HANDLING QUALITIES ASSESSMENT OF A BLENDED WING BODY CONFIGURATION UNDER UNCERTAINTY CONSIDERATIONS

Y. J. Hasan[(1)], J. Schwithal[(1)], T. Pfeiffer[(2)], C. M. Liersch[(3)] and G. Looye[(4)]

[(1)] DLR, Institute of Flight Systems, 38108 Braunschweig
[(2)] DLR, Air Transportation Systems, 21079 Hamburg
[(3)] DLR, Institute of Aerodynamics and Flow Technology, 38108 Braunschweig
[(4)] DLR, Institute of System Dynamics and Control, 82234 Weßling

Abstract

The unconventional shape of the blended wing body configuration affects its flight dynamics significantly. Therefore, a handling qualities assessment of blended wing body configurations requires particular attention, optimally at an early stage of the development process in order to enter design changes already during the preliminary design phase. However, flight dynamic investigations at such an early state are subject to considerable uncertainty, originating from simplifying model assumptions, unknown external conditions, lack of empirical data and more. The topic of this paper is to analyse the handling qualities of the blended wing body configuration designed within the project FrEACs (*Future Enhanced Aircraft Configurations*) of the DLR (*German Aerospace Center*) under uncertainty considerations. The first part of this paper investigates influences of single parameter variations on different handling quality criteria for longitudinal and lateral-directional motion. The position of the centre of gravity is found to have significant impact on the considered longitudinal criteria. The lateral-directional motion is also influenced by the position of the centre of gravity. In addition, aerodynamic damping derivatives and moments of inertia also affect the lateral-directional criteria significantly, having an about equally dominant impact. The second part of this work investigates the probability that uncertainties, occurring in the design process, lead to different handling qualities than intended. Therefor various parameters are varied simultaneously assuming a random normal distribution.

NOMENCLATURE

Symbols

C_{lp}, C_{mq}, C_{nr}	Aerodynamic damping derivatives
$C_{L\alpha}$	Lift curve slope
C_D, C_L	Coefficients of drag, lift
C_m	Pitching moment coefficient
D	Damping ratio
g	Gravitational acceleration
I_{xx}, I_{yy}, I_{zz}	Moments of inertia
k	Factor
l_{MAC}	Mean aerodynamic chord
m_{MTO}	Maximum takeoff mass
n_z	Vertical load factor
Ma	Mach number
N	Number of samples
p, q, r	Roll, pitch, yaw rate
t, T	Time, time constant
T_2	Time-to-double
x_{AC}	Position of aerodynamic centre in x-direction
x_{CG}	Position of centre of gravity in x-direction
α	Angle of attack
β	Angle of sideslip
γ	Flight path angle
Δ	Increment/decrement
ζ, η, ξ	Deflections of rudder, elevator, aileron
μ	Statistical mean value
σ	Standard deviation
Φ, Θ, Ψ	Angles of roll, pitch, yaw
Ψ_β	Dutch roll-sideslip phase angle
ω_0	Natural frequency

Indices

dr	Dutch roll
p	Phugoid
sp	Short period

Abbreviations

BWB	Blended Wing Body
CAP	Control Anticipation Parameter
CG	Centre of Gravity
CMU	CPACS Mass Breakdown Updater
CPACS	Common Parametric Aircraft Configuration Schema
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DOF	Degree Of Freedom

FrEACs	Future Enhanced Aircraft Configurations
HAREM	Handling Qualities Research and Evaluation using Matlab
HQ	Handling Qualities
ICAO	International Civil Aviation Organization
RCE	Remote Component Environment
VLM	Vortex Lattice Method
XML	Extensible Markup Language

1. INTRODUCTION

Current commercial aviation forecasts predict a considerable increase of civil air traffic in the near future. According to the ICAO (***I**nternational **C**ivil **A**viation **O**rganization*), the volume of passenger and cargo air traffic will more than double within the next 20 years [1]. Moreover, kerosene prices are expected to rise further and environmental issues are getting increasingly important. These trends translate into more stringent requirements for future aircraft, demanding a significant reduction of fuel consumption and noise emission.

The BWB (***B**lended **W**ing **B**ody*) is an aircraft configuration that has the potential to overcome these challenges. Its fuselage is flattened and smoothly blended into the wings. Thereby, it has a higher lift contribution than the fuselage of conventional aircraft and it reduces the relative wetted area. Consequently, cruise lift-to-drag ratios can be increased by more than 20 % compared to equivalent conventional aircraft, as theoretical and experimental investigations have shown [2, 3]. In addition, the particular shape of the BWB allows an engine integration on top of the fuselage. This form of shielding can significantly reduce the downwards noise emission [4], which makes the BWB one of the most promising aircraft configurations in terms of noise reduction [5].

On the other hand, the BWB configuration has some major drawbacks. Cabin pressurisation is one important issue. Due to the large fuselage width paired with the relatively low height, the pressurisation of the cabin leads to non-uniform structural bending loads that are large in the middle parts [6]. There are some cabin design concepts to deal with this challenge [7]. However, these concepts are always associated with a relatively high structural mass. Another important disadvantage, mainly resulting from the tailless design of the BWB, concerns flying properties and controllability. Several investigations have proven that BWB configurations usually suffer from low directional stability and yaw damping, and the static margin of BWB configurations often needs to be small to realise sufficient pitch control authority [8, 9]. For these shortcomings in flight dynamics, BWB configurations normally require flight control systems that provide the desired handling qualities [10].

Altogether, a proper and thorough BWB design with regard to flight dynamics necessitates the integration of handling quality investigations into the design process. However, flight dynamic analyses consider the aircraft in its entirety and require thus results from several foregoing disciplines like mass distributions or aerodynamic parameters. Particularly at an early stage of the design process, each of these results is subject to a large amount of uncertainties, leading to errors due to model assumptions, unknown external conditions, lack of empirical data and more. The resulting degree of uncertainty of the handling qualities assessment is even higher since it combines the foregoing errors with those coming from the flight dynamic investigations itself.

A way of dealing with uncertainties is to estimate them for chosen design parameters and to integrate them into the calculations. Doing so, the dependencies of the results on design parameters can be quantified. These dependencies provide information on whether a design parameter needs to be determined with a higher accuracy. This might be the case if it has a very strong influence on certain handling qualities. In addition, the overall probability of undesirable results can be estimated at an early stage, allowing to enter design changes already during the preliminary design phase.

Within the project FrEACs (***F**ut**u**re **E**nhanced **A**ircraft **C**onfigurations*) [11], several institutes of the DLR (*German Aerospace Center*) worked on the design of, among others, a BWB configuration. Therefor a multidisciplinary central tool chain combining preliminary estimation of masses, numerical aerodynamic computations, generation of flight dynamic models, optionally the implementation of flight control systems and flight mechanical analyses was set up. A key aspect was the quantification of uncertainties and their propagation throughout the design process.

This paper deals with the BWB configuration developed in FrEACs and focuses on the handling qualities assessment of the configuration without flight control system. Therefor Section 2 presents the BWB configuration analysed in this work and points out its specific flight mechanical characteristics. Subsequently, Section 3 describes the central workflow, used to perform preliminary calculations concerning aircraft mass, aerodynamics and handling qualities. Finally, Section 4 demonstrates the Blended Wing Body's handling qualities by means of some selected criteria, both for longitudinal and lateral-directional motion. It furthermore investigates the impact of uncertainties, both by a sequential variation of single design parameters and by a simultaneous random variation of multiple parameters. The results obtained in this work can be used further to improve both the BWB geometry and the design process.

2. THE BLENDED WING BODY CONFIGURATION

The considered BWB is a long range aircraft, designed to carry up to 450 passengers with a maximum takeoff mass of around 450 metric tons. It has a wing span of 64 m and a length of around 40 m. Figure 1 provides a sketch of the BWB configuration developed within FrEACs.

As shown, it is equipped with three turbofan engines, mounted on top of the fuselage near the trailing edge.

