INITIAL ASSESSMENT OF STABILITY AND CONTROLLABILITY IN THE EARLY STAGE OF COMBAT AIRCRAFT DESIGN

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Abstract

This paper presents a methodology for the assessment of stability and controllability of combat aircraft in the early stage of aircraft design. Requirements on stability and controllability are driving factors for the design of control effectors of a combat aircraft to ensure sufficient control power throughout its intended missions. A theoretical background on stability and controllability requirements is outlined. Prerequisites such as aerodynamic data sets and a flight dynamics model are addressed. A workflow providing high-fidelity aerodynamic data by means of multi-fidelity surrogate modelling is explained. It contains the essential steps of generating such aerodynamic data sets already during conceptual and preliminary design. Based on aerodynamics, propulsion and mass properties a flight dynamics model for six degrees of freedom aircraft simulations is applied for the stability and controllability assessment. Furthermore, a software tool has been developed which calculates the available control power for comparison with the requirements. For demonstration of the methodology, a generic triple-delta combat aircraft called DLR Future Fighter Demonstrator (DLR-FFD) is introduced. It is being developed within the DLR project Diabolo and contains an initial control concept to be investigated. Additional details on the requirements defined for the DLR-FFD are given. Finally, obtained results are assessed and discussed in terms of aerodynamic characteristics and with respect to the given stability and controllability requirements. A conclusion of the analysis is drawn in terms of the investigated control effectors. The analysis revealed that both longitudinal and lateral/directional controllability requirements are not yet fully met and the aircraft design has to be reviewed.

Keywords

Diabolo, stability, controllability, combat aircraft design, multi-fidelity

NOMENCLATURE

Abbreviations

CAP	Control Anticipation Parameter
CFD	Computational Fluid Dynamics
COAST	CPACS-Oriented Aircraft Simulation Tool
CPACS	Common Parametric Aircraft Configuration Schema
DLR	German Aerospace Center
FFD	Future Fighter Demonstrator
HQ	Handling Qualities
LCDP	Lateral Control Departure Parameter
LEVCON	Leading Edge Vortex Controller
LOES	Low Order Equivalent System
MAC	Mean Aerodynamic Chord
RANS	Reynolds-Averaged Navier-Stokes
RCE	Remote Component Environment
WGS	World Geodetic System
XML	Extensible Markup Language

List of symbols

C_l	Rolling moment coefficient (–)
$C_{l\beta}$	Rolling moment coefficient derivative w.r.t. sideslip angle (1/rad)
$C_{l\xi}$	Rolling moment coefficient derivative w.r.t. aileron deflection (1/rad)
C_m	Pitching moment coefficient (–)
C_n	Yawing moment coefficient (–)
$C_{n\beta}$	Yawing moment coefficient derivative w.r.t. sideslip angle (1/rad)
$C_{n\xi}$	Yawing moment coefficient derivative w.r.t. aileron deflection (1/rad)
C_L	Lift coefficient (-)
$C_{L\alpha}$	Lift coefficient gradient w.r.t. angle of attack (1/rad)
g	Gravitational acceleration (m/s²)
I_x	Moment of inertia w.r.t. body x-axis (kgm²)
I_{xz}	Product of inertia w.r.t. body xz-axes (kgm²)
I_y	Moment of inertia w.r.t. body y-axis (kgm²)
I_z	Moment of inertia w.r.t. body z-axis (kgm²)
K_p	Factor of roll acceleration versus roll rate (1/s)
L, M, N	Rolling, pitching, yawing moment (Nm)
$n_{z\alpha}$	Vertical load factor gradient w.r.t. angle of attack (1/rad)
p, q, r	Roll, pitch, yaw rate (rad/s)
S	Wing area (m²)
V	Airspeed (m/s)
α	Angle of attack (rad)
β	Angle of sideslip (rad)
ζ_{sp}	Short period damping ratio (-)
ρ	Air density (kg/m³)
ω_{sp}	Short period natural frequency (rad/s)

1. INTRODUCTION

The DLR project Diabolo deals with technologies and design of next generation military aircraft configurations. One focus of the project is on strengthening and expanding the skills for the design and evaluation of military combat aircraft. Therefore, the DLR Future Fighter Demonstrator (DLR-FFD), a generic combat aircraft with a triple-delta-shaped wing, is being developed in a collaborative design process. The aircraft is shown in FIG 1. For data exchange between the different tools within the project, the data exchange file format Common Parametric Aircraft Configuration Schema (CPACS) [1] is used. It is primarily developed by DLR, but supported and used by experts from the aircraft design community inside and outside DLR. It is developed on an open-source basis and freely available on the Internet [2].

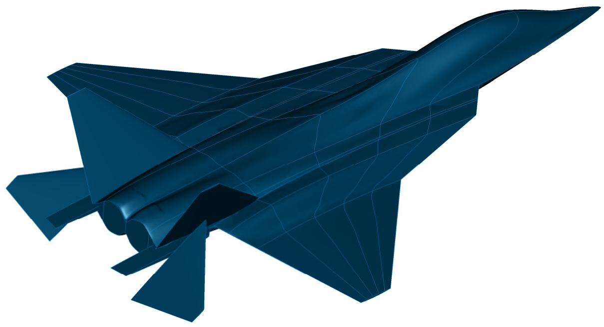

FIG 1. DLR Future Fighter Demonstrator (DLR-FFD)

