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Aircraft directional stability and vertical tail design: A review of semi-empirical methods

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A B S T R A C T

Aircraft directional stability and control are related to vertical tail design. The safety, performance, and flight qualities of an aircraft also depend on a correct empennage sizing. Specifically, the vertical tail is responsible for the aircraft yaw stability and control. If these characteristics are not well balanced, the entire aircraft design may fail. Stability and control are often evaluated, especially in the preliminary design phase, with semi-empirical methods, which are based on the results of experimental investigations performed in the past decades, and occasionally are merged with data provided by theoretical assumptions. This paper reviews the standard semi-empirical methods usually applied in the estimation of airplane directional stability derivatives in preliminary design, highlighting the advantages and drawbacks of these approaches that were developed from wind tunnel tests performed mainly on fighter airplane configurations of the first decades of the past century, and discussing their applicability on current transport aircraft configurations. Recent investigations made by the authors have shown the limit of these methods, proving the existence of aerodynamic interference effects in sideslip conditions which are not adequately considered in classical formulations. The article continues with a concise review of the numerical methods for aerodynamics and their applicability in aircraft design, highlighting how Reynolds-Averaged Navier-Stokes (RANS) solvers are well-suited to attain reliable results in attached flow conditions, with reasonable computational times. From the results of RANS simulations on a modular model of a representative regional turboprop airplane layout, the authors have developed a modern method to evaluate the vertical tail and fuselage contributions to aircraft directional stability. The investigation on the modular model has permitted an effective analysis of the aerodynamic interference effects by moving, changing, and expanding the available airplane components. Wind tunnel tests over a wide range of airplane configurations have been used to validate the numerical approach. The comparison between the proposed method and the standard semi-empirical methods available in literature proves the reliability of the innovative approach, according to the available experimental data collected in the wind tunnel test campaign.

1. Introduction

The empennages in traditional aircraft configurations (Fig. 1) perform three fundamental functions: (*i*) they provide static and dynamic *stability*; (*ii*) through their movable parts, they enable aircraft *control*; (*iii*) they allow to reach a state of equilibrium in each flight condition.

Tail surfaces sizing and shaping are almost exclusively determined by stability and control considerations. Both horizontal and vertical tailplanes usually operate at only a fraction of their lift capability, since stall conditions should never be achieved. The vertical tail provides directional (i.e. around the vertical axis) equilibrium, stability, and control. The concept of equilibrium is inherent to the absence of accelerations on the aircraft. Directional stability is the aircraft tendency to return to the initial equilibrium condition, if perturbed. Directional control is the aircraft ability to maintain equilibrium at a desired *sideslip* angle, i.e. the angle between the relative wind and the aircraft longitudinal axis [1]. From the dynamic point of view, the role of the vertical tail is to provide *yaw damping*, that is to reduce the oscillations around the vertical axis (dynamic directional stability). If the aircraft directional stability is too small with respect to its lateral stability (i.e. around the

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Nomenclature

Acronyms

AGILE	Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DES	Detached Eddy Simulation
DII	Dipartimento di Ingegneria Industriale
DNS	Direct Navier-Stokes
ESDU	Engineering Science Data Unit
F	fuselage
FV	fuselage – vertical tail combination
H	horizontal tail
LES	Large Eddy Simulation
m.a.c.	mean aerodynamic chord
MDO	Multidisciplinary Design Optimization
NACA	National Advisory Committee for Aeronautics
OAD	Overall Aircraft Design
RANS	Reynolds-Averaged Navier-Stokes
SCoPE	Sistema Cooperativo Per Elaborazioni scientifiche multidisciplinari
USAF DATCOM	United States Air Force Data Compendium
V	vertical tail
W	wing
WFV	wing – fuselage – vertical tail combination
WFVH	wing – fuselage – vertical tail – horizontal tail combination