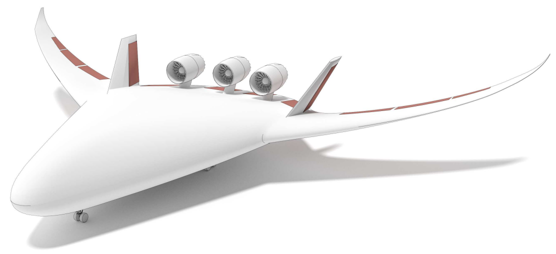


FIGURE 1. Conceptual sketch of the blended wing body configuration developed within FrEACs

This way, a downwards noise emission reduction is achieved by profiting from shielding effects. The BWB is designed tailless and with two relatively small vertical tailplanes, that frame the engines. Figure 2 shows the control concept for the configuration.

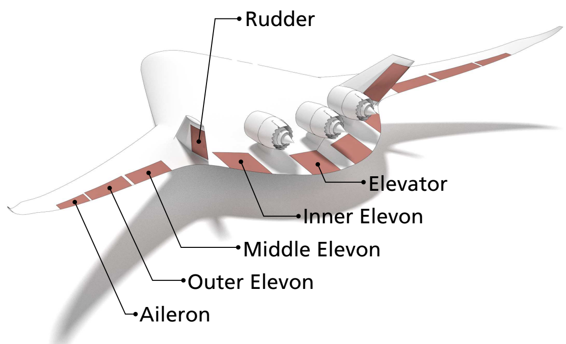


FIGURE 2. Control surfaces of the blended wing body configuration

This work investigates handling qualities of the aircraft's clean configuration. This BWB configuration generates rolling moments using an aileron and up to three elevons. Pitch trimming is performed using the elevator and the inner elevons. The BWB furthermore possesses two rudders for yawing moment generation.

It is obvious that the BWB differs considerably from conventional aircraft. These distinctive geometry differences have an impact on flight dynamic properties of the BWB. The most important aspects can be determined qualitatively:

- The BWB has no horizontal tailplane.
- Due to the specific shape of the fuselage, the BWB has a lower moment of inertia about the pitch axis and a relatively high moment of inertia about the roll axis.
- The short fuselage leads to short lever arms of the pitch and yaw control surfaces.

These thoughts clarify the importance of flight dynamic investigations for the BWB. A careful design of the BWB with respect to handling qualities both in longitudinal and lateral-directional motion is crucial.

3. WORKFLOW

This section presents the central tool chain used to perform the calculations of this work and provides a rough overview of the integrated tools. Figure 3 illustrates the complete workflow for the BWB, implemented in RCE (***R**emote **C**omponent **E**nvironment*)[1] [12]. RCE is an integration environment to support multidisciplinary analyses of complex systems. Using central workflows set up by users, RCE connects integrated tools that are provided by servers and realises the exchange of data between the tools. This way, as soon as the tools are integrated, analyses incorporating various disciplines can be conducted with little effort.

The exchange between different tools furthermore requires the use of a uniform data structure. Within this work, the ***C**ommon **P**arametric **A**ircraft **C**onfiguration **S**chema* (CPACS)[2] [13, 14] is used. It refers to an XML (*E**x**tensible **M**arkup **L**anguage*) based data specification, containing various parameters that are arranged in a standardised structure. CPACS gathers information on the air vehicle as well as the tool-specific setup and stores the resulting tool outputs. The use of CPACS demands an adaptation of the respective tools to the data structure, which is realised using wrappers. Thereby, the wrapper reads in the CPACS-based files, collects the required information and converts it into tool-specific inputs. In an analogous manner, the wrapper imports tool outputs and writes it into the CPACS-based files.

As shown by Figure 3, the complete workflow is based on a predefined BWB geometry and it begins by loading an engine performance map ("TWdat"). In the following, an initial analysis is undertaken, which estimates masses, performs simple aerodynamic calculations and estimates mission fuel. Section 3.1 describes the initial analysis in more detail. Subsequently, numerical aerodynamic calculations are performed (Section 3.2) and flight mechanical analyses are conducted (Section 3.3).

3.1. Initial Analysis

Within the initial analysis, the central workflow first estimates the operating empty mass of the BWB. Therefor the tool labeled "Masses" divides the aircraft geometry into several segments and approximates the respective segment masses using an area mass approach [15, 16].

Next, the tool CMU (***C**PACS **M**ass Breakdown **U**pdater*) calculates the resulting CG (***C**entre of **G**ravity*) position and moments of inertia.

At the same time, the MATLAB-based tool "Tornado"[3] [17] is used for computation of aerodynamic coefficients, derivatives and polars. In Tornado a so-called

[1] RCE is an open source software developed and continuously enhanced by DLR. It can be downloaded at *www.rcenvironment.de*.

[2] CPACS is an open source data format developed by DLR. It is constantly extended to account for novel tools. The description and an exemplary file can be downloaded at *www.cpacs.de*.

[3] Tornado is an open source software, first implemented by the Royal Institute of Technology in Stockholm. It is further being developed and is available at *www.tornado.redhammer.se*.

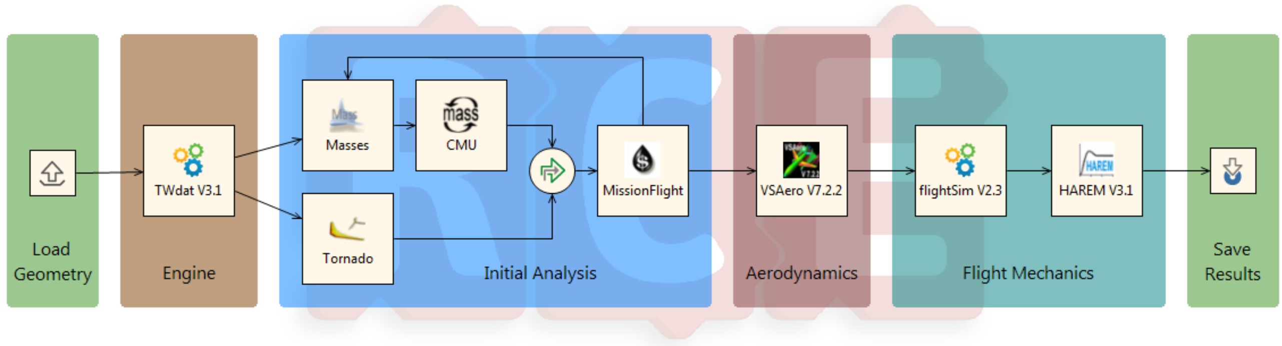


FIGURE 3. Central workflow for investigations of the BWB, including an initial analysis and mass estimation, aerodynamics computation, generation of a flight dynamic model and handling qualities assessment

***V**ortex **L**attice **M**ethod* (VLM) is implemented. It incorporates additional functions to account for viscosity and compressibility effects.

The CPACS files arising from the masses and aerodynamics branch of the workflow are then merged. Finally, the tool labelled "Mission Flight" trims the aircraft in cruise conditions and estimates the required fuel mass for a given mission specification.

With the updated fuel mass, also segment masses, CG position and moments of inertia are updated.

3.2. Aerodynamics

After the initial analysis, the workflow proceeds with more accurate aerodynamic computations using the commercial 3D panel method software VSAero[4]. It is based on potential flow theory, including compressibility correction, and determines induced drag by means of a wake consideration in the so-called "Trefftz"-plane. In addition, viscous and wave drag are estimated using a DLR handbook methods tool. It approximates viscous drag using flat plate theory, combined with a form factor for thickness effects, and wave drag using the approach of Korn-Mason [18, 19].

A four-dimensional aerodynamic map is generated using the aerodynamic tools. It serves as basis for interpolation within the flight mechanical analyses. The map provides data for

- 4 different Mach numbers ([0.2, 0.5, 0.8, 0.85]),
- 3 different Reynolds numbers ($[1.0 \cdot 10^8, 1.5 \cdot 10^8, 2.0 \cdot 10^8]$),
- 3 different angles of sideslip ($[-5°, 0°, 5°]$) and
- 12 different angles of attack ($[-5°, -2°, -1°, 0°, 1°, 2°, 3°, 5°, 7.5°, 10°, 15°, 20°]$).

For each point of the map, a couple of aerodynamic parameters is determined, which include

- 3 force coefficients,
- 3 moment coefficients and
- 18 derivatives accounting for the change of the force and moment coefficients due to the rotation rates.