A flight mechanical analysis is conducted as part of the design process to check whether the aircraft performs as required. In this paper, the focus is on stability and controllability requirements which are an important part of flight mechanics. Ref. [3] presents an overview on typical requirements with respect to stability and controllability for combat aircraft. In particular, the aerodynamic properties are the driving factor for the flight mechanical behaviour of the aircraft, for which reason highly accurate aerodynamic data are needed for the analysis. Up to now, aerodynamic data with the required accuracy was not yet available in the conceptual design process. Therefore, a workflow providing high-fidelity-based aerodynamic data by means of multi-fidelity surrogate modelling is explained in this paper to overcome the aforementioned limitations on data availability. In addition, a flight dynamics model is needed for an assessment tool which was developed and applied within the project. By using the generated highly accurate aerodynamic data set in conjunction with the developed assessment tool, it is now possible to perform an initial assessment of stability and controllability even in the early stage of combat aircraft design. Findings of this assessment can be fed back in the design process and enable the aircraft designer to modify the aircraft at an early stage.

The stability and controllability requirements covered in the analysis are introduced in section 2. The description of the assessment tool which was developed within the project is also included in section 2. A workflow for multi-fidelity aerodynamic data set generation is presented in section 3, and section 4 briefly describes the aircraft simulation framework which is used by the assessment tool. Finally, an application example of the assessment tool is addressed in section 5 followed by a conclusion.

2. STABILITY AND CONTROL ASSESSMENT

2.1. Stability and Controllability Requirements

2.1.1. Longitudinal Motion

In order to understand the controllability requirements in the longitudinal motion the different tasks of the pitch axis control laws have to be considered. An agile and precise manoeuvre build up has to be ensured as well as the stabilisation of the aircraft within the entire flight envelope. For a fighter aircraft this includes operating at high angles of attack.

In this paper, only the most demanding controllability requirement for unstable aircraft is considered. A sufficient negative pitching moment with full deflection of the pitch control surfaces must still be available at maximum lift in order to return the aircraft to normal flight attitudes. The so-called *pitch recovery moment*, which defines the required pitch down capability at high angles of attack, has to be derived from different aspects. The required pitch recovery moment is always determined at low dynamic pressure, i.e. at low airspeed, whereas higher airspeeds are expected to be covered by low airspeed controllability requirements. Therefore, the anticipated lowest airspeed has to be defined. In addition, there are requirements for manoeuvre in pitch, i.e. maximum angle of attack and angle of attack rate.

Handling qualities criteria are used to derive demands on flight dynamics. One of the most important handling qualities parameters for assessing manoeuvrability is named *control anticipation parameter* (CAP), which defines the required pitch acceleration for a load factor change commanded by the pilot:

(1) $$CAP = \frac{\dot{q}_{(t=0)}}{\Delta n_{z(t\rightarrow\infty)}}$$

It is based on the LOES (Low Order Equivalent System) short period mode approximation and assesses the natural frequency of the short period mode in relation to stationary change of the vertical load factor with the angle of attack. It can therefore also be expressed as [4]:

(2) $$\mathrm{CAP} = \frac{\omega_{sp}^2}{n_{z\alpha}}$$

If the CAP is too small the initial aircraft response is too sluggish and the pilot tends to apply too large control inputs. In contrast, if the CAP is too large the initial aircraft response is too fast and the pilot tends to apply too small control inputs. In the last decades, limits for the control anticipation parameter have been development and defined in [4] as shown in FIG 2. They are applicable for non-terminal flight phases requiring manoeuvring, precision tracking, or precise flight-path control.

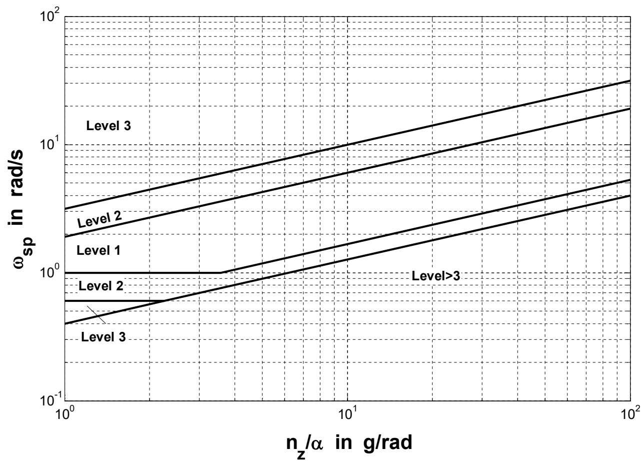

FIG 2. Typical handling qualities level derived from CAP

The criterion also determines the handling qualities level of the damping of the short period mode:

Level	Minimum	Maximum
1	0.35	1.3
2	0.25	2.0

TAB 1. Requirements on damping ratio of the short period mode

The load factor gradient $n_{z\alpha}$ can be calculated with the following formula:

(3) $$n_{z\alpha} = \frac{C_{L\alpha}\rho V^2 S}{2mg}$$

The lift coefficient due to angle of attack derivative

(4) $$C_{L\alpha} = \frac{\Delta C_L}{\Delta\alpha}$$

can be derived from aerodynamic data set at the linear region of the lift curve. By knowing the load factor gradient $n_{z\alpha}$ one can obtain the short period frequency ω_{sp} and damping ζ_{sp} from FIG 2 and TAB 1. For the analysis, a reference model can be used which is presented in FIG 3.

