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Control allocation performance for blended wing body aircraft and its impact on control surface design

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ABSTRACT

Due to highly redundant and strongly coupled control surface configurations of future aircraft, advanced control allocation algorithms have been proposed to optimize the allocation of control power to control surfaces. These algorithms typically assume linear control surface effectiveness. The effect of this assumption was tested by measuring the overall aerodynamic performance of several control allocation algorithms in a wind tunnel experiment with the Zero Emission Flying Testbed (ZEFT) blended wing body aircraft model, which was developed at Delft University of Technology. In addition, several aerodynamic analysis methods, including a 3D RANS CFD method, were tested on their ability to accurately predict the (non)linear control surface effects. The wind tunnel results showed that angle of attack (α) and control surface deflection angle (δ) had the strongest effect on control moment nonlinearities. Typical losses at maximum deflection angle were 10–30% compared to a linear assumption. Control surface interaction effects on the overall performance were limited. Some control allocation algorithms achieved only 50% of the requested moment in the wind tunnel. It is therefore recommended to include control allocation selection and performance evaluation in early design stages to avoid costly redesigns. The RANS CFD analysis showed promising results for tracking control moment response as a function of δ for all three moment axes.

1. Introduction

Although the feasibility of the Blended Wing Body (BWB) concept is very convincing, there are still significant challenges due to the lack of a conventional empennage. The BWB layout significantly complicates the control system design, due to (a) the assignment of multiple functions to control surfaces and (b) the increasing number of control surfaces for accurate control in all flight regimes [12]. For example, the deflection of an aileron will cause a change in the local lift and drag contributions, thus causing a roll, pitch and yaw moment to change around the aircraft body axes. Control based on drag can be used for yaw control by deflecting control surfaces on the outer section of the wing. This can be a useful solution to compensate for the absence of a conventional vertical tail plane or a small moment arm of the vertical tail plane.

There are two main regimes of control of interest for BWB designs: (1) the high speed regime, in which aircraft trim with low drag is important, and (2) the low speed regime, in which aircraft controllability is important. This paper focuses on the controllability aspect of BWB design in the low speed regime. The resulting control moment **m** due to the deflection of (a combination of) control surfaces **u** can be expressed as a simple relation if the control derivatives are assumed to be linear:

$$m = B \cdot u \tag{1}$$

$$m = \begin{bmatrix} C_l \\ C_m \\ C_n \end{bmatrix}, \qquad B = \begin{bmatrix} C_{l_{\delta_1}} & C_{m_{\delta_1}} & C_{n_{\delta_1}} \\ . & . & . \\ . & . & . \\ . & . & . \\ . & . & . \\ . & . & . \\ C_{l_{\delta_i}} & C_{m_{\delta_i}} & C_{n_{\delta_i}} \end{bmatrix} \quad \text{and} \quad u = \begin{bmatrix} \delta_1 \\ . \\ . \\ . \\ . \\ . \\ \delta_i \end{bmatrix}$$

Here, the moment vector **m** contains the non-dimensional roll, pitch and yaw moments coefficients (respectively C_l, C_m and C_n). The control effectiveness matrix **B** represents the linearized control surface aerodynamics. Each element of the matrix is a non-dimensional control moment derivative with respect to control surface deflection angle δ. There are three columns to represent the three moments (pitch, roll and yaw). The number of rows depends on the number of control surfaces. The control vector **u** contains the control surface deflection angles δ for control surfaces 1 to i.

The increased complexity of control surface configurations due to high redundancy and coupling, as well as the necessity for 'damage tolerant' designs that can reconfigure or adapt when a failure occurs, were some of the main incentives for the development of advanced Control Allocation (CA) algorithms in the last

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Nomenclature

B	Control effectiveness matrix	
C_l	Roll moment coefficient $[\frac{L}{(1/2)\rho V_\infty^2 Sb}]$	
$C_{l,\delta}$	Roll moment effectiveness $[\frac{dC_l}{d\delta}]$	
C_m	Pitch moment coefficient $[\frac{M}{(1/2)\rho V_\infty^2 S\bar{c}}]$	
C_n	Yaw moment coefficient $[\frac{N}{(1/2)\rho V_\infty^2 Sb}]$	
J	Objective function in optimization problem	
L	Roll moment	N m
M	Pitch moment	N m
$\mathbf{m}, \mathbf{m}_d$	Control moment vector, desired or commanded	
N	Yaw moment	N m
$\mathbf{u}, \mathbf{u}_p$	Control vector, preferred control vector	
V	Wind speed	m/s

Greek symbols

α	Angle of attack	°
κ–ε	Turbulence model	
δ, δ_{max}	Control surface deflection angle, maximum angle	°
ε	Factor used in a mixed optimization to apply priority between expressions	

