction

This paper presents a deep investigation on the aerodynamics of the vertical tail, in particular on the sideforce coefficient that affects the directional stability and control of the airplane. A reliable tailplane design needs an accurate determination of the stability derivatives. Extreme flight conditions often set severe design requirements for tail surfaces, like minimum control speed with One Engine Inoperative (OEI) or maximum cross-wind aircraft capability: stability and control must be ensured even in very large angles of sideslip, up to 25° [18]. These requirements are stated by the Federal Aviation Authorities (FAA) and by the European Aviation Safety Agency (EASA). Vertical plane design criteria also depend on the type of airplane (and so the flow regime), engine numbers and position, wing–fuselage and horizontal tail position [30]. These factors affect the estimation of stability derivatives (the variation of aerodynamic coefficients with the independent variable, the angle of sideslip). This process is somewhat complicated since it involves asymmetrical flow behind the wing–fuselage combination and lateral cross-control. A compromise in high lift gradient and low aspect ratio and taper ratio must be considered [18,23].

From the '30s to the '50s, in the USA, the National Advisory Committee for Aeronautics (NACA) provided a huge amount of results on the directional stability on isolated vertical tailplanes, partial and complete aircraft configurations obtained through many hours of wind-tunnel tests. These results were summed up in a new design procedure completely reported and described in the United States Air Force Data Compendium (USAF DATCOM) by Finck [7]. The investigations were focused on the attempt to separate the effects of fuselage, wing and horizontal tail from the isolated vertical tail. Lots of geometries were tested, from the early years to the '50s, i.e. rectangular, elliptical and swept wings, symmetrical and unsymmetrical airfoils, slender bodies with rounded

* Corresponding author.
E-mail addresses: fabrizio.nicolosi@unina.it (F. Nicolosi), pierluigi.dellavecchia@unina.it (P. Della Vecchia), dancili@gmail.com (D. Ciliberti).

[1] Associate Professor.
[2] PhD Student.
[3] Student.

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Nomenclature

α	angle of attack
β	angle of sideslip
λ	taper ratio
λ_h	horizontal tailplane taper ratio
λ_v	vertical tailplane taper ratio
θ	upsweep angle
Δ	difference
Λ	sweep angle
Λ_{hLE}	horizontal tailplane leading edge sweep angle
Λ_{hTE}	horizontal tailplane trailing edge sweep angle
Λ_{vLE}	vertical tailplane leading edge sweep angle
Λ_{vTE}	vertical tailplane trailing edge sweep angle
A	wing aspect ratio
A_F	vertical tailplane aspect ratio (ESDU)
A_h	horizontal tailplane aspect ratio
A_v	vertical tailplane aspect ratio
A_{ve}	vertical tailplane effective aspect ratio (USAF DATCOM)
C_D	drag coefficient
C_{De}	effective drag coefficient
C_L	lift coefficient
$C_{L\alpha}$	lift curve slope
$C_{\mathcal{L}}$	rolling moment coefficient (complete airplane)
C_M	pitching moment coefficient
C_N	yawing moment coefficient (complete airplane)
C_Y	sideforce coefficient (complete airplane)
$C_{N\beta}$	yawing moment coefficient due to sideslip (complete airplane)
$C_{Y\beta}$	sideforce coefficient due to sideslip (complete airplane)
$C_{\mathcal{L}\beta}$	rolling moment coefficient due to sideslip (complete airplane)
$C_{N\beta v}$	vertical tailplane yawing moment coefficient due to sideslip
$C_{Y\beta v}$	vertical tailplane sideforce coefficient due to sideslip
$C_{\mathcal{L}\beta v}$	vertical tailplane rolling moment coefficient due to sideslip
S	wing planform area
S_h	horizontal tailplane surface
S_v	vertical tailplane surface
V	velocity
V_∞	free-stream velocity
V_h	horizontal tailplane volumetric coefficient
V_v	vertical tailplane volumetric coefficient
$2r$	fuselage thickness in the region of vertical tail
b	wing span
b_v	vertical tailplane span
b_{v1}	vertical tailplane span extended to the fuselage centerline
c_v	(generic) vertical tail chord
d_f	fuselage diameter
l_c	fuselage tail cone length
l_f	fuselage length
l_n	fuselage nose length
mac	mean aerodynamic chord
r_f	fuselage radius
$x_{ac,mac}$	longitudinal position of the *mac* aerodynamic center
x_{hLE}	longitudinal position of the horizontal tail *mac* leading edge
x_{vLE}	longitudinal position of the vertical tail *mac* leading edge
x_{wLE}	longitudinal position of the wing *mac* leading edge
z_h	position of the horizontal tailplane on the vertical tailplane
z_v	vertical position of the aerodynamic center of the vertical tail from C.G.
z_w	wing position in fuselage