Furthermore, control surface deflections are considered in the form of delta values for the change of the force and moment coefficients. These values are provided for all 12 control surfaces for every combination of Mach number, Reynolds number, angle of sideslip and angle of attack, each being characterised using the three deflection angles for minimum, zero and maximum deflection.

Aerodynamic parameters are obtained from the aerodynamic map by interpolation. The drag coefficient, for instance, is given by

$$C_D = C_D(Ma, Re, \alpha, \beta) + \Delta C_D(Ma, Re, \alpha, \beta, \zeta, \eta, \xi). \quad (1)$$

Figure 4 shows the surface pressure distribution and the surface grid for the BWB exemplarily for one operating point at a Mach number of 0.8, a lift coefficient of 0.5 and an angle of sideslip of 3°. The right rudder and both ailerons are deflected.

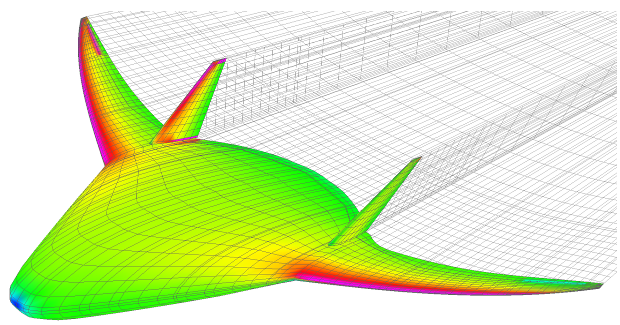


FIGURE 4. Surface pressure distribution and surface grid for BWB calculated with VSAero at Mach number of $Ma = 0.8$, lift coefficient of $C_L = 0.5$ and sideslip angle of $\beta = 3°$ with aileron deflection of $\xi = -25°$ and deflection of the right rudder of $\zeta = -12.5°$

[4]Further information on VSAero can be found online at *www.ami.aero/software-computing/amis-computational-fluid-dynamics-tools/vsaero/*

3.3. Flight Mechanics

The last step of the workflow depicted in Figure 3 addresses flight mechanical analyses. For handling quality assessment two DLR tools are integrated into the workflow. The first tool, called flightSim [20], generates and provides different types of aircraft models. These include 3DOF (***D**egree **O**f **F**reedom*) models for mission simulations, 6DOF models, optionally trimmed and linearised about the operating point, for flight dynamics simulations and more. Furthermore, closed-loop models with automatically generated flight control systems can be provided. However, within this work, focus is on flight dynamic investigations of the uncontrolled BWB. Hence, solely the 6DOF open-loop models are used here.

The second DLR tool, HAREM (***H**andling Qualities **Re**search and **E**valuation using **M**atlab*) [21–23], assesses handling qualities of aircraft by means of various criteria for longitudinal and lateral-directional motion. HAREM both contains criteria that require linearised aircraft models and those that work with the time history of the flight dynamic simulation itself. The results are stored in the output CPACS file and can optionally be exported in the form of plots.

Ultimately, the workflow (Figure 3) saves the results in a final CPACS file. This file contains all information and results provided by the utilised tools. It thus provides a complete data set consisting of engine data, masses, centre of gravity, moments of inertia, an aerodynamic map, trim data and handling quality levels.

3.4. Uncertainties

The consideration of statistical uncertainties is a main goal of this work. A high amount of samples is necessary in order to obtain significant results. However, the workflow as presented in Figure 3 requires high computational effort and is very time consuming, which is mainly driven by the calculation of the aerodynamic map. Therefore, this workflow is not feasible for the integration of uncertainties. Instead, the reduced workflow, depicted in Figure 5 is used. It loads the CPACS data file, already containing the aerodynamic map. Rather than introducing uncertainties into each tool and propagating them through the complete process, this workflow executes the tool "Uncertainty" before the flight mechanical analysis. The tool can make alterations of different types to user-specified parameters. In this work, the tool is used in two manners.

The first part of this work considers the qualitative influences of certain parameters on different handling quality criteria. Within this part, the tool is used to apply sequential variations to the parameters, listed in Table 1. Thereby, each of the parameters is varied one after another, while the others are kept constant. The variations are applied each within the borders specified in Table 1 and using ten equidistant variation steps.

According to the respective parameters, the variations are applied in different manners. The parameters x_{CG},

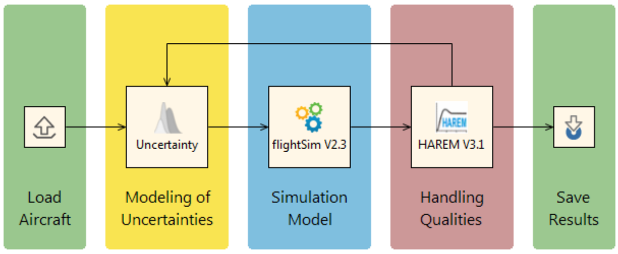


FIGURE 5. Reduced workflow for handling quality assessment under uncertainty considerations

Uncertainty Parameter		Variation Limits	
Drag Coefficient	C_D	−10 %	+10 %
Pitching Moment Coefficient	C_m	−10 %	+10 %
Aerodynamic Damping Derivatives	C_{lp}	−10 %	+10 %
	C_{mq}	−10 %	+10 %
	C_{nr}	−30 %	+30 %
Centre of Gravity	x_{CG}	−5 %	+5 %
Maximum Takeoff Mass	m_{MTO}	−2 %	+2 %
Moments of Inertia	I_{xx}	−10 %	+10 %
	I_{yy}	−10 %	+10 %
	I_{zz}	−10 %	+10 %

TABLE 1. Parameters that are varied sequentially and with equidistant steps and the respective variation limits

m_{MTO}, I_{xx}, I_{yy} and I_{zz} can be varied directly. The aerodynamic parameters C_D, C_m, C_{lp}, C_{mq} and C_{nr} are varied by a multiplication of all basic values in the aerodynamic map with the same uncertainty factor. For the drag coefficient the variation yields

$$C_D = k_{C_D} \cdot C_D(Ma, Re, \alpha, \beta) + \Delta C_D(Ma, Re, \alpha, \beta, \zeta, \eta, \xi), \quad (2)$$

where the uncertainty factor for the drag coefficient k_{C_D} is in the range of 0.9 and 1.1 for the given variation limits.

Within the second study, the tool is executed in order to model uncertainties using a Monte Carlo Simulation. The parameters in Table 2 are varied simultaneously and randomly using a normal distribution. The values for the standard deviations are mainly based on industrial experience [24].

While force and moment coefficients and the aerodynamic damping derivatives can be accessed directly through the aerodynamic map, parameters related to flow angles like for instance the lift curve slope $C_{L\alpha}$ are not explicitly available. A variation of such parameters is done by modifying the breakpoints for α and β of the aerodynamic map by multiplication with the same randomly varied factor.

Such a variation also has an effect on the other parameters. For the drag coefficient it leads to

$$C_D = C_D(Ma, Re, k_\alpha \cdot \alpha, \beta) + \Delta C_D(Ma, Re, k_\alpha \cdot \alpha, \beta, \zeta, \eta, \xi), \quad (3)$$

where k_α represents the uncertainty factor for the angle of attack.

A variation of the CG position refers to the value of the CG position with respect to the aircraft nose. It has to be noted that the CG position is chosen for aircraft and is therefore, to a certain extent, not subject to uncertainties. However, it is included in this work in order to show its influence on handling qualities. The handling quality dependences can furthermore be used to limit the allowable CG range.

Uncertainty Parameter		Standard Deviation
Angle of Attack	α	10 %
Angle of Sideslip	β	30 %
Drag Coefficient	C_D	10 %
Pitching Moment Coefficient	C_m	10 %
Aerodynamic Damping Derivatives	C_{lp}	10 %
	C_{mq}	10 %
	C_{nr}	30 %
Centre of Gravity	x_{CG}	5 %
Maximum Takeoff Mass	m_{MTO}	2 %
Moments of Inertia	I_{xx}	10 %
	I_{yy}	10 %
	I_{zz}	10 %

TABLE 2. Parameters that are varied simultaneously and randomly using a normal distribution and the respective standard deviations

It has to be noted that dependencies between parameters are not considered here, since it is one aim of this work to analyse the effects single parameters have on handling qualities. This means that, for instance, a variation of the CG is not succeeded by an update of the moments of inertia in this work.