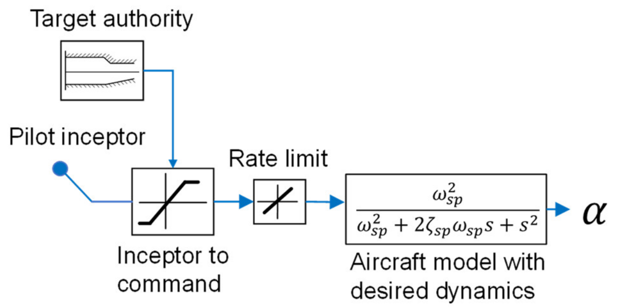

FIG 3. Reference model for analysis of longitudinal motion

The simulation of the reference model with the desired aircraft dynamics provides α, $\dot{\alpha}$, and $\dot{q}$ as shown exemplarily in FIG 4.

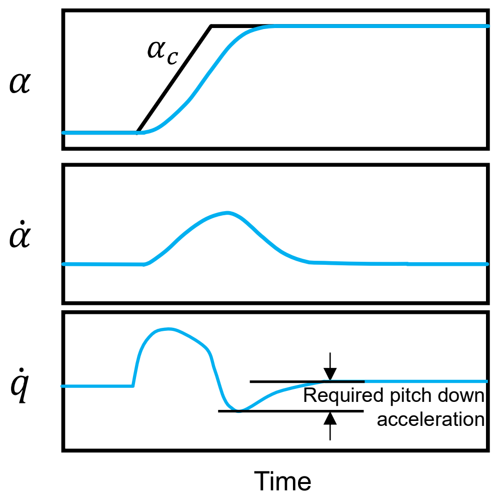

FIG 4. Longitudinal motion reference model output for angle of attack input.

The pitching moment can be determined as follows by neglecting the influence of the engines:

(5) $$M = I_y\dot{q} - I_{xz}(r^2 - p^2) - (I_z - I_x)pr$$

It is assumed now that the product of inertia I_{xz} is small compared to the moments of inertia, therefore this term is neglected. In order to ensure $\dot{\beta} = 0$ during the roll manoeuvre, the following Eq. (6) must be fulfilled.

(6) $$r = p\tan\alpha$$

Replacing $r = p\tan\alpha$ in Eq. (5) yields:

(7) $$M = I_y\dot{q} - (I_z - I_x)p^2\tan\alpha$$

The last term represents the pitch up effects due to rolling. At this stage of the design phase the influence due to rolling is neglected as well. That therefore leaves only the following term:

(8) $$M = I_y\dot{q}$$

The pitch down acceleration $\dot{q}$ is obtained from the analysis of the reference model with the desired aircraft dynamics. The calculated pitching moment represents the pitch recovery moment which is drawn as an orange constant line in FIG 5.

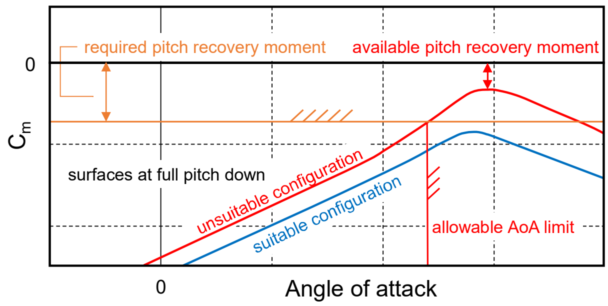

FIG 5. Comparison of required and available pitch recovery moment

The available pitching moment with elevator full pitch down is now compared with the required pitch recovery moment. The blue pitching moment curve represents a good aircraft configuration because the entire curve is below the required pitch recovery moment line. In contrast the red curve intersects the pitch recovery moment line and is partially above. In this case the aircraft operation must be limited to a maximum allowable angle of attack which is indicated as a vertical red line in order to ensure a safe flight. This aircraft configuration would have to be improved in order to fly higher angles of attack.

2.1.2. Lateral/Directional Motion

The lateral motion of an aircraft includes both rolling and yawing motion. Analogue to the longitudinal motion, sufficient control power potential has also to be provided to the lateral/directional axes for several tasks. A key attribute in terms of fighter agility is high roll performance which is required to quickly and accurately position the flight velocity vector in the desired direction. The requirements for high roll accelerations can be derived from FIG 6. The figure shows a roll manoeuvre with a commanded roll rate including roll onset and roll stop. The response of the aircraft in terms of roll rate and roll acceleration is shown by the blue curves. Both the required roll rate and roll acceleration are usually provided in the aircraft design specifications.

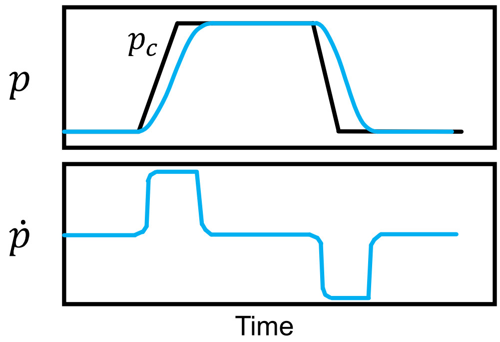

FIG 6. Roll manoeuvre with roll rate and roll acceleration. The black line represents the commanded roll rate and the blue curves the response of the aircraft.

The required roll control power can be calculated with the following Eq. (9):

(9) $$L = I_x\dot{p} - I_{xz}(\dot{r} + pq) - (I_y - I_z)qr$$

With constant angle of attack and by neglecting the product of inertia I_{xz} and by assuming pitching rate $q = 0$, Eq. (9) can be simplified to:

(10) $$L = I_x\dot{p}$$

In order to ensure of sufficiently large roll acceleration, the roll rate is multiplied by a factor which is part of the requirements.

