CONTROLLABILITY OF BLENDED WING BODY AIRCRAFT

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Abstract

Several research studies indicate that the Blended Wing Body concept offers a significant performance improvement compared to conventional civil transportation aircraft due to its efficient aerodynamic configuration. Technical challenges are currently present in nearly all key areas of the design of a Blended Wing Body aircraft as a result of its highly integrated design. The aim of the current research is the development of a tool that automatically generates a nonlinear flight mechanics model of a Blended Wing Body aircraft within a Multidisciplinary Design Optimization framework. The main purpose of the model is to assess the controllability of the aircraft in the conceptual design phase via desktop and piloted simulation. Specific topics of interest to be investigated are handling qualities in normal operation and with failure states present. The model will also serve as a baseline for the development of control allocation schemes. Results obtained by analyzing the model can be used for the preliminary design of the aerodynamic control surfaces in terms of size, position and arrangement.

1 Introduction

Tailless aircraft have become a topic of renewed interest over the last decades because they offer the potential of improved performance over conventional designs due to their highly efficient aerodynamic configuration. Current civil interest in tailless aircraft is mainly inspired by the design of the blended wing body (BWB) configuration [1], [2]. Several studies on the BWB concept indicate drastic performance improvements such as approximately 28% reduced fuel burn per passenger compared to a conventional configuration [2]. Nevertheless, technical challenges are present in nearly all key areas of the design of a Blended Wing Body aircraft due to its highly integrated design [1], [3].

One of the major technical challenges is that of stability and control. In contrast to the common belief, flying wing aircraft can be designed to be inherently stable [4]. Originally, wing sweep was used in combination with downloaded outer wing sections. These outer wing sections have the same functionality as the horizontal tail of a conventional fixed wing aircraft configuration. This effectively makes the aerodynamic wing span smaller than the actual wing span and this has prevented flying wing aircraft from reaching their performance potential [1]. The advent of fly-by-wire technology and active control systems has made it possible to actively stabilize unstable aircraft configurations. This means that tailless aircraft do not necessarily have to be designed to be inherently stable anymore and thus a performance improvement can be achieved. Control is generally achieved by placing several aerodynamic control surfaces on the trailing edge of the aircraft and, when present, on the trailing edge of vertical aerodynamic surfaces. In some cases, drag rudders near the wing tips are used for yaw control. In general, tailless have a weak directional stability and a small yaw damping [4], especially those without vertical aerodynamic surfaces. The control configuration poses several problems. Control power is low in pitch and yaw due to small moment arms. This can have serious implications with respect to safety, especially when failure states are present. It is possible for some control surfaces to perform multiple functions, for example, roll control surfaces can also be used for pitch control. Besides, it is also possible to have a redundant number of control surfaces. Eventually, the allocation of the control surfaces becomes a critical issue [5], [6].

Clearly, a proper design of the size, shape and arrangement of aerodynamic control surfaces is necessary for the successful development of a BWB aircraft. Ideally, it should be possible to analyze controllability and related issues rapidly in the conceptual design phase with a detailed flight mechanics model. However, such a model is generally not available in this design phase. Furthermore, no statistics or other reference information from previous BWB commercial programs is available to support the designers in developing such a novel configuration. Hence, intensive use of (high fidelity) analysis tools is recommended to gain knowledge of the BWB performance and lower the associated development risk. However, the use of high fidelity analysis tools in the conceptual design phase is an additional challenge for the designer, considering the large amount of time required to set up suitable analysis models.