Abbreviations

BWB	Blended wing body
CS	Control surface
DA	Direct allocation
FXP	Fixed-point iteration method
LP-1	Linear programming l_1-norm method
LP-DA	Linear programming direct allocation method
LTT	Low turbulence low speed tunnel at Delft University of Technology
SST	Shear stress transport
WPI	Weighted pseudo-inverse method
ZEFT	Zero emission flying testbed

two decades. CA algorithms generally solve the problem of assigning the right amount of control effort to the right control surfaces. For the linear case, Eq. (1) is solved to find the control vector **u** that provides a requested moment **m**. For aircraft with multiple (redundant) control surfaces, there is usually an infinite number of solutions to this problem. Thus, an optimal solution should be found. However, there are various ways to define an optimal solution. For example it can be the objective to: (1) minimize the control effort, (2) minimize aerodynamic drag, (3) use the most effective control surfaces, (4) have minimal computational effort to guarantee that the solution is found fast enough for real time applications, (5) have a simple solution that can be created by means of a mechanical control system, (6) take into account the overall load distribution for structural reasons, etc. A whole range of different CA algorithms can be found in literature, each with a different objective, different method and its own advantages and disadvantages. Durham [9] first introduced the concept of Direct Allocation (DA) in the 1990s. Later Buffington [6] introduced an alternative formulation by (a) minimizing the error between the achieved moment, **m**, and the desired moment, $\mathbf{m}_d$, and (b) minimizing the error between the control vector, **u**, and a preferred control vector, $\mathbf{u}_p$. This is called a mixed optimization problem and is shown in Eq. (2), where J is the objective function to be minimized and ε determines priority to the left and right hand expressions. The parameter ε, which is typically small can be specified by the designer of the algorithm

$$\min J = \|Bu - m_d\| + \varepsilon\|u - u_p\| \tag{2}$$

The majority of proposed CA algorithms differ from each other in two ways: (a) the norms (l_1, l_2 or l_∞) they use to express the errors in Eq. (2), and (b) the mathematical implementation to solve the optimization problem. The l_p norm (where $p \geqslant 1$ is a real number) is defined as follows.

$$\|x_p\| = \left(\sum_{i=1}^{n} |x_i|^p\right)^{1/p} \tag{3}$$

Although quadratic and nonlinear optimization algorithms are available, the linearity assumption greatly simplifies the optimization problem and allows it to be solved quickly and robustly. The disadvantage is that the linearization is expected to produce errors in the predicted control moments due to the presence of nonlinear effects. These nonlinearities are caused by changes in the boundary layer state, e.g. due to boundary layer transition or separation.

Recent work in this field [1,2] has been mainly been done on the numerical performance of different formulations of the CA problem and easy implementation into robust linear programming software. Nevertheless several novel methods have been proposed to include nonlinear aerodynamic effects in control allocation. Doman and Oppenheimer [8] investigated a feedback control/control allocation method that utilizes a dynamic inversion-based control law to address inaccuracies caused by linear assumptions. In 2003 Bolender and Doman formulated the nonlinear control allocation problem as a piecewise linear function in [3] and later looked at constructing the nonlinear attainable moment set for use with Durham's DA method in [4]. More recently Bodson [2] looked at the advantages of using l_∞-formulations of the CA problem to incorporate load balancing the solution, i.e. spreading control effort across all available control surfaces. In that scenario, nonlinear effects due to large control surface deflections will be reduced. On the other hand, significant nonlinear effects may be introduced due to aerodynamic interaction effects between control surfaces.

To the authors' best knowledge, no investigation has been done on the consequences of CA algorithm selection for the early design stages (conceptual/preliminary) of a Blended Wing Body aircraft, in terms of control surface sizing and placement. Moreover, little experimental aerodynamic data [10,11,20] has been produced on (a) what variables are dominant in causing nonlinearity in the control effectiveness curves, and (b) what the effect of CA algorithm selection is on aerodynamic performance. Most current early design stage methodologies used for predicting control surface effectiveness (see for example textbook or handbook methods [19,13,15,7], supporting analysis tools [22] and design software [16]) do not include nonlinear effects such as interaction effects between control surfaces, nor do they take into account the effect of control allocation algorithm selection. The discrepancy between the predicted performance in the early design stages and actual performance could potentially lead to costly redesign or resizing of the control surfaces.

The aim of this research is to test the linearity assumption in the control effectiveness matrix **B** by measuring the aerodynamic performance of several control allocation algorithms in a wind tunnel experiment. Furthermore, the effect of several variables (δ, α, V and $\delta_{1\rightarrow 2}$) on nonlinearities in the control moment curves was investigated. Finally, four computational aerodynamic analysis methods were assessed for their ability to take nonlinear aerodynamic effects into consideration, enabling the assessment of CA performance.