(11) $$\dot{p} = K_p p$$

In terms of yaw control power, the corresponding equation reads:

(12) $$N = I_z\dot{r} - I_{xz}(\dot{p} + qr) - (I_x - I_y)pq$$

Again, with constant angle of attack and by neglecting the product of inertia term I_{xz} and by assuming pitch rate $q = 0$, Eq. (9) can be simplified to:

(13) $$N = I_z\dot{r}$$

In order to achieve a roll manoeuvre around the flight velocity vector ($\dot{\beta} = 0$), the required yawing moment coefficient can be obtained via:

(14) $$C_n = \frac{I_z}{I_x}C_l\tan\alpha$$

Given Eq. (14), roll performance requirements at high angles of attack are the driving factor for the sizing of the control effectors which control yaw.

At small angles of attack the lateral stability is mainly determined by the yawing moment due to sideslip $C_{n\beta}$. The impact of the rolling moment due to sideslip $C_{l\beta}$ plays only a minor role. At high angles of attack, due to the low moments of inertia of fighter aircraft about the longitudinal motion, directional stability can be described by the so-called dynamic lateral stability. It is also known as Weissman-criterion or $C_{n\beta,dyn}$-criterion and consists of the yawing moment due to sideslip $C_{n\beta}$ and rolling moment due to sideslip $C_{l\beta}$. The criterion is defined as follows [5]:

(15) $$C_{n\beta,dyn} = C_{n\beta}\cos\alpha - C_{l\beta}\frac{I_z}{I_x}\sin\alpha \geq 0.1$$

Here, the rolling moment due to sideslip $C_{l\beta}$ is the dominant part at high angles of attack whereas the yawing moment due to sideslip $C_{n\beta}$ plays only a minor role. Both spin and departure tendency are small as long as the following requirement is also fulfilled [6]:

$$LCDP = C_{n\beta} - C_{l\beta}\frac{C_{n\xi}}{C_{l\xi}} > 0 \tag{16}$$

where LCDP stands for *lateral control departure parameter*.

However, the prediction of these parameters at high angles of attack is challenging, since they are more influenced by flow separations due to vortex breakdown and vortex-vortex interactions. That requires an aerodynamic data set where these effects are represented in the aerodynamic models.

2.2. Assessment Tool

An assessment tool was developed within the project in order to determine and assess the stability and controllability requirements. It is implemented in MATLAB® / Simulink and makes use of the aircraft simulation framework COAST (CPACS-Oriented Aircraft Simulation Tool) which is introduced in section 4.

The software tool itself starts with the import of the required data from the CPACS file using the same wrapper functions as described in section 4. The data is imported into a MATLAB-structure array allowing easy access to the data within the software tool. In the next step, the flight point is determined at which the pitch recovery moment is to be analysed. As outlined in subsection 2.1.1, the anticipated lowest airspeed has to be set. It was decided to use the stall speed at 1g load factor, which is defined as the speed at which the aircraft can develop a lift force (normal to the flight path) equal to its weight. The stall speed is also denoted as V_{s1g}. The required pitch recovery moment is the dimensioning factor for the elevator design. That means that the elevator has not yet been dimensioned at this design stage and consequently the aircraft cannot yet be trimmed. Thus, the available lift force of the aircraft does not include any additional lift due to elevator deflection. Furthermore, the engine influence is likewise not considered. Based on these assumptions, the stall speed is calculated in a sub-routine for a representative altitude within the assumed flight envelope which is covered by the aerodynamic data set.

For the altitude, a new point performance definition is created consisting of the altitude, the stall speed and the corresponding Mach number, and the angle of attack. In addition, a new controllability requirement is set up with a link to the new point performance definition and the weight and balance-case. Both the new point performance definition and the new controllability requirement are added to the structure array. The calculated data is returned to the main routine, which then loops over the points to be analysed.

This loop is repeated for each controllability requirement. Depending on the considered motion (longitudinal or lateral/directional, respectively), different calculations are carried out.

Inside the longitudinal motion branch the lift coefficient gradient with respect to the angle of attack is determined from the aerodynamic data set in an area where the lift is linear. This parameter is needed for the calculation of the load factor gradient $n_{z\alpha}$ (cf. Eq. (3)). In addition, the maximum achievable lift and the corresponding angle of attack are taken from the aerodynamic data set. The angle of attack at maximum lift represents the maximum angle of attack authority.

Finally, the short period frequency is determined depending on the chosen damping. Now, all relevant parameters are available to calculate the required pitch down acceleration. For that, a reference model of 2nd order is used as described in FIG 3. Having now all needed input parameters at hand, the reference model is evaluated to determine the required pitch down acceleration as described in subsection 2.1.1. By using Eq. (8) the software tool calculates the pitching moment requirement and the results are added to the structure array.

Within the branch for the lateral/directional motion the required rolling and yawing moments are computed as described in subsection 2.1.2, each for roll onset and roll stop as defined in the controllability requirements. The outcomes are amended to the structure array for further processing.

After going through one of the branches, a flight dynamics model is created using the simulation tool COAST. The available moments are determined, again in different branches depending on the motion under consideration.

For the longitudinal controllability requirement, the pitching moment with control effectors at full pitch down versus angle of attack is calculated using COAST and plotted over the entire angle of attack range. The previously computed required pitch recovery moment is added to the plot by means of a constant line. As explained in FIG 5, the highest data point of the pitching moment versus angle of attack curve is the maximum available pitch recovery moment and has to be below the constant line. In addition, stability and control derivatives are obtained by a linearization of the forces and moments at the current flight point. The results are returned both as a plot and as entries in the structure array.