The highly integrated and multidisciplinary nature of the BWB design requires an integrated design method. Many research institutes, universities, industry and government agencies are currently investigating the possibilities offered by the so-called Multidisciplinary Design Optimization (MDO) methodology. However, a number of issues has still to be solved in order to tap the full MDO potential. On this purpose, a *Design and Engineering Engine* (DEE) has been under development for several years at the Design of Aircraft and Rotorcraft group of the University of Technology in Delft [7]. This system is essentially a modular framework to support distributed multidisciplinary design and optimization. The DEE is defined as an advanced design environment, where the design process of complex products can be supported and accelerated through the automation of non-creative and repetitive design activities [8]. Its basic structure is summarized in Fig. 1. As one can see, the DEE is built from several software modules, which can be installed and running at different locations. Key component of the DEE is the *Multi Model Generator* (MMG), which is a knowledge based engineering (KBE) application able to model different aircraft configurations and configurations' variants, based on a large set of input parameters. The *Initiator* is responsible to initialize the parameters values for the MMG (e.g., wing span, sweep angle and type of airfoils). Furthermore the MMG is able to automate the generation of specific data for various analysis tools, directly in the required format. For example, the outer shape of an aircraft is translated into clouds of points or panel, as required by the selected aerodynamic analysis tool, which has to calculate parameters such as maximum lift over drag ratio. The DEE is designed to support the MDO typical iterative approach: results from all the analysis tools are subsequently evaluated with the *Converger & Evaluator* module. If the requirements are met by the calculated specifications, then the process is stopped, otherwise, another aircraft configuration/variant is generated and another iteration is performed. An agent based communication framework [7], [8] is responsible for handling the data exchange between the various DEE components and control the overall process.

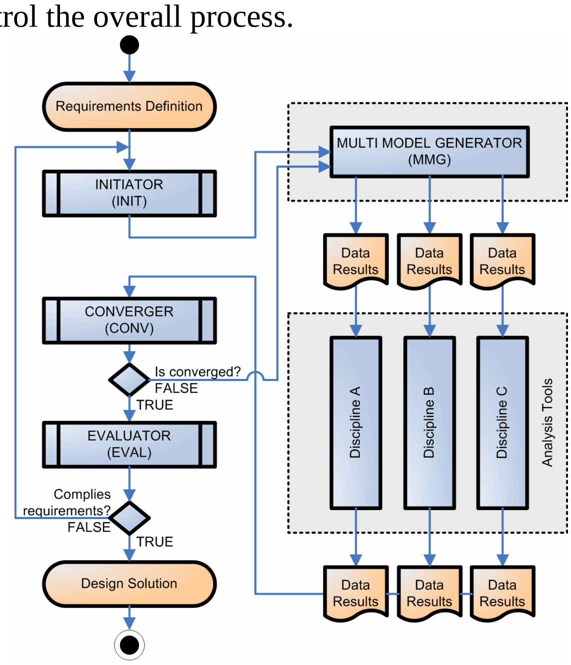

Fig. 1: Design Engineering Engine (DEE)

The aim of the current research is the development of a tool that generates a flight mechanics model automatically within the DEE. The flight mechanics model allows the designer to analyze the controllability of the aircraft in the conceptual design phase via desktop simulation and piloted simulations. The model can be used for (1) handling qualities analysis, (2) analysis of failure states, (3) the development of control allocation systems and finally (4) for the development of flight control laws. The flight mechanics model coupled to the DEE can serve as a tool for the design (sizing / placement) of control surfaces.

The structure of this paper is the following. The setup and functions of the flight mechanics model are described in Section 2. The process that generates this model automatically within the DEE is described in Section 3. Results, which include a limited handling qualities analysis of a generic Blended Wing Body aircraft, are presented in Section 4. Finally, conclusions and recommendations are presented.

2 Flight Mechanics Model

The baseline reference aircraft used for the development of the nonlinear aircraft model is based on the reference BWB aircraft (Fig. 2) developed in the European project MOB [9].

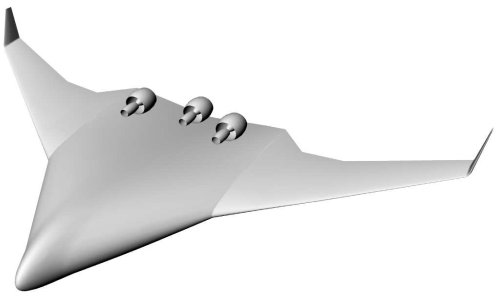

Fig. 2: Reference aircraft

This aircraft, a blended wing body configuration, was the result of a multidisciplinary design optimization performed by a consortium of companies, research institutes and universities. The initial aircraft design, which served as a starting point of the optimization, was made by Cranfield University. Geometric data and inertial data for this aircraft are taken from [10] and [11], respectively.