or sharp edges, tails of different aspect ratio and size [3,4,6,10,22]. Performed tests dealt with geometries quite different from the actual transport airplanes, being more similar to World War II fighter aircraft. In fact most of the work of the NACA was pushed by war and if the aim of the early tests was to gain a certain knowledge on the physics of the problem of directional stability and control [10] and on the mutual interference among aircraft components [6], later tests aimed to improve stability and maneuverability of high-speed combat aircrafts [22].

A first effect studied (1939) by Bamber and House [3] was the aerodynamic interference of the wing–fuselage relative position on the aircraft sideslip derivatives. The general trend revealed an increase in sideforce coefficient due to sideslip $C_{Y\beta}$ and yawing moment derivative $C_{N\beta}$ when moving the wing from high to low position in fuselage, mainly due to the sidewash induced on the vertical tail by the wing–body combination. Interestingly, the effect of the angle of attack on $C_{N\beta}$ is very small.

Queijo and Wolhart [22] evaluated the effect of the fuselage on the vertical tailplane by defining an effective aspect ratio A_{ve}. The vertical tail effectiveness increased as it became small compared to the fuselage. No wing and no horizontal tailplane were mounted.

The effect of size and position of horizontal tail was studied by Brewer and Lichtenstein [4]. The 'final' fin effective aspect ratio was found to be a function of both fuselage and horizontal tail position and size, being maximum when the horizontal plane is located on the fuselage or on the tip of the vertical tail.

Apart from the NACA, in the UK, the Engineering Science Data Unit (ESDU) proposed an alternative method to compute the vertical tailplane contribution to directional stability in presence of body, wing and horizontal tailplane, described by Gilbey et al. [8]. This method contemplates conventional geometries, a circular fuselage and a value for the sidewash held constant respect to wing aspect ratio. It is a synthesis of experimental analyses done from NACA, British Aerospace, SAAB and others, from the '40s to the '70s, linked together with potential flow theory where the data were highly scattered. The theory at the base is found in the work of Weber and Hawk [31], who suppose that a fin–body–tailplane combination at incidence (or sideslip) develops a complex vortex system that induces a constant velocity along the fin span.

Until the '70s only wind-tunnel tests could provide useful info about directional stability [29], especially for the high subsonic and supersonic flow regimes, because of vorticity and shock waves [13], then computer programs appeared on the scene. Examples of panel codes used for evaluation of airplane directional stability and control can be found in Lamb et al. [12] and in Park et al. [20].

Other and more recent (last 15 years) CFD methods make use of finite differences [1], Finite Element Method (FEM) [19] and finite volume methods and any further step in stability and control analysis techniques saw a return to the study of the low subsonic flow field [19,20].

The complexity and costs of wind-tunnel tests and the increasing viscosity effects at high angles of incidence led to more and more complex CFD tools, as panel methods that account for viscosity and Navier–Stokes solvers [9,11,17].

As a matter of fact, the evaluation of lateral-directional stability derivatives for subsonic airplanes is mainly based on a couple of