The analysis of the lateral/directional motion is more comprehensive. In order to achieve maximum roll performance, full roll command has to be applied. Due to the yaw-roll-coupling a yawing moment occurs, which must be compensated by a yaw input. Unfortunately, the yaw input reduces in return the roll performance. For the analysis, the roll command input is set to full and the yaw input is increased step by step. For every step, both the yawing and rolling moment are calculated and after the final step, both yawing and rolling moment are plotted against the yaw input. From the plot it can be easily seen if enough yaw power is available and if roll performance is (still) sufficient. In addition, stability and control derivatives are obtained by a linearization of the forces and moments at the current flight point. This procedure is repeated for every lateral/directional controllability requirement included in the CPACS file.

Back to the main routine, the results are written to the CPACS file. This allows an easy and simple disclosure of the analysis results to relevant disciplines within the development process.

An essential prerequisite for the application of the analysis tool just described is aerodynamic data covering the typical flight envelope of the analysed aircraft. As outlined before, for the assessment of advanced combat aircraft operating at high angles of attack reliable data need to be provided in the aerodynamic performance map. In general, this cannot be achieved by relying only on low-fidelity aerodynamic tools such as simple linear aerodynamic models. Data with higher fidelity must be considered that also models the nonlinear aerodynamic characteristics. The approach used within the project to generate aerodynamic data sets is described in the section 3. As mentioned above, an aircraft simulation framework is needed which is introduced in section 4.

3. AERODYNAMIC DATA SET

Aerodynamic modelling at early design stages must account for evolving data fidelity and availability while considering multiple design configurations. In [7] a multi-fidelity aerodynamic data set generation workflow is developed which provides the capability to efficiently generate high-fidelity-based aerodynamic data sets. This includes a comprehensive parametric modelling and automation starting from the first representation of the geometry over the coupling of geometry and Computational Fluid Dynamics (CFD) meshing capabilities and all the way to the aerodynamic model generation and evaluation.
All aerodynamic data sets follow the superposition principle of the CPACS data format for aerodynamic analysis and are subdivided into three sections: First, a full-factorial baseline performance map, second, quasi-steady dynamic derivatives obtained at the flight points of the baseline map and, third, multiple increment maps of the aerodynamic coefficients due to control surface deflections. The baseline map is defined for parameter combinations of altitude, Mach number, angle of sideslip and angle of attack. All aerodynamic coefficients related to control surface deflections are computed as increment values to the baseline map for multiple deflection angles. Following the assumption that data from the different sections are relatively independent from each other, they can be combined using the principle of superposition. Under this assumption, it is further possible to provide data sets which are built from different sources, e.g. increment maps from low-fidelity aerodynamics and a baseline performance map predicted by multi-fidelity surrogate models which are built by using both, low- and high-fidelity data sources. The workflow for creating this aerodynamic model is depicted in FIG 7.

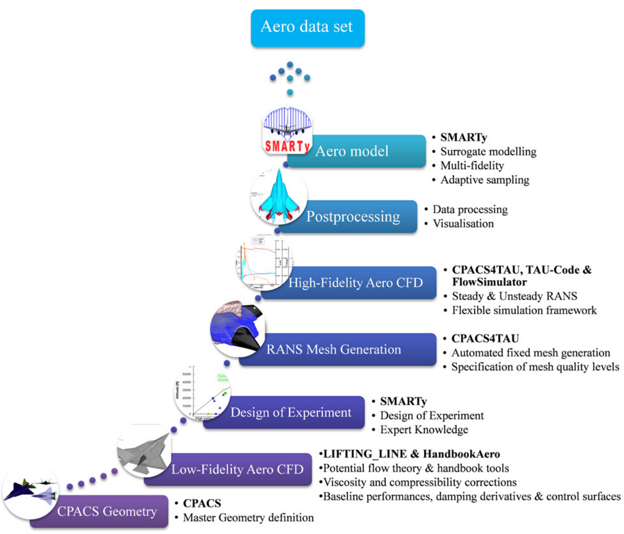

FIG 7. Multi-fidelity aerodynamic data set generation workflow.

In the example presented here, aerodynamic tools of varying fidelity are embedded into the workflow. On the lower end, the DLR open source tool LIFTING_LINE is used [8, 9]. Based on the linearized potential flow equations for thin aerofoils, LIFTING_LINE can simulate steady and quasi-steady flow fields around nearly arbitrary systems of three-dimensional wings, including the deflection of control surfaces. A compressibility correction according to Goethert is included in LIFTING_LINE, while the DLR HandbookAero tool provides viscous effects using a flat plate analogy in conjunction with an empirical thickness correction according to Raymer [10].
On the other end, the DLR TAU-Code [11] as a hybrid unstructured CFD solver for solving the Euler or Reynolds-Averaged Navier-Stokes (RANS) equations is applied. This high-fidelity aerodynamic tool is embedded into the workflow either by means of multi-disciplinary simulation processes using the FlowSimulator framework [12] or by the CPACS4TAU toolwrapper [7] which incorporates an automated mesh generation capability.
Finally, a multi-fidelity surrogate modelling approach [13] as implemented in the DLR Surrogate Modeling for AeRo data Toolbox Python package (SMARTy) [14] is used to combine data sources of different fidelity for predicting aerodynamic quantities throughout the whole envelope. The SMARTy toolbox comes along with various different modelling approaches to address regression, model reduction and data fusion tasks based upon data derived from design of experiment and adaptive sample refinement algorithms. The complete multi-fidelity modelling workflow is mostly integrated into DLR's conceptual aircraft design system [15–17] which enables multi-disciplinary modelling and analysis relying on DLR's in-house software Remote Component Environment (RCE) [18].