The flight mechanics model is required to have a high level of generality and maintainability. Generality refers to the ability to model different aircraft (hence different BWB variants, as well as different aircraft configurations) with minimal effort. Maintainability refers to the ability to change the level of fidelity of the flight mechanics model components with little effort [12].

The flight mechanics model is developed from scratch in the Matlab / Simulink environment. This model will allow the user to have full understanding of every single process in the simulation. It will also be easy to model some unconventional specific aircraft dependent modules within this environment. The model has a modular structure in order to make it possible to have several (groups of) people working on the same model at the same time and to ensure the continuous development of the model. Furthermore, it allows the automatic generation of flight mechanics models early in the design process. This will be explained in detail in Section 3. The different modules are presented in Section 2.1. The various functions of the model; e.g. time domain simulations, are described in Section 2.2.

2.1 Sub modules

2.1.1 Equations of motion and aircraft structure

A typical assumption in deriving the conventional equations of motion for flight mechanics applications is that the aircraft mass and the mass distribution are constant. However, this assumption is not made here for two reasons. First, it can be beneficial for BWB aircraft, to use fuel transfer from one tank to another to change the location of the c.g. to trim the aircraft. Second, it should be possible to model airframe flexibility. The fuel transfer system was used on the Concorde [13] to balance the 6 feet backward shift of the center of lift occurring at Mach 2 flying speed. In general, moment changes can be balanced using elevons, however, this reduces control power and also causes a significant amount of drag. The use of fuel transfer system yields a reduction of the trim drag contribution. There are additional benefits of such a system. First, at low speeds, shifting the c.g. backwards can be used in combination with an elevon deflection to create the same function as a conventional flap. Second, the aircraft can be put out of balance on purpose in order to increase maneuverability. Since the conventional equations of motion for a rigid body aircraft do not hold in case of fuel transfer and airframe flexibility, it was decided to model the aircraft using multi-body dynamics. The Matlab/Simulink toolbox SimMechanics has been used to model the dynamic effects of fuel transfer and consumption. Besides, the flight mechanics model is set up in a fashion that enables the user to add as many additional bodies as desired, which makes it possible to represent the complete aircraft structure as a flexible body. The effect of structural flexibility on the flight dynamics is indeed an important topic and an area of future research.

2.1.2 Aerodynamics

The aerodynamic module has a selective level of fidelity. If the aircraft design is still in a very early stage and the shape is not yet determined in all detail, then a simple aerodynamic model can be used. The flight mechanics model should then only be used to make simple performance calculations. On the other hand, if the shape of the aircraft is clearly defined then it is possible to perform more elaborate calculations to compute the aerodynamic forces. Various methods are available with different levels of fidelity and computational effort. The choice of the adequate aerodynamic model to be used depends actually on the purpose of the flight mechanics model. If the flight mechanics model is used within a multi-disciplinary design optimization then it might be beneficial to use a panel method [14] because the calculation time required is much less than that of CFD calculations. On the other hand, if the flight mechanics model will be used for piloted simulation, then the aerodynamic calculation will only have to be performed once and then CFD might become a good option. The current aerodynamic model has three levels of fidelity:

1. Vortex lattice method in combination with empirical handbook methods for drag prediction
2. First order panel method with viscous boundary layer integration
3. Wind tunnel results