Figure 6, shows the density function of a normal distribution with respect to the standard deviation. It illustrates the extent of the random parameter variations applied here. For instance, as shown in Table 2 the drag coefficient C_D is varied randomly using a standard deviation of 10 %. This means that with a probability of 68.3 %, the application of the random variation leads to a new value of the drag coefficient which is between 90 % and 110 % of the initial value.

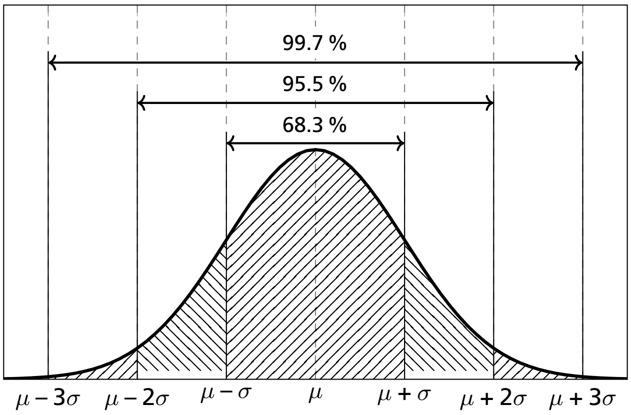


FIGURE 6. Density function of the normal distribution along with its deviation intervals

4. HANDLING QUALITIES ASSESSMENT

This section deals with handling quality assessment of the BWB by means of different criteria for longitudinal and lateral-directional motion. Section 4.1 considers both quantitative and qualitative influences of sequential parameter changes on handling qualities. Section 4.2 examines the impact of simultaneous random parameter variations.

Generally speaking, handling quality criteria serve to assess the suitability of an air vehicle for completing different missions from a piloting point of view. They are thus based on subjective perceptions. As a consequence, a universal assessment of an aircraft's handling qualities is not possible. Instead, they depend on many factors, including flight conditions and aircraft size. The criteria are usually empiric and based on pilot evaluation.

A multitude of handling quality criteria are formulated in MIL-F-8785C [25] and MIL-STD-1797A [26]. Therein, three HQ Levels (*Handling Quality Levels*) are defined. Table 3 summarises these levels along with their significations. In addition, an assessment of "Level > 3" can be assigned to a criterion. Such an evaluation signifies a non-controllable aircraft behaviour and is unacceptable.

HQ Level	Signification
Level 1	Satisfactory
Level 2	Acceptable
Level 3	Controllable

TABLE 3. Different HQ Levels for handling quality assessment as defined by MIL-STD-1797A [26]

Within this work, handling qualities are investigated for an operating point at a height of 2000 m and a Mach number of 0.4. These flight conditions roughly correspond to the beginning of the landing approach before flap and slat deflection. This way, the BWB's clean configuration is analysed at low speed. This operating point is chosen, since most of the handling qualities are supposed to be more challenging for the BWB at low speed due to the reduced effectiveness of the control surfaces.

Consequently, the flight phase category regarded in this work is "CAT. C", which comprises terminal flight phases like takeoff and landing. Besides, due to its size and its expected application as passenger aircraft, aircraft "Class III", destined for heavy aircraft, is assigned to the BWB[5].

4.1. Sequential Variation of Parameters

In order to design an aircraft with adequate handling qualities, prior knowledge of parameter influences on flight dynamic characteristics and their magnitude can be very useful. Not only can the aircraft geometry be modified more efficiently, but the design process can be improved. The knowledge allows to decide which parameters require more careful consideration during the design phase and which parameters can be estimated more roughly without significantly changing the accuracy of investigations. In this work, the particular parameter influences for BWB are investigated. Furthermore, the quantitative consequences with respect to HQ Levels for the given values listed in Table 1 are regarded.

In this section, the parameters listed in Table 1 are varied within the respective variation limits using ten equidistant steps. The variations are applied sequentially for every parameter while the other parameters are kept constant.

4.1.1. Static Margin

The static margin is defined as the distance between the aerodynamic centre of the complete aircraft and the CG, normalised by the mean aerodynamic chord. It can be expressed as

$$\frac{x_{AC} - x_{CG}}{l_{MAC}} = -\frac{dC_m}{dC_L}. \tag{4}$$

For longitudinal stability, the static margin must be greater than zero. This signifies an aerodynamic centre location behind the CG and implies that the derivative of pitching moment with respect to lift coefficient is negative. This way, an outer disturbance, leading to a change in angle of attack is counteracted.

Figure 7 shows the static margin in relation to the CG position and the pitching moment coefficient. As expected, there is a mostly linear dependency on the CG position. A shift of the CG position rearwards leads to a reduction of the static margin. An increase of the CG position of more than about 2 % even leads to a loss of static longitudinal stability.

The pitching moment coefficient has only a weak influence on the static margin. As described in Section 3.4,

[5]Further information on aircraft classification and flight phase categories can likewise be found in MIL-STD-1797A [26]

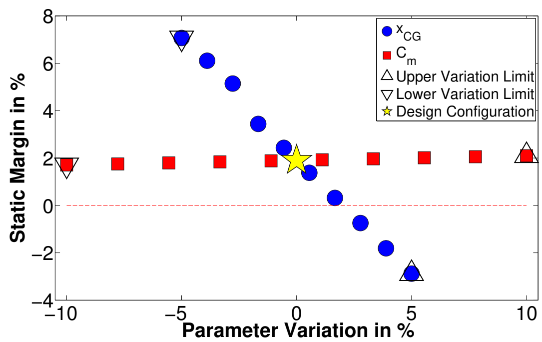


FIGURE 7. Static margin for a sequential variation of CG position and pitching moment coefficient

the pitching moment coefficient is varied by a multiplication of all values in the aerodynamic map with the respective uncertainty factor. While the lift coefficient stays constant, the associated C_m changes. This leads to a change of dC_m/dC_L. According to Eq. (4) this results in a change in static margin due to a shift of the position of the aerodynamic centre.

4.1.2. Control Anticipation Parameter (CAP)

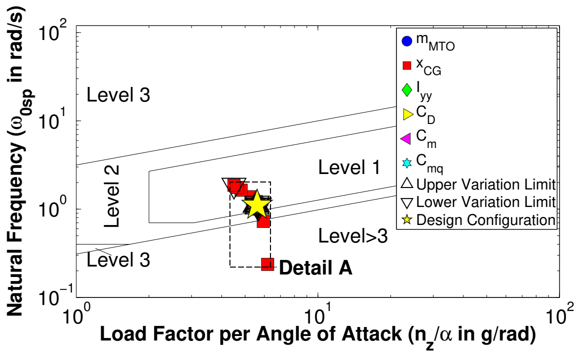
The CAP (***C****ontrol* ***A****nticipation* ***P****arameter*) criterion, as documented in MIL-F-8785C [25] defines limits for the natural frequency of the short period. It particularly intends to realise a certain longitudinal aircraft agility. Therefor, the CAP is defined, which represents the ratio of an initial pitch acceleration and the respective steady-state load factor due to an elevator step input. It is approximately given by[6]

$$CAP = \frac{\ddot{\Theta}(t=0)}{n_z(t \to \infty)} \approx \frac{\omega_{0sp}^2}{n_z/\alpha}. \tag{5}$$

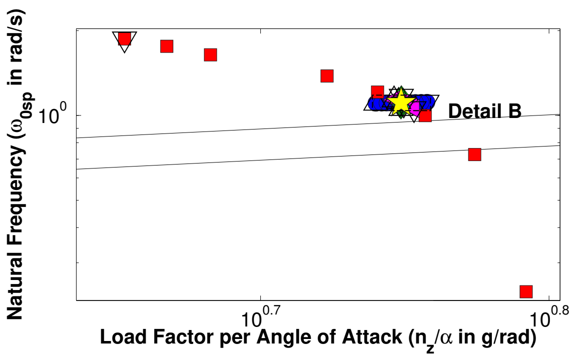
Figure 8 shows the CAP criterion plot for the BWB considering sequential parameter variation and using the linearised flight dynamic model. The CAP can generally be interpreted in such a way, that the aircraft's response is too sluggish in case of a small CAP (below "Level 2" band in the figure). As a consequence, the pilot tends to oversteer. On the other hand, for too large values of the CAP (above "Level 2" band), the aircraft reacts too agile and understeering is an issue.