In [7] an aerodynamic data set is generated for the DLR-FFD which is used and extended in this work. Low-fidelity and high-fidelity aerodynamic tool evaluations for different geometrical design iterations are conducted to obtain input data for the multi-fidelity aerodynamic surrogate model. Here, for instance time-averaged unsteady RANS simulations are able to model the vortex-dominated flow characteristics, as seen in FIG 8, that are present at moderate and high angles of attack for such combat aircraft configurations, whereas the low-fidelity aerodynamic tools, based on potential flow theory, neglect most of these effects.

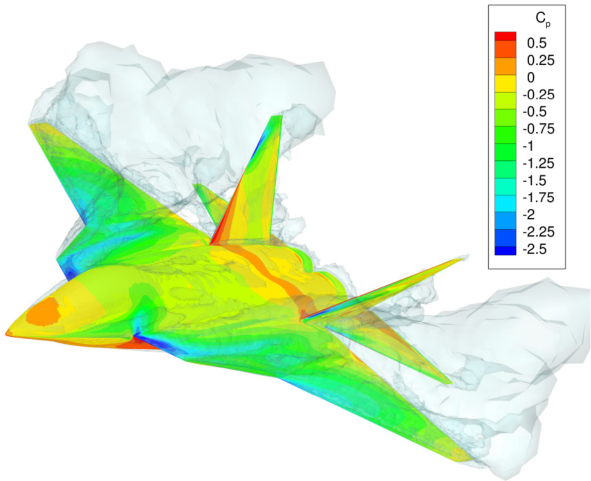

FIG 8. A vortex-dominated flow field obtained by a time-averaged unsteady RANS simulation for the DLR-FFD at Mach 0.57 under sideslip conditions. The surface pressure distribution and iso-surfaces of the Q criterion show the footprints and the formation of vortices at the leading edges.

Differences in the modelling fidelity can also be found in the global aerodynamic performance quantities, such as the lift coefficient as shown in FIG 9 vs the angle of attack.

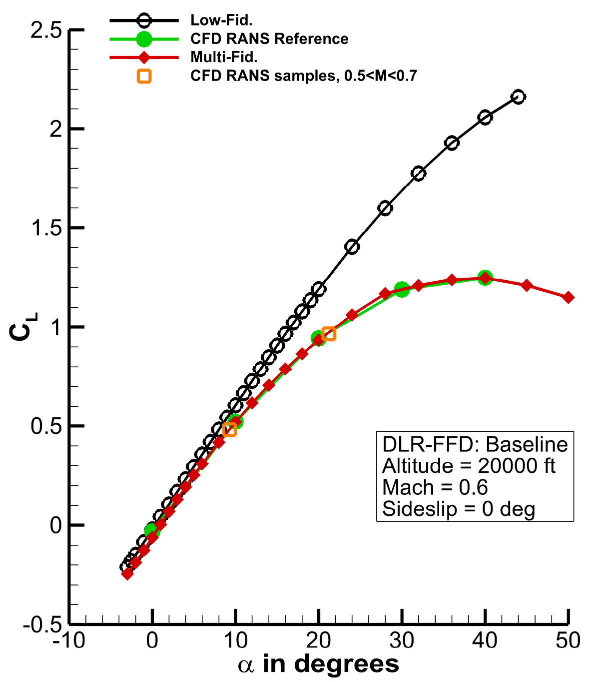

FIG 9. Comparison of low-fidelity aerodynamic analysis using potential flow theory, high-fidelity CFD based on RANS and multi-fidelity aerodynamic modelling in terms of the lift coefficient C_L versus angle of attack α.

An intermediate aerodynamic data set reflecting the current design status of the DLR-FFD is built for a first assessment of Stability and Control involving the aircraft simulation framework introduced in the following section 4. For the combination of different aerodynamic modelling fidelities and design iterations hierarchical surrogate models [19] are used. Multiple hierarchical layers are staggered, starting with low-fidelity data of the initial design and ending with high-fidelity time-averaged unsteady RANS data for the latest design version. Up to four hierarchical layers that comprise the initial design and first design iteration are included. Note that a subsequently required mesh refinement to improve the pitching moment coefficient prediction based on CFD contributes one of these four layers. Such a hierarchical modelling approach allows to account for model and data history and tends to reduce the amount of high-fidelity data needed for each new design iteration.

Besides geometry modifications from one design iteration to another, also smaller corrections can be applied to the data set. FIG 10 shows the correction of the pitching moment coefficient by means of a multi-fidelity surrogate model. Here, a revision of the data set revealed the need for a retroactive modification of the CFD RANS mesh. The new multi-fidelity surrogate model includes very few new samples for the revised CFD mesh while correcting the trend of a previously fitted multi-fidelity surrogate model which is based on data that are obtained for the initial CFD RANS mesh and from low-fidelity aerodynamics.