The first option available as aerodynamic model is the 'vortex lattice method'. This method is an extension from the classical Prandtl lifting line theory [15]. In the lifting line theory, a finite wing is modeled by placing a large number of horseshoe vortices along a single line. In the vortex lattice method on the other hand, the wing is divided by several panels. Each of these panels has a horseshoe vortex attached to it. So instead of a lifting line, the vortex lattice method makes use of a lifting surface. The strength of the vortices is unknown at first and is calculated by making use of a boundary condition. The flow, a summation of the free stream flow and the flow induced by the horseshoe vortices, must be tangent at any point on the surface of the body. The code used in the context of this paper is called Tornado [16], [17]. A Prandtl-Glauert correction [18] is used to account for high Mach numbers in this code. A Trefftz plane analysis [19] is conducted to calculate the induced drag. Tornado is used as a virtual wind tunnel to calculate the aerodynamic forces for a range of static and dynamic flight conditions. Mach number, angle of attack, angle of sideslip, angular rates and control surface deflections are the considered variables. Even though a wing is three dimensional, the vortex lattice method is still essentially a two dimensional method because the body is represented with a flat surface with only two independent variables. Since the drag prediction of the vortex lattice method is not accurate, the model has been extended with a simple analytic prediction of the parasite drag [20] and the wave drag [20], [21] at transonic Mach numbers. This combination of methods is useful in the early design stages, as they are relatively simple and computationally fast.

The second aerodynamic model available is a panel method with integral viscous boundary layer. Various panel methods have been implemented in computer codes over the years. The analysis tool used here is called VSAERO [22], which implements a first order panel method, extended with several features such as an integral viscous boundary layer, Prandtl-Glauert correction for high Mach numbers and a Trefftz plane analysis to calculate the induced drag. It is also possible to exclude the viscous boundary layer feature and use in combination the empirical methods of the first option to account for parasite drag and wave drag. Similarly to the vortex lattice method (Tornado), also VSAERO is used as a virtual wind tunnel to calculate the aerodynamic forces for various static and dynamic conditions. An example of the pressure distribution over a BWB, calculated with VSAERO, is presented in Fig. 3.

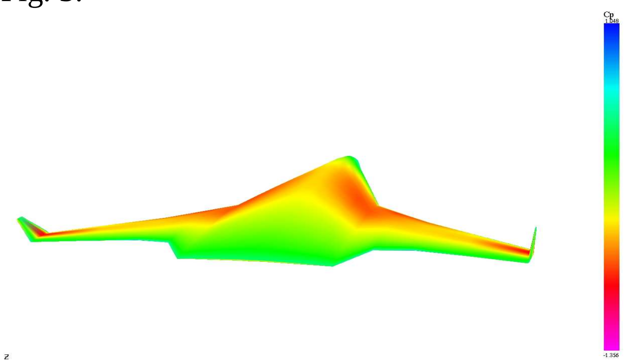

Fig. 3: Example pressure distribution calculated with VSAERO

The most accurate and final option available is to include wind tunnel data in the form of aerodynamic lookup tables. However, this requires the availability of a wind tunnel model and a series of wind tunnel tests and measurements. This is not always possible early in the design phase or when the flight mechanics model is used in a multidisciplinary design optimization. It can be useful in the detailed design phase when piloted simulations are required with the flight dynamics model.

The primary aim for the future is to include aerodynamic models with a higher level of fidelity and, when necessary, coupled to a structural dynamic model.

2.1.3 Propulsion

The propulsion system of the aircraft consists of three turbofan engines. Again, an engine model with a selective level of fidelity is available in the flight mechanics model. The first and most simple option is designated as an ‘ideal’ engine model. This is merely a thrust vector which instantaneously reacts to throttle changes. This option is useful if no information on the propulsion system is available whatsoever. The second option is a static engine model. This model generates a thrust vector based on the flight condition (Mach number and altitude) and the fuel flow (engine setting). No engine dynamics are included in this option. The relationships between Mach number, altitude, fuel flow and engine thrust are calculated offline for a whole range of conditions with the Gas Turbine Simulation program described in [23]. This is a high fidelity tool capable of simulating static and dynamic performance for both the design condition and the off-design condition. Detailed analyses of specific engine components are possible with this program. Currently, only the static analysis is used. It is recommended for future work to include a dynamic engine model as the third option. This third model can make use of the dynamic performance calculations of GSP or a new model can be developed. The modeling of engine dynamics is necessary if for example engine failures are simulated or when maneuvers are performed in which engine dynamics play an important role, such as take-off and landing.