Figure 8a provides the complete criterion plot for flight phase "CAT. C" and aircraft "Class III" and lists the parameters that are varied within the limits given in Table 1. The design configuration, representing the BWB without consideration of uncertainties, achieves "Level 1" in this criterion. The corresponding point is certainly located near the lower boundary to the "Level 2" band. Accordingly, small parameter changes can already lead to handling quality degradation. Figure 8b provides an enlarged view of Detail A. Figure 8c furthermore enlarges Detail B.

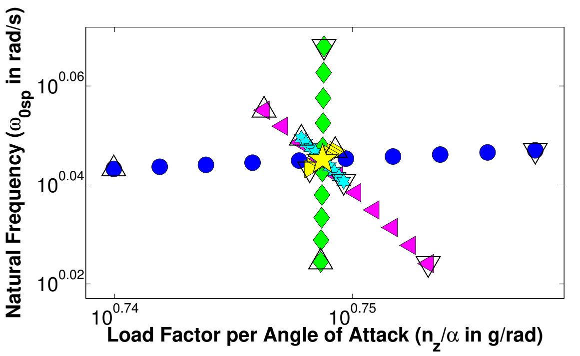
[6]In this approximation it is assumed that the change of lift due to the elevator deflection is small compared to the resulting pitching moment. For blended wing body configurations, this assumption represents a simplification.



(a) Overall view



(b) Enlarged view of Detail A



(c) Enlarged view of Detail B

FIGURE 8. CAP criterion for sequential variation of single parameters on the basis of the linearised flight dynamic model

With the given parameter variation range, the impact of I_{yy} is rather small. Detail B shows that a smaller pitch moment of inertia increases longitudinal agility. For the given BWB variations of I_{yy} and C_m are not critical for the limits. However, due to the small margin to the "Level 2" band, an increase of I_{yy} combined with a decrease of C_m can be crucial.

The parameters C_D and C_{mq} have very little effect. For the latter this might be explained by the small value of C_{mq} of the design configuration. Since pitch damping of this BWB is small, the changes due to variation are also small.

The given data points always refer to an operating point for the trimmed aircraft. A change of mass primarily requires a different lift coefficient. Therefore, trim angles of attack are different. Mass modifications thus merely result in a shift along the horizontal axis. Since this shift is nearly parallel to the HQ Level boundaries, mass variations are uncritical for longitudinal agility.

The position of the centre of gravity and the pitching moment coefficient have a qualitatively similar influence on this criterion. Thereby, the CG variation impact is very strong. A shift rearwards decreases longitudinal agility considerably. A negative static margin, being the case for the last three data points (compare Figure 7), leads to a rapid decrease of the short period natural frequency, combined with an uncontrollable aircraft behaviour ("Level 3"). However, it can be seen that the fourth last data point, which corresponds to a positive static margin already leads to an HQ Level of "Level 3". As a consequence, the allowable range of the CG position, which is already small for this BWB, is reduced further.

For the two most aft CG locations the BWB does not show an oscillatory short period mode any more. Instead, the mode turns into an aperiodic motion. Hence, these data points are not present in the plot.

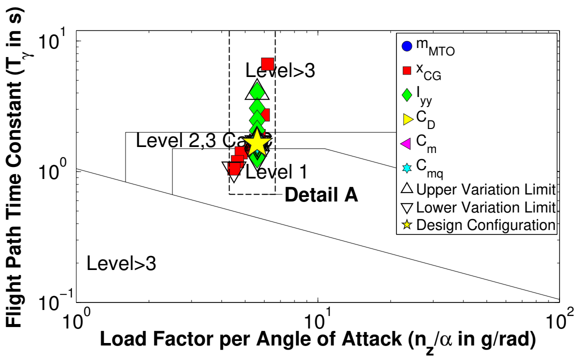
4.1.3. Flight Path Time Delay

The criterion for the flight path time delay investigates the step response of the flight path angle γ to an elevator deflection. The flight path time constant T_γ characterises this delay. The larger it is, the longer it takes until the desired flight path angle is achieved. Figure 9 shows the criterion plot for flight phase "CAT. C" and aircraft "Class III"'. It shows the data points considering sequential parameter variations using the linearised flight dynamic model.

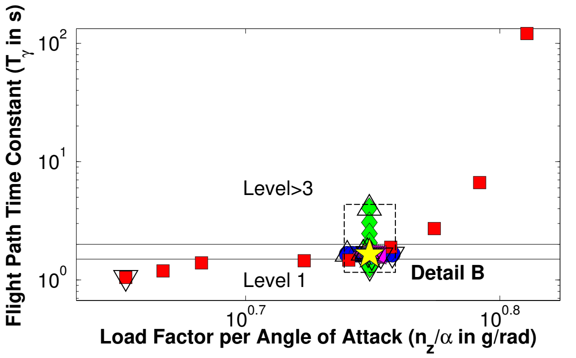
As illustrated by Figure 9a, the design configuration is located in the small band indicating "Level 3" handling qualities for "Class III" aircraft. Figure 9b provides the Detail view of the plot. Similar to the CAP criterion, a mass variation only has an impact on the horizontal location.

For this criterion, the influence of the moment of inertia about the pitch axis is perceivable. The higher it is, the higher the flight path time constant becomes. Due to the position of the design configuration in this criterion plot, a slight reduction of I_{yy} can be realised to improve the HQ Level.

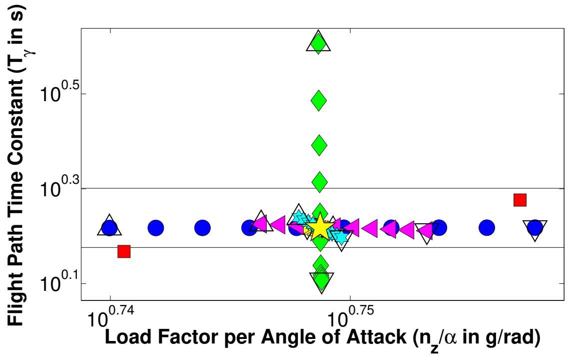
As for the CAP criterion, a variation of the CG has a strong influence. A reduction in static margin goes along with an increase of T_γ. Finally, for negative static longitudinal stability, being the case for the three most aft CG locations, the BWB shows an uncontrollable behaviour and the flight path constant grows rapidly.



(a) Overall view



(b) Enlarged view of Detail A



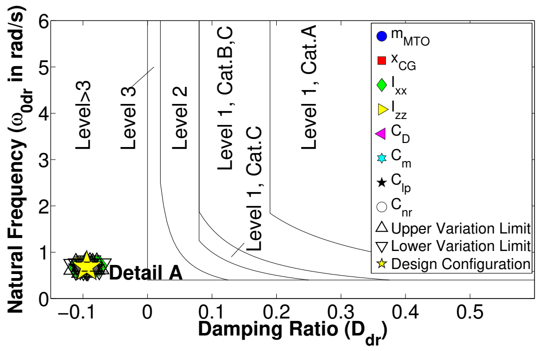
(c) Enlarged view of Detail B

FIGURE 9. Flight path time delay criterion for sequential variation of single parameters on the basis of the linearised flight dynamic model

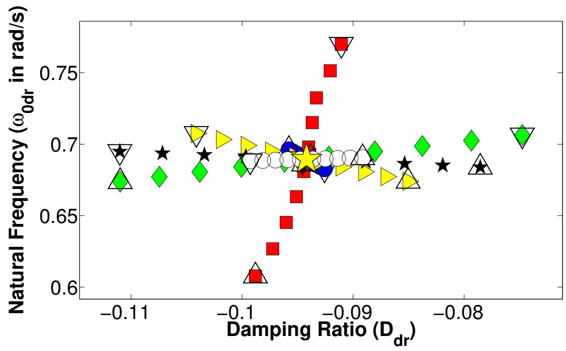
4.1.4. Dutch Roll

This section deals with the Dutch roll of the lateral-directional motion. The linearised flight dynamic model is used for the analyses. Figure 10 shows the criterion plot according to MIL-STD-1797A [26], which constrains characteristic parameters of this mode to assure a stable motion with a sufficiently high natural frequency. As shown by the overall view in Figure 10a, the design configuration has an uncontrollable Dutch roll..

