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Integrated design of flight control surfaces and laws for new aircraft configurations

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Abstract: Control architecture sizing is a main challenge for new aircraft design like blended wing-body design. This aircraft configuration typically features redundant elevons located at the trailing edge of the wing, acting simultaneously on pitch and roll axes. The problem of integrated design of control surface sizes and flight control laws for an unstable blended wing-body aircraft is addressed here. Latest tools for H_∞ non-smooth optimization of structured controllers are used to optimize in a single step the gains for both longitudinal and lateral control laws, and a control allocation module, while minimizing control surfaces total span. Following constraints are ensured: maximal deflection angles and rates for 1) pilot longitudinal pull-up 2) pilot bank angle order and 3) longitudinal turbulence. Using this coupled approach, significant gains in terms of outer elevons span compared to the initial layout are demonstrated, while closed-loop handling qualities constraints are guaranteed.

Keywords: Integrated design, Flight Control Law, Aircraft, H_∞ control, Dynamics, BWB

1. INTRODUCTION

Among other disruptive aircraft configurations, the Blended Wing-Body (BWB) was identified for years as a promising candidate for the future of civil aviation Liebeck (2004). The rationale for this game-changing configuration is as follows: instead of considering separate geometrical components for each basic function of an aircraft, namely *Lift*, *Transport*, *Control* and *Propulsion*, the BWB gathers the three former functions into a single lifting surface. As a consequence of this functions merging, an overall improved efficiency is expected, implying significant gains in terms of fuel consumption Martínez-Val and Pérez (2005); Liebeck (2004); Qin et al. (2004); Bolsunovsky et al. (2001). This paper focuses on an Airbus long-range BWB configuration.

Major challenges yet to be solved before a potential entry into service include control-related issues Roman et al. (2000). These issues first originate from the nature of the control devices used for this configuration: the BWB is controlled with multi-control surfaces, also named elevons, usually spanning the whole trailing-edge and acting as pitch and roll devices. Among challenges implied by this technology, new handling qualities criteria are required in order to take into account the combined authority of control surfaces on longitudinal and lateral axes. This was already addressed in a previous work Saucez and Boiffier (2012).

Then concerning control surfaces area sizing, two phenomena have a combined detrimental effect both on actuators mass and power consumption Roskam (1985). On the one hand, trailing edge elevons induce high aerodynamic hinge moments due to their large area. On the other hand, high deflection rates result from the longitudinal stabilization of an unstable configuration. Indeed the Airbus BWB features a negative static margin, specially at low speed (see section 2.2), i.e. an unstable short-period mode. For that reason it requires a permanent Stability Augmentation System (SAS) in order to guarantee adequate safety and handling qualities. However it was shown in a previous study Denieul et al. (2015a) that the more unstable an aircraft, the faster its control surfaces need to move in order to maintain the equilibrium under disturbance. This effect is even increased on the BWB, for elevons lack longitudinal lever arm with respect to center of gravity (CG). During preliminary design phase, control surfaces pitch efficiency should then be sought to be maximized, for instance by increasing control surfaces area as much as possible, which is conflicting with previously mentioned requirement on hinge moments limitation.

Both large hinge moments and high deflection rates have a direct impact on FCS sizing and secondary power con-

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sumption. Indeed as stated by Garmendia et al. Garmendia et al. (2014), secondary power for FCS P_{FCS} may be evaluated in a preliminary way by the equation (1):

$$P_{FCS} = \sum_{i=1}^{n_{controls}} HM_i^{max}.\dot{\theta}_i^{max} \quad (1)$$

where HM_i^{max} and $\dot{\theta}_i^{max}$ are the maximum hinge moment and maximum deflection rate of the i-th control surface respectively, and $n_{controls}$ is the number of control surfaces.

At preliminary design phase, when actuators sizing is not yet frozen, deflection rate is a direct consequence of control laws design. Also the traditional way of sizing conventional control surfaces considers simplified open-loop handling qualities criteria, such as roll rate target for the ailerons or pitch rate target for the elevator. Such an approach is no more valid for BWB control surface sizing due to the natural pitch instability: control surface areas may be largely sized by stabilization requirements, so sizing requires considering control laws at the early design phase. Control laws design in turn depends on control surfaces effectiveness. This coupled problem is known in control community as *plant-controller optimization* or *integrated design and control*. Classical way of handling this problem involves an iterative approach: effectors are sized based on engineering rules, then a control law is designed. If requirements are not met, then the sizing is changed based on the existing control law, and so on. However it is proved Fathy et al. (2001) that beyond being time-consuming, this approach may miss the optimum because of the tightly coupled nature of the problem. Consequently, several approaches are seeking solving these combined problems in a single step. "Plant-controller optimization" was studied in a variety of domains, such as chemistry Ricardez-Sandoval et al. (2009), autonomous underwater vehicles Silvestre et al. (1998) and astronautics Alazard et al. (2013); Denieul et al. (2015b,a).