2.1.4 Flight control system

The flight control module consists of the complete path from pilot input to the control surface deflection. Four pilot inputs (lateral, directional, longitudinal and thrust) and additional inputs can be provided when desired. The pilot inputs are transformed into control surface deflections. Unconventional aircraft, such as the blended wing body have multiple control surfaces which can be used for more than one function. The aircraft under investigation has 15 control surfaces along the trailing edge. This poses the problem of control surface allocation because many different control configurations are possible. It is up to the designer to decide on the control surface allocation. In essence it is a trade-off between control power in different axes. To clarify this, all surfaces can be deflected simultaneously to their maximum deflection angle in order to create a very large pitching moment. However, this leaves no roll control power.

The control allocation system transforms the pilot inputs into the control surface deflection demands. Currently this is represented in the flight mechanics model as a matrix gain. In real-life this can be a mechanical system or part of a fly-by-wire system. The advantage of a fly-by-wire system is that the control allocation schedule can be dependent on the flight condition. For example, after an engine failure, it might be very difficult to control the yawing motion of the aircraft. The control allocation system can then be reconfigured in-flight such that more yaw control power is available with the control surfaces. This, of course, will result in less control power in pitch and roll. The investigation of control allocation systems for a blended wing body aircraft is an area of future research. Once the control surface deflection demands are known, they are treated as inputs for an actuator model. This actuator model is then connected to the aerodynamic model of the control surfaces. The actuator model consists of a linear model (first, second or higher order) model describing the actuator dynamics, in conjunction with a rate limiter and a saturation limiter. The user can select which kind of actuator model is desired. For the BWB, the actuator dynamics are represented with a second order system with a natural frequency of 30 rad/s and a damping of 0.7. The saturation limits of all actuators are set to +30/-30 deg. Rate limits are not present (set to infinity)

2.1.4 Other

Other modules present in the model are (1) an atmospheric model and (2) a landing gear model. The atmospheric model is based on the international standard atmosphere. Currently, wind shear models and turbulence models are being added to the atmospheric module to represent the wind / turbulence conditions that can be encountered during flight.

2.2 Functions of the flight mechanics model

2.2.1 Aircraft trim

Aircraft trim is obtained via the Jacobian method [24]. At first, the initial conditions (altitude, airspeed, flight path angle, turn rate, heading angle and angle of sideslip) of the aircraft are specified. An initial guess c_0 is then made for the control vector c. This vector consists of the controls, the pitch attitude, roll angle and the flight track angle. The related accelerations a_0 are then calculated by the flight mechanics model. The acceleration vector does not solely consist of the accelerations, but also includes the sideslip angle.

$$a_0 = \begin{pmatrix} \dot{p} & \dot{q} & \dot{r} & \dot{u} & \dot{v} & \dot{w} & \beta - \beta_{desired} \end{pmatrix} \quad (1)$$

$$c_0 = \begin{pmatrix} x_a & x_b & x_c & x_p & \phi & \theta & \chi \end{pmatrix} \quad (2)$$

Partial derivatives are then calculated by perturbing the nonlinear aircraft model and they are stored in a Jacobian matrix J. The change of the acceleration vector as a function of the change of the control vector is then described with equation 3.

$$\Delta a = J \Delta c \quad (3)$$

From this equation one can estimate the change of the control vector that is required to drive the accelerations to zero.

$$\Delta c = -J^{-1} \Delta a_0 \quad (4)$$

$$c_1 = c_0 + \Delta c \quad (5)$$

The new control vector can then be used in the nonlinear aircraft model and the whole process described above is repeated. The iterative process is terminated once the acceleration vector is within desired limits (close to zero).

2.2.2 Linear aircraft models

A linear aircraft model can be derived from the nonlinear aircraft model once the trim condition is calculated. This model has the standard state space representation.