The Detail view provided by Figure 10b shows that an increase of both aerodynamic damping derivatives C_{lp} and C_{nr} has the expected damping effect, while the natural frequency remains rather unchanged. The moments of inertia, however, have oppositional effects. While in-



(a) Overall view



(b) Enlarged view of Detail A

FIGURE 10. Dutch roll damping ratio and natural frequency for sequential variation of single parameters on the basis of the linearised flight dynamic model

creasing the moment about the yaw axis I_{zz} has a stabilising effect, the moment about the roll axis I_{xx} needs to be decreased to increase damping. As already addressed in section 4.1.2, a shift of the CG causes a change in static margin. As a consequence, the Dutch roll natural frequency is influenced.

It has to be noted that a forward CG position would also result in a higher yaw damping due to an increased vertical tailplane lever arm. However, as already mentioned, in this work, the aerodynamic damping derivatives are computed globally for the design configuration and are not modified due to the CG shift. Therefore, the effect of lever arm augmentation of vertical tailplane is not reproduced here. Similar to the longitudinal motion, the effect of C_D variations is negligible.

4.1.5. Roll Performance

Another criterion for lateral-directional motion, as formulated in MIL-F-8785C [25], assesses the roll performance. The criterion intends to ensure that the aircraft has a sufficiently high agility about the roll axis. Therefore,"Class III" aircraft has to accomplish a critical bank angle of 30° in a specified time using full roll control input. For this criterion, the non-linear flight dynamic model is used. Figure 11 shows the criterion plot. It includes the time limits for flight phase "CAT. C" and "Class III" aircraft and the roll angle over time. Variations of the CG, the moment of inertia about the longitudinal axis and the roll damping derivative are applied.

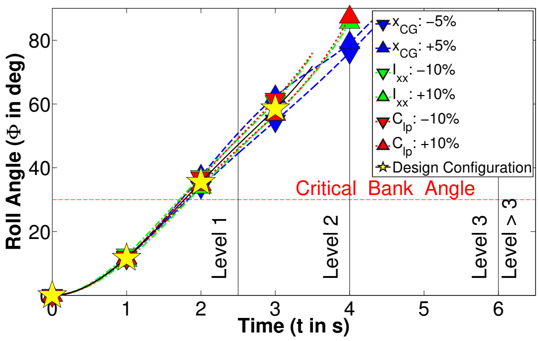


FIGURE 11. Roll performance criterion for variation of the CG position, the moment of inertia about the roll axis and the roll damping derivative on the basis of the non-linear flight dynamic model

For the sake of visibility, the roll angle graph is presented only for the design configuration and the outer variation limits of x_{CG}, I_{xx} and C_{lp}. In all cases, the BWB shows a satisfactory behaviour, reaching the critical bank angle in less than two seconds. The differences arising from parameter variations merely have a mentionable impact at higher roll angles.

4.2. Simultaneous Random Variation of Parameters

In addition to the foregoing analysis on sequential parameter variations, this section deals with simultaneous random parameter variations. This way, it can be estimated, whether it is likely that uncertainties lead to handling quality degradations compared to the design configuration. Thereby, the risk of undesired characteristics can be assessed. In addition, the aircraft can be modified on the basis of these results in order to minimise these risks.

All parameters documented in Table 2 are varied simultaneously. Normal distributions with the respective standard deviations given in the table are applied.

4.2.1. CAP

Figure 12 shows the CAP criterion as introduced in Section 4.1.2. It depicts the HQ Levels for 1000 BWB configurations that are subject to simultaneous random parameter variations. Data points with positive static margin are represented by blue circles and and those with negative static margin are illustrated using green squares. As indicated in Section 4.1.2, negative static margin leads to an aircraft response that is too sluggish, corresponding to uncontrollable behaviour ("Level > 3"). On the other hand, for a positive static margin, the majority of configurations achieves a CAP assessment of at least "Level 2".

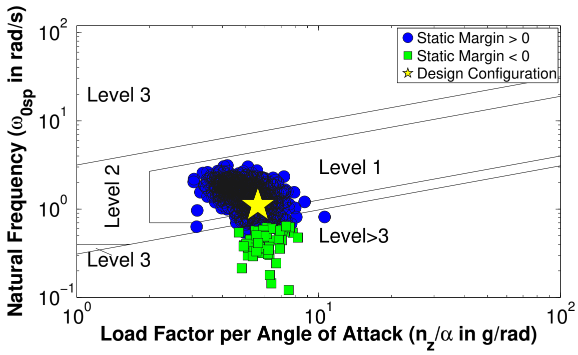


FIGURE 12. CAP criterion for simultaneous random parameter variation and dependency on static margin on the basis of the linearised flight dynamic model

The design configuration is located in the "Level 1" band near the bottom limit towards "Level 2". Altogether, around 60% of the configurations represent handling qualities being at least controllable[7]. It is apparent that a modification of the design configuration in such a way that its short period natural frequency is roughly doubled, would significantly increase the amount of at least controllable configurations. Judging from Figure 8, this can mainly be achieved by a forward shift of the CG.

4.2.2. Dutch Roll

The Dutch roll damping ratio and natural frequency are illustrated in Figure 13 for simultaneous random parameter variations. The data points are distinguished according to the amount of roll and yaw damping compared to the design configuration. In the legend, $\Delta|C_{lp}| > 0$ and $\Delta|C_{nr}| > 0$ mean that both roll and yaw damping of the respective configuration are higher than those of the design configuration. None of the configurations achieves an HQ Level better than "Level > 3".

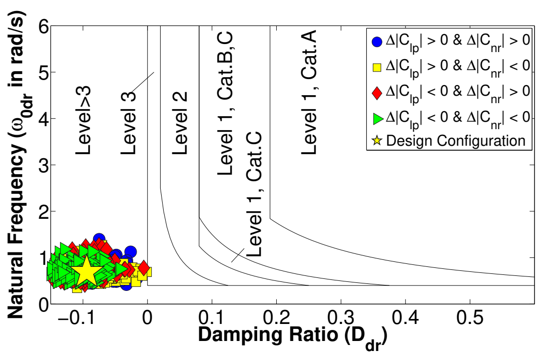


FIGURE 13. Dutch roll damping ratio and natural frequency for simultaneous random parameter variation and dependency on aerodynamic damping derivatives on the basis of the linearised flight dynamic model

[7]Several configurations with a negative static margin either have a natural frequency lower than the limits of the criterion plot or do not represent a classical oscillatory short period motion. They are therefore not depicted in the figure.

The design configuration has a Dutch roll damping ratio of around $D_{dr} \approx -0.1$. Those data points that come near to at least controllable aircraft behaviour in terms of the Dutch roll have at least one damping derivative increased compared to the design configuration.

Figure 13 illustrates that the BWB's Dutch roll mode is very challenging. Even favourable parameter combinations are not sufficient to enable a controllable motion for the BWB. This indicates that this BWB can only be handled with a flight control system.

4.2.3. Maximum Sideslip Due to Roll Control

Another handling quality criterion for the lateral-directional motion, as presented in MIL-F-8785C [25], addresses the maximum change of sideslip occurring due to step roll control inputs, which the pilot can handle. This criterion is particularly intended to be used for aircraft with a Dutch roll mode, dominated by yaw motion, as it is the case for this BWB. For these aircraft, Dutch roll motion can easily be excited by yaw motion [26]. Therefore, the pilot needs to counteract sideslip angles using the rudder. This criterion intends to limit the change of sideslip that appears at turn entries and recoveries in order to not overburden the pilot. Figure 14 shows the plot for this criterion.