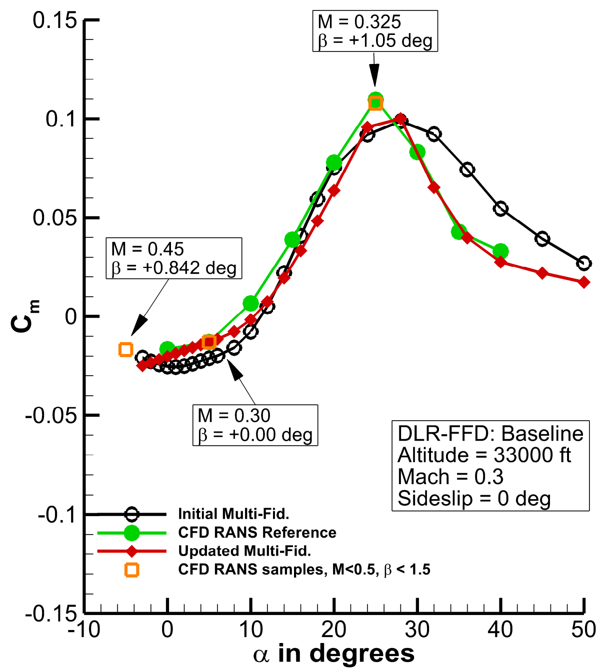

FIG 10. Correction of the pitching moment coefficient C_m for an updated RANS CFD mesh through means of multi-fidelity aerodynamic modelling.

The final data set is provided for a combat ceiling of 50 000 feet and covers a Mach range from subsonic ($M = 0.2$) to supersonic ($M = 2.0$) flight speeds, angles of attack up to 50 degrees and sideslip angles up to 5 degrees for the baseline performance map, which is predicted using the multi-fidelity surrogate model. All increment values obtained for the control effectors are based on low-fidelity simulation data.

More than 300 000 entries are computed using LIFTING_LINE for the full subsonic flight envelope of the initial design from which 9120 points belong to the baseline performance map. The multi-fidelity surrogate model is enriched by 209 samples obtained by the DLR TAU-Code which are distributed over multiple design iterations and in addition split into training and reference samples. While the latter is unseen by the multi-fidelity surrogate model, the training set consists of 123 samples which are used to fit the model. When combining the baseline performance map given by the multi-fidelity predictions with all increment maps which are based on regression models that solely use low-fidelity data information, the CPACS data set holds more than 500 000 entries covering the whole flight envelope of the aircraft.

4. AIRCRAFT SIMULATION FRAMEWORK

For the evaluation of the aircraft's flight dynamics, the assessment tool described in subsection 2.2 uses the 6-degrees-of-freedom fixed-wing aircraft simulation tool COAST. It is specifically tailored to the structure of CPACS and was designed for the usage in MDO (multi-disciplinary optimization) toolchains. This section provides a short description of COAST; for details, the interested reader is referred to [20].

COAST utilizes so-called *wrapper functions* to import the relevant data from CPACS and to bring the data into a pre-defined structure. The wrapper functions rely on the respective MATLAB interfaces of the TiXI [21] and TiGL [22] libraries, which are XML parsers extended by CPACS-specific capabilities and processing functionalities. Each field (e.g., propulsion, aerodynamics) has its own designated wrapper function to specifically parse and import the corresponding data into MATLAB and bring it into the required format. While some components of the COAST model are specifically tailored to CPACS, several modules are implemented generically and do not share any direct interface to the CPACS structure, as shown in FIG 11.

In the core model of COAST, all non-CPACS-specific components are implemented in Simulink, such as the equations of motion or the sensor models. It incorporates a World Geodetic System 1984 (WGS84) geodetic model [23] and the atmosphere is modelled after the 1976 US Standard Atmosphere model [24]. In the current version of COAST, the equations of motion assume a rigid body, although they might be extended to include flexible degrees of freedom in a future update since the required data can generally be provided via the CPACS standard. All CPACS-specific components, such as the engines, the aerodynamic data, and the control linkages, are implemented in C++ and interfaced by Simulink via S-functions [25], which provides higher flexibility and better computational performance.

As part of the COAST framework, MATLAB functions for trimming and numerical linearization are provided. Stability and control derivatives can be extracted from the resulting linear system using designated functions. Among the obtainable derivatives are, for example, classic stability derivatives such as $C_{m\alpha}$ and $C_{n\beta}$, but also controllability quantities such as the lateral control divergence parameter [26] or the control (input) matrix. This allows easy evaluation of high-level stability and control indicators in early stages of aircraft design, and it aids the usage of tools such as the stability and controllability assessment tool.