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \quad (6)$$

$$\vec{y} = C\vec{x} + D\vec{u}$$

The linear aircraft model is obtained via numerical perturbation of the nonlinear model. The simplest configuration of the model results in a 13-state model (9 rigid body states combined with 3 states for the position of the aircraft). The inclusion of actuator dynamics, engine dynamics, structural dynamics or other dynamics will result in a linear model with more than 13 states. The inputs of the linear model can either be the (four) pilot inputs or the actual control inputs (control surface deflection, engine setting, etc.). The linear model of the aircraft with four pilot inputs can be used for handling qualities and performance investigations. The linear model with the actual control inputs can be used for automatic flight control system design or for the design of control allocation systems. It is possible to select any variable of the nonlinear model as output of the linear model.

2.2.3 Handling Qualities analysis

A handling qualities toolbox was developed for the flight mechanics model. The following handling qualities can be evaluated by the toolbox:

- Longitudinal static stability
- Longitudinal speed stability
- Maneuvering stability
- Phugoid criterion
- Short period frequency requirements
- Gibson criterion
- Control Anticipation Parameter (CAP)
- Dutch roll requirement
- Roll mode
- Spiral
- Coupled roll spiral mode
- Lateral directional static stability

This toolbox primarily uses time domain simulations on the nonlinear model to determine handling qualities. In some cases, the linear aircraft models are used to determine handling qualities.

2.2.4 Performance analysis

A toolbox is created that allows a basic performance analysis of the aircraft model. Performance diagrams (thrust and/or power as a function of airspeed) can be determined by trimming the aircraft at various flight conditions. The results can be used to determine parameters such as maximum rate of climb, steepest flight path angle, etc. Currently, the toolbox is being extended with the option for unmanned mission simulation to calculate the fuel consumption during a complete mission.

3 Automatic generation of the flight mechanics model

3.1 General overview of the process

Figure 4 shows the flow of data from the Multi-Model Generator (MMG) to the Flight Mechanics Model (FMM) with a focus on the aerodynamic information.

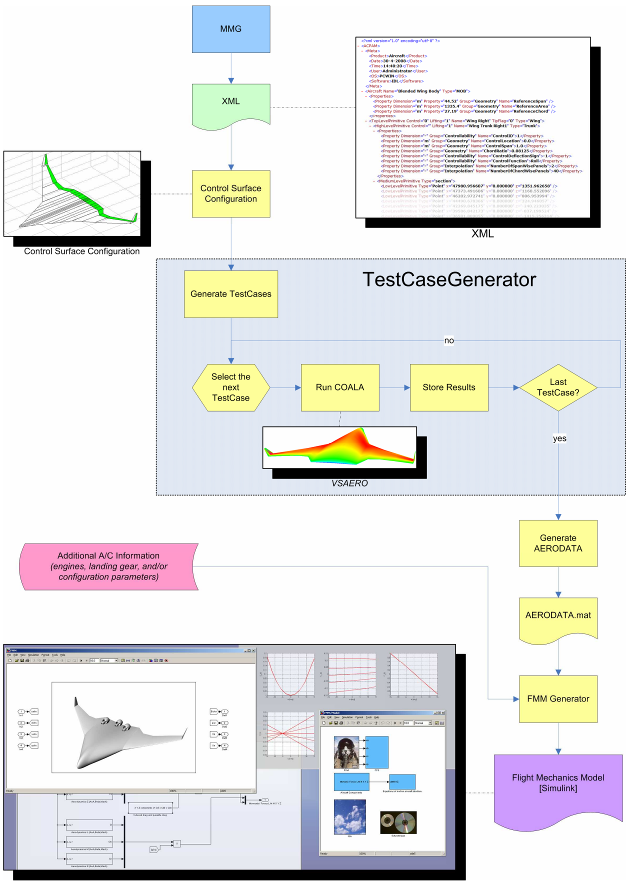

Fig. 4: Process overview

3.2 Defining the aircraft in the multi model generator

As discussed in more detail in [7] and [25], designers can use the MMG to model various aircraft configurations by combining and adjusting a number of elementary building blocks, called High Level Primitives (HLPs). So far, *Wing-trunk*, *Fuselage-trunk*, *Engine-Part* and *Connection-element* are the main four HLPs available in the MMG. In order to model the BWB configuration at hand it was sufficient to use more instantiations of the wing-trunk HLP only. The parametric definition of this primitive allows the designer to model wing elements with curved leading and trailing edges, to specify any value of twist, sweep and dihedral angle and to decide for chord, thickness and position of airfoils to be used