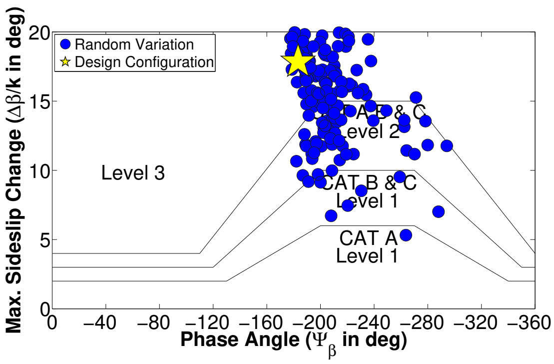


FIGURE 14. Maximum allowable change of sideslip angle criterion for simultaneous random parameter variation on the basis of the non-linear flight dynamic model

The vertical axis represents the maximum change of sideslip $\Delta\beta$ divided by a factor k, that depends on various conditions containing flight phase and aircraft category. The horizontal axis represents the phase angle of the Dutch roll component of sideslip Ψ_β. The limits in the criterion plot are based on pilot coordination issues. In the region of criterion limits at larger values for $\Delta\beta/k$, which is for a Ψ_β between –90° and –360°, the pilot can deflect aileron and rudder in the same sense while in the other region cross controlling is necessary. Since pilots have a smaller tolerance towards cross controlling, the limits are lower in the latter case [26].

The results depicted in Figure 14 are computed using the non-linearised flight dynamic model. As shown, the design configuration achieves "Level 3" handling qualities for this criterion. Nevertheless, the data points for simultaneous random parameter variations are widespread over the criterion plot.

4.2.4. HQ Level Distributions for Simultaneous Parameter Variations

This section finally focusses on the quantitative results of the simultaneous random parameter variation. Figure 15 shows the probability distributions for the HQ Levels of each criterion considered here. The first eight criteria (a - h) deal with the linearised model and the results are calculated for 1000 samples. The last two criteria (i, j) are based on the non-linear model. Due to the higher computational effort to obtain the model and handling qualities results, an amount of 250 samples is used. The red and striped bars indicate the HQ Levels of the design configuration.

The first part (Figure 15a) shows the static margin distribution. As already shown, this BWB configuration suffers from a relatively small static margin. As a consequence, the simultaneous random variations go along with around 36 % of configurations that lose static longitudinal stability.

Figure 15b represents a criterion, which assesses the phugoid mode. According to MIL-F-8785C [25], phugoid damping needs to exceed certain values to achieve either "Level 1" or "Level 2". An unstable phugoid is also tolerable, if its doubling time is high enough. Table 4 provides these threshold values, that apply to all flight phases and aircraft classes.

HQ Level	Requirement
Level 1	Phugoid Damping $D_p > 0.04$
Level 2	Phugoid Damping $D_p > 0$
Level 3	Phugoid Time to Double $T_2 > 55$ s

TABLE 4. Phugoid limits and respective HQ Levels [25]

The design configuration obtains an assessment of "Level 2". This HQ Level also applies to the majority of cases (60 %). Around 37 % even achieve "Level 1", while a controllable behaviour or worse have a probability of 2 %.

Figure 15c depicts the distribution for the CAP criterion. As already discussed in section 4.2.1, the design configuration shows satisfactory handling qualities. Nevertheless, an uncontrollable behaviour occurs in nearly 40 % of cases.

Figure 15d provides the distribution for the short period damping ratios. The associated limits are defined by MIL-F-8785C [25]. Table 5 summarises these values for flight phases "CAT. A" and "CAT. C".

The short period damping distribution is similar to the one for the CAP criterion. The design configuration achieves "Level 1", "Level 2" rarely occurs, while the probability of a "Level 3" assessment is high.

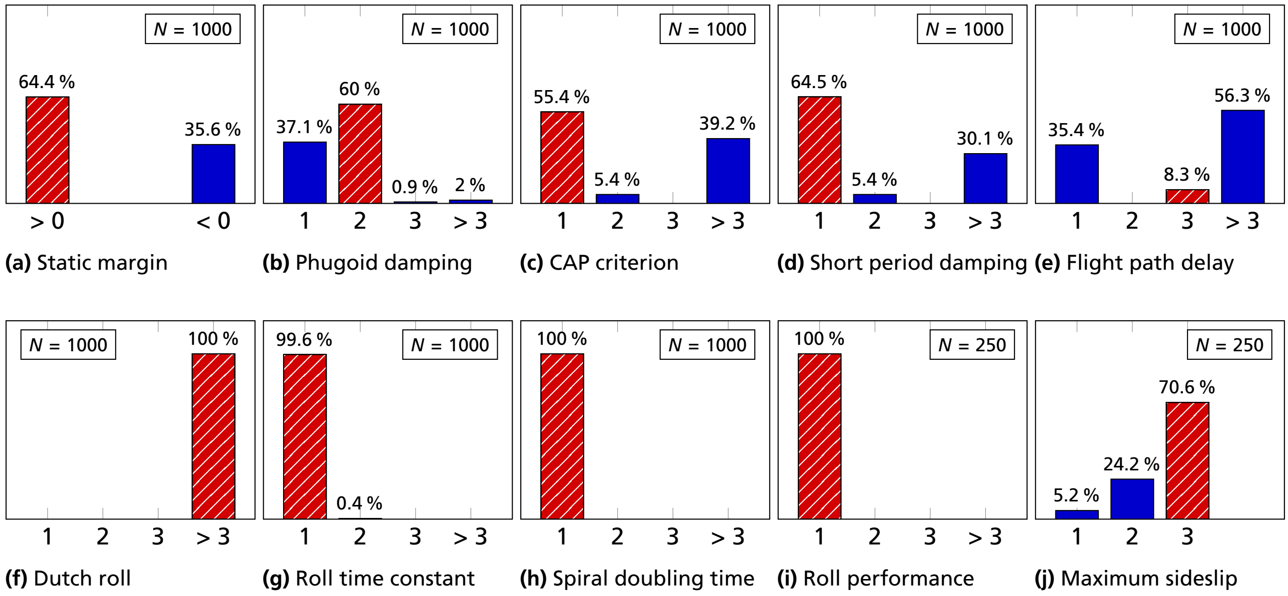


FIGURE 15. Distribution of static margin and handling qualities criterion levels for phugoid damping, flight path delay, CAP, short period damping, Dutch roll damping ratio and natural frequency, roll time constant, spiral amplitude time to double, roll performance and maximum sideslip, taking simultaneous random variation of design parameters into account; striped red bars represent the respective level reached by the BWB without consideration of uncertainties

HQ Level	Minimum Damping	Maximum Damping
Level 1	0.35	1.3
Level 2	0.25	2
Level 3	0.15	–

TABLE 5. Short period damping limits and respective HQ Levels for flight phases "CAT. A" and "CAT. C" [25]

Figure 15e presents the flight path time delay distribution for the longitudinal motion. Even though the design configuration is still controllable in terms of the flight path time delay, "Level > 3", having a percentage of about 56 %, is most probable.

The second row displays criteria for the lateral-directional motion. Figure 15f depicts the distribution for the Dutch roll criterion. As already shown in Figure 13, the BWB's Dutch roll is uncontrollable without exception.

The following two figures give attention to roll and spiral mode. Figure 15g shows a criterion defined in MIL-F-8785C [25]for the roll time constant. Table 6 provides the respective limits. With a few exceptions, the BWB reaches satisfactory handling qualities in the roll mode.

Figure 15h shows a criterion for spiral damping. The limits according to MIL-F-8785C [25] are documented in Table 7. All BWB configurations have a sufficiently damped spiral mode and achieve thus "Level 1" handling qualities.

HQ Level	Roll Time Constant
Level 1	1.4 s
Level 2	3 s
Level 3	10 s

TABLE 6. Roll time constant limits and respective HQ Levels for flight phases "CAT. C" and aircraft "Class III" [25]

HQ Level	Spiral Time to Double
Level 1	12 s
Level 2	8 s
Level 3	4 s

TABLE 7. Time-to-double limits and respective HQ Levels for flight phases "CAT. A" and "CAT. C" [25]

The non-linear roll performance criterion, as shown in Figure 15i, limits the time required by an aircraft to achieve a critical bank angle (compare section 4.1.5). For all variations this bank angle is reached in less than 2.5 s, leading to "Level 1" roll performance.

Finally, Figure 15j shows the distribution for the maximum allowable change of sideslip angle for turn entries and recoveries. As already discussed, the majority of variations (around 71 %) shows a controllable behaviour. The probability of acceptable handling qualities is about 24 % and with slightly more than 5 % favourable parameter variations that lead to satisfactory handling qualities are rather unlikely.