Notation

A	wing aspect ratio
A_h	horizontal tailplane aspect ratio
A_v	vertical tailplane aspect ratio
$A_{v\mathrm{eff}}$	vertical tailplane effective aspect ratio
B	compressibility parameter $\sqrt{1-M^2}$
C_h	hinge moment coefficient
$C_{\mathscr{L}}$	airplane rolling moment coefficient
$C_{L\alpha v}$	vertical tail lift curve slope
$C_{\mathscr{L}\beta}$	airplane rolling moment coefficient derivative due to sideslip
C_N	airplane yawing moment coefficient
C_{Nf}	fuselage yawing moment coefficient
C_{Nv}	vertical tail yawing moment coefficient
$C_{N\beta}$	airplane yawing moment coefficient derivative due to sideslip
$C_{N\beta f}$	fuselage yawing moment coefficient derivative due to sideslip
$C_{N\beta h}$	horizontal tail yawing moment coefficient derivative due to sideslip
$C_{N\beta v}$	vertical tail yawing moment coefficient derivative due to sideslip
$C_{N\beta w}$	wing yawing moment coefficient derivative due to sideslip
$C_{Y\beta}$	airplane sideforce coefficient derivative due to sideslip
D_f	fuselage max diameter
K_{Fv}	coefficient to account for fuselage interference on vertical tail
K_{Hf}	coefficient to account for horizontal tail interference on fuselage
K_{Hv}	coefficient to account for horizontal tail interference on vertical tail
K_{Vf}	coefficient to account for vertical tail interference on fuselage
K_{Wf}	coefficient to account for wing interference on fuselage
K_{Wv}	coefficient to account for wing interference on vertical tail
L_f	fuselage length
L_n	fuselage nose length
L_t	fuselage tail-cone length
S	wing planform area
S_r	rudder planform area
S_{front}	fuselage frontal area
S_h	horizontal tailplane area
S_v	vertical tailplane area
$V_{s\mathrm{TO}}$	take-off stall speed
V_∞	asymptotic velocity
b	wing span
b_v	vertical tailplane span
b_{v1}	vertical tailplane span extended to the fuselage centerline
c_r	rudder m.a.c.
d_f	fuselage equivalent diameter
d_{fv}	fuselage height at vertical tail aerodynamic center
l_v	vertical tail directional moment arm
r_f	fuselage max radius
y^+	dimensionless wall distance
z_{ftc}	height of the fuselage tail-cone
z_h	position of the horizontal tail on the vertical tail
z_w	wing position in fuselage
α	angle of attack
β	angle of sideslip
λ	taper ratio
Δ	difference
Λ	sweep angle

longitudinal axis), the aircraft tends to oscillate in yaw as the pilot gives rudder or aileron inputs. This tendency is called *dutch roll* and makes precise directional control difficult.

Extreme flight conditions usually set design requirements for tail surfaces, as minimum control speed with one engine inoperative (Fig. 2) or maximum cross-wind capability (Fig. 3). Stability and control must be ensured even in large angles of sideslip as 25° [2]. The design of a vertical tailplane depends mainly on the type of airplane (configuration layout, flow regime, aesthetics, costs), and on engines number and position. For a given layout, the vertical tail design should take into account the relative size and position of other elements in the whole aerodynamic configuration, such as wing, fuselage, and horizontal tail [3]. These factors affect the aircraft *stability derivatives*, i.e. the variation of aerodynamic coefficients with the main flight variables, and, in particular, the vertical fin design influences all derivatives with respect to the angle of sideslip β. Such design is not a simple task, since it involves the prediction of nontrivial phenomena, such as the asymmetrical flow behind the wing-fuselage combination, and the solution of lateral cross-control issues (due to side force on the fin causing a rolling moment).

The following design requirements can be formulated for vertical tailplanes, as suggested in Ref. [2–5]:

1. The vertical fin must provide a sufficient contribution to static and dynamic stability, which is function of the vertical tail lift curve slope and planform area (Fig. 4) or volume coefficient. These are ensured by a sufficiently high value of the derivative

$$C_{N_{\beta_v}} = f\left(C_{L_{\alpha_v}}, \frac{S_v}{S}\frac{l_v}{b}\right) \tag{1}$$