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Efficient roll control using distributed control surfaces and aeroelastic effects

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Abstract

The potential of using multiple leading and trailing edge control surfaces and aeroelastic effects for efficient roll manoeuvring is investigated. Numerical optimization in combination with a simulation model including aeroelastic dynamics is used to design a controller for roll angle tracking. The controller distributes the control power to the individual surfaces such that it minimizes the control effort yet fulfilling roll performance requirements in a wide airspeed envelope. The controller is implemented and experimentally validated using an elastic wind-tunnel model equipped with 16 individual control surfaces. Good correlation between simulations and experiments is obtained although some deviations are observed and discussed. Finally, the choice of the most efficient control surface layout is investigated by evaluating control laws which utilize a subset of the available control surfaces.

Keywords: Active aeroelastic control; Control surface efficiency; Reversal; Optimization; Wind-tunnel testing

1. Introduction

Roll performance of aircraft with outboard trailing edge ailerons is highly dependent on the torsional stiffness of the wing. At high dynamic pressure, the twist moment caused by the deflected aileron results in wing twist that reduces the aileron efficiency significantly. At the reversal speed the effect of the aileron vanishes and beyond the reversal speed the effect is a rolling moment in the opposite direction. The aileron efficiency is often an active constraint during wing structural design, see for example Mantegazza and Ricci [12]. Stiffening of the wing increases surface efficiency but normally leads to significant weight penalty.

Adding a leading edge control surface may be advantageous as the efficiency of such a surface increases with dynamic pressure since the twist moment produced is opposite compared to the moment caused by a trailing edge surface. Cronander and Ringertz [8] show that when using both a leading and trailing edge control surface, a desired roll rate can be maintained even if the stiffness of the wing is significantly reduced, see also Andersen et al. [5] and Dowel et al. [9].

In the previous investigation [8], a simulation model including a single static aeroelastic state was used. The experimental investigations showed that as the requirements on the performance of the controller were increased dynamic aeroelastic effects were observed, which was not predicted by simulations. In this study, a simulation model including both rigid-body dynamics as well as the dynamic aeroelastic behavior of the model is utilized.

The focus of this study is to use multiple leading- and trailing edge control surfaces efficiently by taking advantage of the aeroelastic effects and thereby minimizing the control effort needed for manoeuvring. Minimizing the effort in terms of control surface deflections and hence also deflection rates for manoeuvring, may reduce actuator power requirements or enable use of the control surfaces for additional purposes such as active damping as investigated by Platanitis and Strganac [13]. The focus is not only on the control

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Nomenclature

$\phi, \phi_{\mathrm{ref}}$	Actual roll angle and desired roll angle
LE, TE	Denotes leading edge and trailing edge entities
q_∞, u_∞	Free stream dynamic pressure and airspeed
$\mathbf{z}$	Vector of modeshapes
z_{r}	Rigid body mode
$\mathbf{z}_{\mathrm{e}}, \mathbf{z}_{\mathrm{c}}$	Vectors of elastic modes and of control surface modes
$\mathbf{Q}(s)$	Rational aerodynamic approximation
s	Laplace variable
$\mathbf{A}_0, \mathbf{A}_1, \mathbf{A}_2,$ $\mathbf{D}, \mathbf{R}, \mathbf{E}$	Coefficients of $\mathbf{Q}(s)$
$\mathbf{x}, \hat{\mathbf{x}}$	State vectors
$\mathbf{a}$	Vector of aerodynamic states
$\mathbf{A}, \mathbf{B}, \mathbf{C}$	State space system; state, input and output matrices
$\mathbf{u}$	Vector of controls
y	State space output
M_x	Rolling moment
e	Error between desired and actual roll angle

k_P, k_D	Individual values of proportional and derivative gains
u_c, u	Servo control signal and actual servo output
ω_0, ζ	Servo resonance frequency and damping
T_r, M	Rise time and overshoot
W, T_f	Control effort and final time
$\mathbf{P}$	Weighting matrix
$\mathbf{I}$	Identity matrix
n_f	Number of time steps from 0 to T_f
n_c	Number of control surfaces
U	Matrix of control surface deflections
$\underline{\mathbf{k}}_P, \bar{\mathbf{k}}_P$	Lower and upper bounds of $\mathbf{k}_P$
$\underline{\mathbf{k}}_D, \bar{\mathbf{k}}_D$	Lower and upper bounds of $\mathbf{k}_D$
$\mathbf{k}_P, \mathbf{k}_D$	Vectors of proportional and derivative gains
δ	Individual control surface deflection
i	Subscript, denoting ith control surface
gr	Subscript, denoting gear ratio
C_{M_x,δ_i}	Rolling moment coefficient derivative with respect to ith control surface
$\boldsymbol{\delta}$	Vector of control surface deflections

design methodology but also on the experimental validation and on the uncertainties involved in the numerical models. Finally, an investigation considering the most advantageous control surface layout is included.

2. The wind-tunnel model and experimental setup

A highly flexible wind-tunnel model is used as test object in this study. The model is mounted on a rigid wind-tunnel sting, free to roll around its length-axis as shown in Fig. 1. The roll angle ϕ is measured using a potentiometer mounted between the sting and the model. The load carrying structure of the wings are two carbon fiber/epoxy internal wing beams. Both beams are clamped to the rigid aluminum center section. Four wing sections are mounted to each elastic beam, each section holding one leading edge (LE) flap and one trailing edge (TE) aileron, giving a total number of 16 control surfaces. The wing cross section is shown in Fig. 2. Each control surface is actuated using an electromechanical servo mounted in the corresponding wing section. All mechanics for control surface actuation is internally mounted in the wing sections to minimize flow disturbance.

The model is designed and the structure is sized to show effects like control reversal within the speed envelope of the low speed wind-tunnel to be used for testing. Moreover, the structure is sized to have a critical flutter speed above the reversal speed of the outermost TE ailerons. The structural

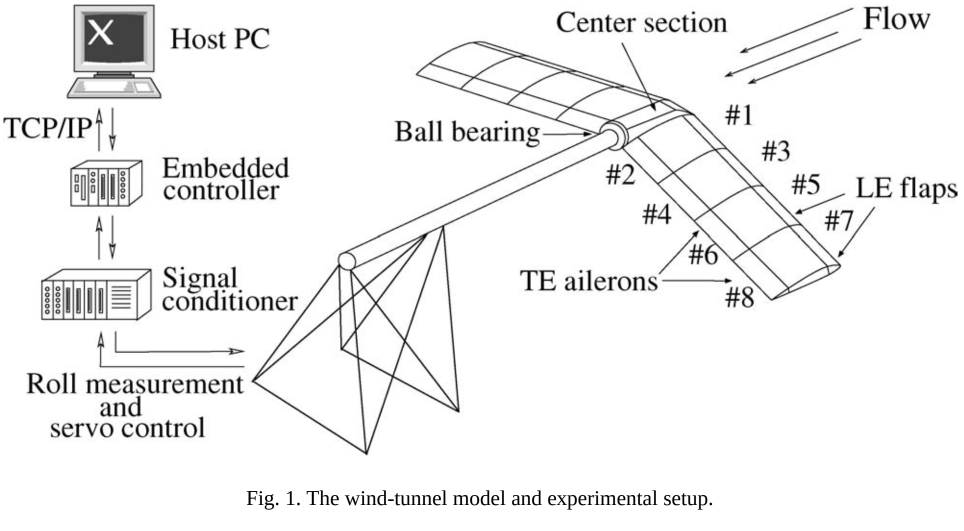

Fig. 1. The wind-tunnel model and experimental setup.