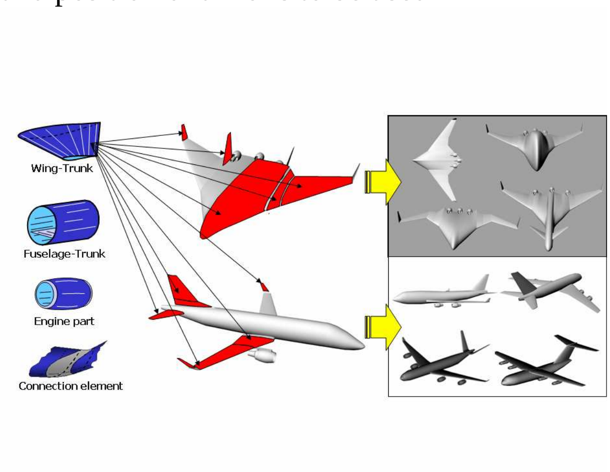

Fig. 5: Elementary building blocks of the multi model generator

Once the BWB shape has been defined, by tuning the various wing-trunk parameters, the MMG is able to automatically preprocess the surface of the aircraft and generate and XML file containing a panel discretization of the aerodynamic surface, as suitable for VSAERO.

3.3 Generating an aerodynamic data set

Aerodynamic data is calculated with VSAERO. To determine the control derivatives, a finite difference can be applied to the flight condition, after which VSAERO is run again for each variation. This is done by means of a in-house developed Matlab routine called COALA [25], which stands for 'COntrollability AnaLysis Application'.

COALA reads in the XML-file generated by the MMG and returns stability or control derivatives. Every instantiation of the wing-trunk primitive may contain a control surface, whose shape and functionality (e.g. chord ratio, span location) can be modified by means of another developed Matlab tool, called Control Surface Configuration (see Figure 4).

To generate a set of aerodynamic data for the flight mechanics model, COALA is executed multiple times, for several different flight conditions. The calculated aerodynamic forces, moments and control derivatives are finally organized in MATLAB data structure called AERODATA and fed to the Flight Mechanics Model Generator described below..

3.4 Flight mechanics model generator

The Flight Mechanics Model (FMM) generator is a code that *automatically* constructs a Simulink model, by connecting the sub modules described in Section 2.1, which are stored in a dedicated library. For example, if the aircraft in consideration has 15 control surfaces, then 15 actuators models are automatically connected to the aerodynamic model of the relative control surfaces. The module library can be easily expanded when more sophisticated modules are developed. This facilitates the 'selective fidelity' of the FMM. The AERODATA structure is read by the Flight Mechanics Model generator in order to fill the aerodynamic module with information.

4 Results

A limited selection of results obtained with the flight mechanics model is presented in this section to give an impression of its capabilities. Results are compared to results found in the literature where possible. First, the longitudinal handling qualities are evaluated. A stable centre of gravity position was chosen with a static margin $K_n = 0.057$. The elevator angles required to trim the aircraft for a range of low speed flight conditions are displayed in Fig. 6 on the next page.

These trim elevator deflections are close to those obtained by Cook and de Castro [27]. At this condition, the trim elevator deflections for the airspeeds considered are deemed to be reasonable. The corresponding angle of attack at the lowest airspeed (65 m/s) is 14 deg. This angle is rather high in terms of passenger comfort.