5. CONCLUSIONS AND OUTLOOK

The aim of this work is the handling qualities assessment of a blended wing body configuration with special attention given to influences of design uncertainties. A multidisciplinary, integrated central tool chain is set up that loads engine data, estimates masses, computes an aerodynamic map, generates a flight dynamic model and assesses its handling qualities using different criteria for longitudinal and lateral-directional motion.

This work considers the blended wing body without flight control system and evaluates its handling qualities for an operating point at the beginning of the landing approach directly before the deflection of high-lift devices. Design uncertainties are modelled by normally distributed random variations of chosen aircraft parameters in a parameter range based on industrial experience.

The first part involves qualitative analyses of parameter influences on handling qualities. Single parameters are sequentially in order to determine nature and magnitude of their impact on different handling qualities. The centre of gravity position has proven to have a significant impact on longitudinal flight dynamics for this blended wing body, altering agility and flight path time delay significantly. The Dutch roll mode is unstable. An increase of the roll and yaw damping derivatives as well as an increase of the moment of inertia about the yaw axis and a decrease of the moment of inertia about the roll axis have a damping effect.

In the second part, parameters are varied simultaneously at random using a Monte Carlo Simulation. The distributions of handling qualities levels are considered. Distributions for longitudinal criteria show a widespread band of different handling qualities levels. The investigations indicate that a forward shift of the centre of gravity or a decrease of the moment of inertia about the pitch axis can improve the handling qualities and reduce the amount of handling quality level variations.

Lateral-directional criteria are merely subject to level variations. This includes the Dutch roll, which is never controllable here, even for the most favourable parameter combination. Different from the longitudinal motion, single parameter adjustments are thus not sufficient to improve the lateral-directional handling qualities. An improvement would thus require more radical geometry changes.

Within the scope of this work, several different criteria were used to evaluate handling qualities for the blended wing body. These criteria have a mostly empiric background and are derived from pilot evaluation data, collected from flight experiments. Hence, they are based on rather subjective perceptions. Certainly, the blended wing body is an unconventional aircraft configuration. It is thus not clear to what extent the criteria are adoptable here. However, the presented criteria at least provide general insights about flight dynamic properties of the blended wing body presented here and their sensitivities to parameter changes.

Future work could include a flight simulator campaign. This way, handling qualities of the blended wing body can be assessed directly from its behaviour during piloted flight using a Cooper-Harper rating scale.

In addition, the outcome of this work could be used to improve the geometry of the blended wing body. According to the results, larger vertical tailplanes or a longer or flatter fuselage could be suitable in order to stabilise the Dutch roll mode. With respect to the longitudinal motion, more accurate methods for mass estimation could be used to obtain more exact results for the moment of inertia about the pitch axis and the centre of gravity position of the empty aircraft.

ACKNOWLEDGEMENTS

The results presented here were obtained in the context of the DLR project FrEACs. The authors would like to express their gratitude to all colleagues who participated in the project and contributed to this work. They particularly thank the DLR Institute of Propulsion for supplying the engine performance map and the DLR Facility Simulation and Software Technology for providing and maintaining the software environment RCE.

REFERENCES

[1] International Civil Aviation Organization, *Global Air Transportation Outlook to 2030 and Trends to 2040, Circular 333, AT/190*. ICAO, 2013.

[2] Liebeck, R. H., “Design of the Blended Wing Body Subsonic Transport”, *Journal of Aircraft*, vol. 41, January - February 2004.

[3] Dmitriev, V. G., Shkadov, L. M., Denisov, V. E., and Gurevich, B. I., “The Flying-Wing Concept - Chances and Risks”, *AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, Ohio*, July 2003.

[4] Clark, L. R. and Gerhold, C. H., “Inlet Noise Reduction by Shielding for the Blended-Wing-Body Airplane”, *5th AIAA/CEAS Aeroacoustics Conference, Greater Seattle. Washington*, no. AIAA-99-1937, May 1999.

[5] Graham, W. R., Hall, C. A., and Vera Morales, M., “The potential of future aircraft technology for noise and pollutant emissions reduction”, *Elsevier, Transport Policy 34*, July 2014.

[6] Hansen, L. U., Heinze, W., and Horst, P., “Blended wing body structures in multidisciplinary predesign”, *Structural and Multidisciplinary Optimization*, vol. 36, Pages 93 to 106, July 2008.

[7] Okonkwo, P. and Smith, H., "Review of evolving trends in blended wing body aircraft design", *Elsevier, Progress in Aerospace Sciences*, vol. 82, April 2016.

[8] De Castro, H. V., "Flying and Handling Qualities of a Fly-by-Wire Blended-Wing-Body Civil Transport Aircraft", PhD Thesis, Cranfield University, School of Engineering, 2003.

[9] Voskuijl, M., La Rocca, G., and Dircken, F., "Controllability of Blended Wing Body Aircraft", *ICAS, 26th International Congress of the Aeronautical Sciences, Anchorage, Alaska, USA*, September 2008.

[10] Kozek, M. and Schirrer, A., *Modeling and Control for a Blended Wing Body Aircraft: A Case Study*, ser. Advances in Industrial Control. Springer International Publishing, 2014.

[11] Pfeiffer, T., Moerland, E., Freund, S., Hasan, Y. J., Bertsch, L., and Flink, J., "FrEACs (Future Enhanced Aircraft Configurations)", *Deutscher Luft und Raumfahrtkongress, München*, September 2017, to be published.

[12] Seider, D., Fischer, P. M., Litz, M., Schreiber, A., and Gerndt, A., "Open Source Software Framework for Applications in Aeronautics and Space", *IEEE Aerospace Conference*, March 2012.

[13] Pfeiffer, T., Nagel, B., Böhnke, D., Rizzi, A., and Voskuijl, M., "Implementation of a Heterogeneous, Variable-Fidelity Framework for Flight Mechanics Analysis in Preliminary Aircraft Design", *Deutscher Luft und Raumfahrtkongress, Bremen*, September 2011.

[14] Nagel, B., Böhnke, D., Gollnick, V., Schmollgruber, P., Rizzi, A., La Rocca, G., and Alonso, J. J., "Communication in Aircraft Design: Can we Establish a Common Language?", *ICAS, 28th International Congress of the Aeronautical Sciences, Brisbane, Australia*, September 2012.

[15] Howe, D., "The Prediction of Aircraft Wing Mass", in *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 1996*, April 1996, Pages 135 to 145.

[16] Howe, D., "Blended Wing Body Airframe Mass Prediction", in *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering 2001*, June 2001, Pages 319 to 331.

[17] Melin, T., "A Vortex Lattice MATLAB Implementation for Linear Aerodynamic Wing Application", Master's thesis, Royal Institute of Technology (KTH), Department of Aeronautics, Stockholm, Sweden, December 2000.

[18] Mason, W. H., "Analytical Models for Technology Integration in Aircraft Design", *AIAA/AHS/SEE Aircraft Design, Systems and Operations Conference, Dayton, Ohio, USA*, 1990.

[19] Gur, O., Mason, W. H., and Schetz, J. A., "Full-Configuration Drag Estimation", *Journal of Aircraft*, vol. 47, no. 4, 2010.

[20] Looye, G., "flightSim - CPACS-based flight dynamics model integration and analysis for use in DLR tool chains", DLR, Internal Report 571-11/05, March 2012.

[21] Duus, G. and Duda, H., "HQML: Ein Programmpaket zur Flugeigenschaftsanalyse unter MATLAB", DLR, Internal Report 111-97/22, 1997.

[22] Duus, G., "Überarbeitung des HAREM Programmpakets", DLR, Internal Report 111-2001/10, 2001.

[23] Ehlers, J., "Flying Qualities Analysis of CPACS Based Aircraft Models - HAREM V2.0", DLR, Internal Report 111-2013/21, 2013.

[24] Bennani, S. and Rouwhorst, W. F. J. A. (Report Resp.), "RealCAM Benchmark Definition", Project REAL (Robust and Efficient Autopilot control Laws design), BRPR-CT98-0627/TP-01, July 2001.

[25] *Military Specification, Flying Qualities of Piloted Airplanes*, MIL-F-8785C, November 1980.

[26] Department of Defense, USA, *Military Standard, Flying Qualities of Piloted Aircraft*, MIL-STD-1797A, July 2001.

