Aerospace Science and Technology 76 (2018) 471–483

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Roll performance assessment of a light aircraft: Flight simulations and flight tests

Fabrizio Nicolosi [a,1], Agostino De Marco [a,2], Vito Sabetta [b], Pierluigi Della Vecchia [a,*,2]

[a] *University of Naples Federico II, Italy*
[b] *Tecnam Costruzioni Aeronautiche, Capua, Italy*

ARTICLE INFO

Article history:
Received 22 September 2017
Received in revised form 8 January 2018
Accepted 12 January 2018
Available online 27 February 2018

Keywords:
Rolling control power
Flight tests
Flight simulation

ABSTRACT

A methodology is presented for the roll performance assessment of a light aircraft. The study is based both on flight simulations and flight tests, focusing on the accurate determination of the lateral control power. The chosen test airplane was a Tecnam P92, a two-seat ultralight aircraft which was specifically equipped with a lightweight and accurate instrumentation for the planned set of flight data measurements. A matrix of flight experiments for the test campaign was established with the support of 6-degree-of-freedom simulations, implementing a carefully constructed baseline dynamic model of the aircraft. The article discusses first the general problem of a reliable evaluation of aircraft roll performance indicators, i.e. the estimation of the aerodynamic derivatives that mainly influence the airplane ability to roll. Next, the results of extensive flight test activities are presented. The analysis of several roll maneuvers performed at different flight speeds and with different aileron maximum deflections showed interesting rolling characteristics for this non-aerobatic aircraft. One notable finding was a clear nonlinear dependency of the aileron efficiency index on aileron deflection amplitude. A control power derivative extracted from flight data in the form of lookup table was used to correct the baseline flight dynamics model. Flight simulations outputs based on the updated model showed a satisfactory agreement with experimental time histories. According to this, the present effort proposes a new method to estimate the aileron control derivative in whole the flight envelope for light aircraft.

1. Introduction

A set of controllability requirements must be met by all aircraft to be certified for commercial use or adopted by the military. Many military airplanes also have additional maneuverability requirements. A poor design of aerosurfaces or their actuation systems often results in a limited amount of control authority available, and hence in the inability to meet the requirements. Thus, a reliable design of flight control surfaces is crucial, and it must be based on the adoption of appropriate methodologies.

Due to the iterative nature of design, it is important for designers to evaluate with good confidence the control authority of candidate concepts as early as possible in the design process. Normally numerous possible configurations are considered before the stability and control specialists start their analysis for the detailed control system design [1,2].

The analysis of control power required to meet controllability specifications at critical flight conditions has always been an important issue in aircraft design. It is well known that aircraft flight qualities are strongly dependent on the set of aerodynamic derivatives that make up the aircraft aerodynamic database. The correct estimation of these quantities, especially the control derivatives, at various flight conditions is often difficult when nonlinear dependencies of aerodynamic coefficients on state variables are involved. The size and placement of control surfaces determines the aircraft control authority. Excessive control authority can translate into increased weight and drag, while inadequate control power can result in a failed design. Thus, the designer's goal when sizing and placing control surfaces is to provide sufficient, yet not excessive, control power to meet the requirements of prescribed maneuvers, military specifications, or certification guidelines [3, Part VII].

This article addresses the traditional, aileron actuated, roll control of light aircraft, which is regulated by the FAR 23 [4] or CS-23 [5] specifications and MIL-STD-1797 guidelines [6]. Since roll controllability requirements must be met also with flaps deployed, the assessment of aircraft roll control derivative is considered a very important issue by designers because a good balance between

---

[*] Corresponding author.
E-mail address: pierluigi.dellavecchia@unina.it (P. Della Vecchia).

[1] Associate Professor, Dept. Industrial Engineering, Naples, 80125, Italy.

[2] Assistant Professor, Dept. Industrial Engineering, Naples, 80125, Italy.