In the field of aeronautics two complementary approaches were studied. The first method considers integrating a stability and control module into a multidisciplinary optimization (MDO) process Perez et al. (2006). A second more control-oriented approach takes advantage of optimization tools developped for controllers design in order to simultaneously optimize a controller and some meaningful physical parameters. Niewoehner and Kaminer (1996) optimized in a single loop a longitudinal controller and elevator control surface using linear matrix inequalities (LMI) framework. More recently, nonsmooth optimization methods enabling structured linear varying paremeters (LPV) controllers were applied to the longitudinal integrated design and control problem Lhachemi et al. (2015).

We propose to extend this approach to longitudinal / lateral integrated design and control of a BWB by optimizing together a three-axes control laws and control surfaces total span, using nonsmooth optimization techniques for fixed structure controllers. The main contribution of this paper is to optimize in a single step the control surfaces span, the control allocation module, and flight control laws, in order to guarantee longitudinal and lateral handling qualities constraints with a minimum control surfaces size.

This paper is organized as follows: in section 2 the flight dynamics models are presented. Then section 3 introduces the strategy for parameterizing the elevons total span, and obtaining a parametrized state-space representation suitable for optimization. The integrated design and control problem of computing structured longitudinal / lateral control laws gains together with optimal elevons size is presented in section 4, and results are discussed in section 5.

2. AIRCRAFT FLIGHT DYNAMICS AND CONTROL

In this section the models used in sections 3 and 4 for design, control and simulation are described. The configuration studied in this paper is a long-range BWB whose planform results from optimization studies on high-speed performance with constraints on low-speed pitching moment Meheut et al. (2012). The focus of this work is the sizing of control surfaces; thus, the planform is considered constant. The planform and initial control surfaces layout are visible on Figure 2(a).

2.1 Linear Model of Flight Dynamics Equations

In order to perform control laws synthesis and linear analysis, Flight Dynamics equations are linearized around equilibrium flight points. These initial equilibria are computed for the following conditions: zero flight path angle, sideslip and bank angle. At a given flight operating conditions in terms of mass (m), Mach number (M) and altitude (H), the 3-axis model state-space representation reads:

$$\dot{X} = AX + BU + B_w w_z \quad (2)$$

$$Y = CX + DU + D_w w_z \quad (3)$$

where $X = [\delta V \;\; \delta\alpha \;\; q \;\; \delta\theta \;\; \beta \;\; p \;\; r \;\; \phi]^T$ is the state vector composed of $\delta V = V - V_e$ the relative airspeed with respect to the equilibrium speed, $\delta\alpha = \alpha - \alpha_e$ and $\delta\theta = \theta - \theta_e$ relative angle of attack and pitch attitude with respect to the equilibrium respectively, sideslip β and p, q, r rotation rates of the aircraft with respect to the earth reference frame in roll, pitch and yaw respectively. $U = [\Delta\delta m^T, \;\; \delta n]^T$ is the control vector composed of $\Delta\delta m = [\Delta\delta m_i]^T, \; i = 1 \dots 10$ with $\Delta\delta m_i = \delta m_i - \delta m_e$ the relative deflection of the $i - th$ elevon control surface with respect to the equilibrium position. Each of the 10 elevons is actuated independently, through a control allocation strategy presented in 4.2. Elevons layout shown in Figure 2(a) is ordered in the control vector as follows: $\delta m_{i,i=1\dots10} = [LDQ1 \dots LDQ5, RDQ1 \dots RDQ5]$. Control vector also contains rudder deflection δn. While two rudders are visible on the configuration of Figure 2(a) (LDR and RDR), it was chosen for sake of clarity to group them as a single control with twice the efficiency of one rudder; the aim of our study is indeed not to size vertical surfaces but only elevons. The output vector $Y = [N_z, \; q, \; \beta, \; p, \; r, \; \phi]^T$ is composed of the vertical load factor Nz and the measured state variables. Finally turbulence effect is included as a vertical velocity w_z expressed in the earth reference frame, under the assumption that it acts as an increment of angle of attack. The model used for turbulence is described in section 2.3.