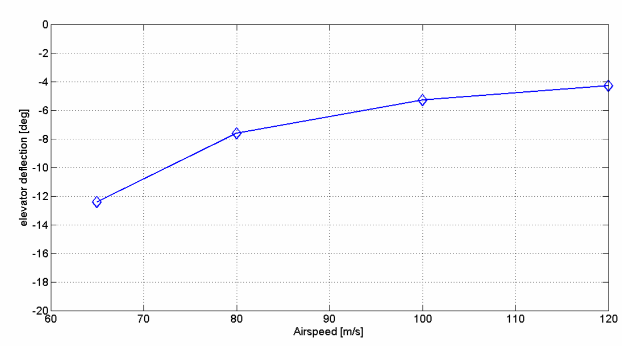

Fig. 6: Elevator angle required in trim

The phugoid and short period frequency and damping are subsequently determined at 100 m/s true airspeed (Table 1). A time domain simulation of the phugoid is displayed in Fig. 7 for both the full nonlinear flight mechanics model and its linear models.

	ω [rad/s]	ζ [-]
Short period	1.09	0.76
Phugoid	0.13	0.022

Table 1: Phugoid and short period

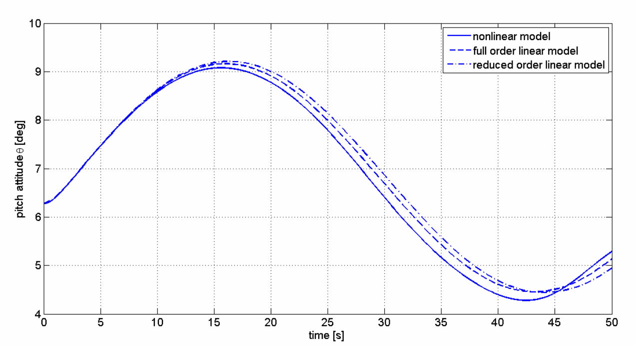

Fig 7: Time domain simulation of Phugoid

The phugoid and short period frequency and damping values correlate closely to those obtained by Cook and the Castro [27]. Furthermore, the time domain results obtained with the linear aircraft models match the nonlinear aircraft model well. Finally, at 100 m/s true airspeed, the aircraft possesses (1) positive longitudinal maneuver stability, and (2) speed stability with the control surfaces fixed. The control anticipation parameter (CAP) and short period requirements for category B flight phases are level 1 at this airspeed.

Lateral directional flying qualities are also briefly investigated for the same flight condition. The aircraft is trimmed in a rate one turn (3 deg/s) and the resulting trim values are; 6.5 deg angle of attack, 28.4 deg bank angle, 5.8 deg pitch attitude, -6.4 deg elevator deflection, -1.2 deg aileron deflection and 3.1 deg rudder deflection. These trim values are considered to be acceptable. The time to double amplitude of the spiral mode is 45 seconds, which is adequate. The dutch roll mode has a frequency ω_{dr} = 0.25 rad/s and a damping ζ_{dr} = -0.23. This mode is unstable. The roll mode time constant is 3.1 seconds which is too large. One can therefore conclude that for this particular flight condition, c.g. location and control allocation schedule, lateral directional handling qualities are inadequate. They can be improved in various ways. However, that is not the purpose of the current research.

In conclusion, this was just a limited investigation into the handling qualities of this aircraft configuration to demonstrate the capabilities of the model. In the future, handling qualities should be investigated with more detail for a wide range of conditions.

Conclusions and Recommendations

A tool is created that automatically generates a flight mechanics model of a Blended Wing Body aircraft automatically within a design engineering engine. In principle, this tool can be used to create a flight mechanics model of any fixed wing aircraft configuration. Coupled to the design engineering engine, it can serve used as a tool for the design (sizing and placement) of control surfaces either manually or within a multidisciplinary design optimization. It can also be used for handling qualities analysis, the design of control allocation systems, the analysis of failure states and the design of flight control laws. Some limited results of the model are presented to demonstrate its capabilities.

It is recommended for future research to increase the fidelity of the model by including airframe flexibility and engine dynamics. Furthermore, a full investigation into the controllability of the Blended Wing Body aircraft should be made for a wide range of flight conditions and aircraft configurations.

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