https://doi.org/10.1016/j.ast.2018.01.041
1270-9638/

List of Symbols

AEI	aileron efficiency index $= p_{ss}b/2V$
β	sideslip angle (rad)
b	wing span (m)
$\bar{c}$	reference chord (m)
$C_{\mathcal{L}\beta}$	dihedral effect coefficient (1/rad)
$C_{\mathcal{L}\delta_A}$	aerodynamic lateral control power coefficient (1/rad)
$C_{\mathcal{L}p}$	aerodynamic roll damping coefficient (1/rad)
$C_{L\alpha,W}$	wing lift curve slope coefficient (1/rad)
$c(y)$	chord of a generic wing section (m)
δ_A	aileron deflection (rad), positive for right aileron up
δ_A^{left}	left aileron deflection (rad), positive if rotated upwards
$\delta_{A,\max}$	maximum aileron deflection in a doublet (rad)
$\delta_{A,\text{max-down}}$	minimum physically achievable aileron deflection (rad)
$\delta_{A,\text{max-up}}$	maximum physically achievable aileron deflection (rad)
δ_A^{right}	right aileron deflection (rad), positive if rotated upwards
$\delta_{A,\text{trim}}$	aileron deflection required in trimmed, wings level flight (rad)
δ_R	rudder deflection (rad), positive if rotated leftwards
$\delta_{R,\text{trim}}$	rudder deflection required in trimmed, wings level flight (rad)
Δt	time to achieve the designated peak aileron deflection (s)
ϕ	aircraft bank angle (rad)
$\phi_{\max}$	maximum bank angle during an aileron doublet maneuver (rad)
I_{xx}	aircraft moment of inertia around the roll axis (kg m^2)
K_A	aileron control power nonlinearity factor
ℓ	wing lift per unit length (N/m)
$\mathcal{L}$	aerodynamic rolling moment (N m)
$\mathcal{L}_\beta$	dimensional dihedral effect derivative (N m/rad)
$\mathcal{L}_{\delta_A}$	dimensional rolling control derivative (N m/rad)
$\mathcal{L}_{\delta_R}$	dimensional cross derivative due to rudder (N m/rad)
$\mathcal{L}_p$	dimensional roll damping derivative (N m s/rad)
p	roll rate (rad/s)
$\dot{p}$	roll acceleration (rad/s^2)
$p_{\max}$	maximum roll rate during an aileron doublet maneuver (rad/s)
p_{ss}	steady-state roll rate due to a step aileron input (rad/s)
$\bar{q}$	dynamic pressure (N/m^2)
r	yaw rate (rad/s)
S	wing reference area (m^2)
τ_A	aileron control efficiency factor
V	flight speed (m/s or km/h)
V_s	stall speed with flaps retracted (m/s or km/h)
V_{s1}	stall speed with flaps set for landing (m/s or km/h)
$V_{s,\text{turn}}$	stall speed with flaps retracted during a turn (m/s or km/h)
y	spanwise coordinate (m)
AHRS	Attitude and Heading Reference System
FTI	Flight Test Instrumentation
IMU	Inertial Measurement Unit

aileron effectiveness and high-lift capabilities due to flaps must be achieved.

Traditionally the design of ailerons has largely relied on the practical experience of aerodynamicists that have been working on the design of control surfaces. The design process is also about the determination of the wheel or stick force of the pilot, which additionally requires a knowledge of the mechanical design of the control system and flight mechanics. However, after the retirement of the experienced aerodynamicists, who started their career in the industry during the 50s, the knowledge is largely gone. Still the potential for cost savings prevails and there is a need for accurate analysis models, which have to be based on a better understanding of the flow phenomena involved [7]. In a steady maneuver, such as a sideslip, a stationary analysis is sufficient. In a stationary roll maneuver a quasi-stationary analysis is needed. An unsteady roll maneuver demands full dynamic analysis. A prerequisite for this is data on the dynamic stability derivatives which have to be determined with an acceptable degree of accuracy. Published literature on airplane roll control and aileron design is rather limited. Comprehensive reviews of published works regarding lateral control surfaces and available data on ailerons were made by Mason et al. [2] and by Soinne [8].

The determination of airplane response to aileron input may be studied by combining flight simulations and flight tests on a representative aircraft. Often, the aerodynamic databases within the models for flight simulations come from low or high fidelity numerical analyses, some of which are validated in wind tunnels [9–11]. The more accurate is the numerical aerodynamic analysis the more reliable is the flight dynamics model [12–14]. In the effort presented here, a methodology of roll performance prediction has been elaborated in the context of a flight test campaign conducted on a Tecnam P92 aircraft. The effort has been supported by the use of engineering flight simulations, both for the design of test maneuvers and for the analysis of flight data. Examples of similar research regarding motorgliders and light aircraft characterization by means of flight test and parameter estimation techniques are found in [15–18]. In the present research the aerodynamic database was initialized with DATCOM semi-empirical models [19, 20] and then refined with the available experimental data [21].

The selected airplane is an ultralight aircraft certified according to the European requirements CS-VLA [22]. For airplanes of this category, the roll response to full aileron input must meet the performance requirements prescribed by CS-VLA part 157. The input is to be abrupt, with time measured from the application of the force. The requirement is for the aircraft to be able to make a given bank angle change, at a given flight speed, in a prescribed time (or less). This is called ‘time to bank’ requirement and corresponds to a prescribed minimum commanded roll rate. For instance, in landing configuration it must be possible to roll the airplane, using a favorable combination of controls, from a steady 30 deg banked turn making a 60 deg bank angle change, so as to reverse the direction of the turn in 4 sec, at a flight speed of 1.3 V_{s1} (i.e. 30% higher than the stall speed with flaps set for landing).

This research shows that some interestingly high values of the aileron efficiency index (AEI) can be observed for the selected aircraft and probably for several airplanes of the same category. In addition, on the basis of measured flight data, it emphasizes the nonlinear behavior of pilot roll control moment as a function of aileron deflection. This behavior has been implemented in a flight simulation model and finally cross-validated.

This manuscript is organized as follows: In the next Section 2 a couple of useful concepts are recalled and reference aerodynamic modeling approaches are stated. Section 3 gives the essential details on the Tecnam P92 aircraft and on the flight test instrumentation used in this research. Section 4 discusses the determination of a test condition matrix with the aid of 1-DoF and 6-DoF flight sim-