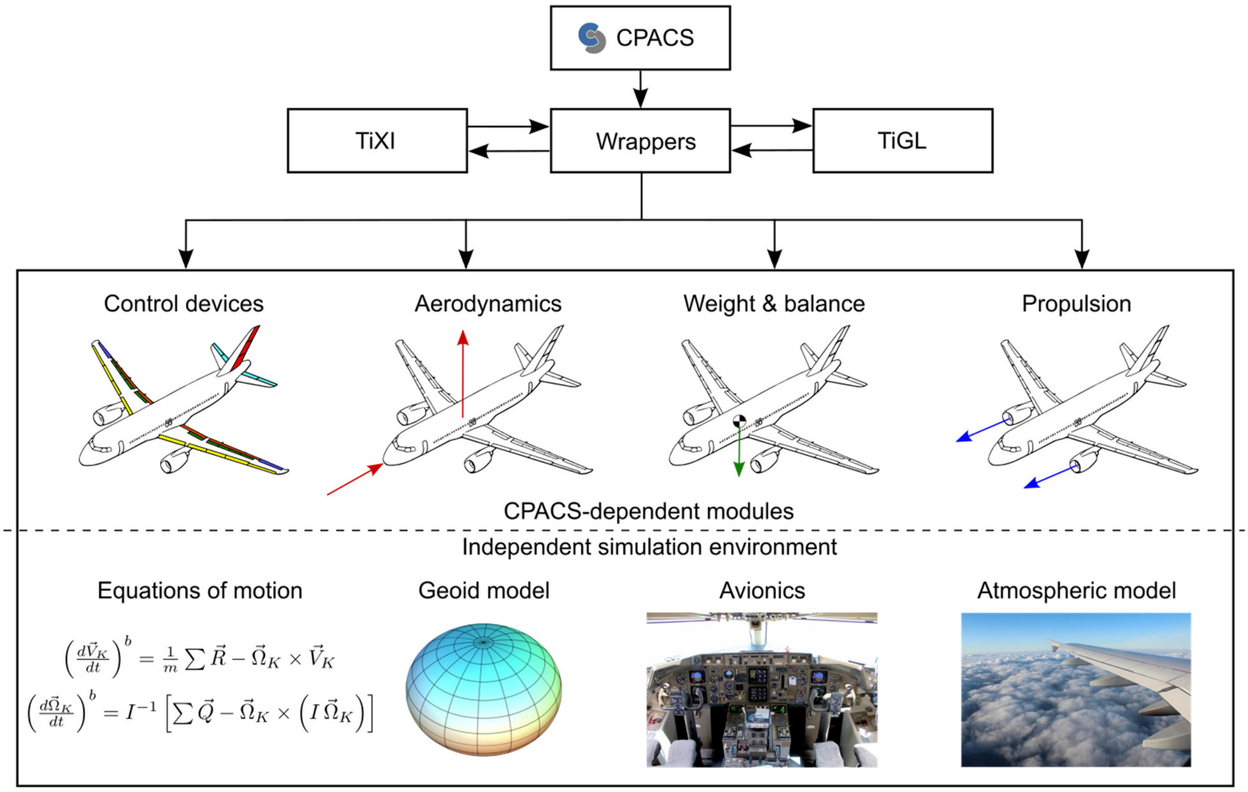

FIG 11. COAST model structure

5. APPLICATION TO THE DLR-FUTURE FIGHTER DEMONSTRATOR (DLR-FFD)

Usually, the procedure described in subsection 2.1 is used to determine the required stability and controllability requirements, and in the next step, the control effectors are chosen and designed to meet the identified requirements. Within the DLR-project Diabolo, the approach has been changed.

A catalogue of requirements has been developed containing the design requirements for the DLR-FFD [27]. It includes requirements regarding the geometry, performance, payload requirements etc. Based on this catalogue, a combat aircraft configuration has been initiated using an automated tool for the initiation of military aircraft configurations [28]. Within this tool, a large knowledge base containing empirical correlations from a multitude of disciplines is combined with an automated constraint analysis as well as a mission analysis capability.

The aircraft configuration DLR-FFD returned by the software tool [28] was then used for an analysis against the stability and controllability requirements. Results and feedback are provided to the relevant disciplines.

5.1. Aircraft Configuration

The DLR-FFD is a generic triple-delta combat aircraft configuration which is designed for research purposes within the DLR project Diabolo. The initial control concept is based on the design of present combat aircraft, i.e. an all-movable elevator and, for low observability reasons, a V-tail. Thrust-vectoring is not intended at this design stage. These parameters served as input parameters for the automated tool to initiate the aircraft as described above. The obtained aircraft configuration is shown in FIG 12.

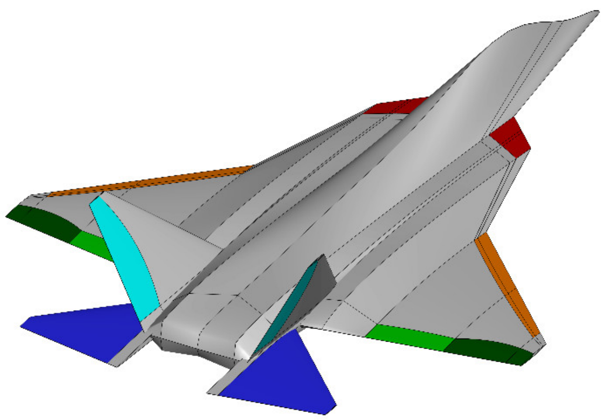

FIG 12. DLR Future Fighter Demonstrator (DLR-FFD) with highlighted control effectors

Apart from the all-movable elevator (dark blue) and the V-tail with the cyan-highlighted rudders, the aircraft configuration features an inner (green) and an outer (dark green) aileron on each side. Two slats (orange) und two so-called LEVCONs (Leading Edge Vortex Controller) (red) complete the initial control effectors of the DLR-FFD. However, slats and LEVCONs are not yet considered at this design stage.

As explained in [20], the cockpit control inputs are mapped to different control effectors. The mapping is defined via the control distributors. For the DLR-FFD, the mapping is listed in TAB 2.

controlDistributor	controlElement
rollDistributor	outerAileron_RH
	innerAileron_RH
	outerAileron_LH
	innerAileron_LH
pitchDistributor	elevator_RH
	elevator_LH
yawDistributor	rudder_RH
	rudder_LH

TAB 2. Mapping of control distributors to control elements

For example, a roll command input is executed by using the inner and outer ailerons.

5.2. Analysis of Longitudinal Motion

There are no dedicated controllability requirements listed in the catalogue of requirements [27] regarding the longitudinal motion. An additional general requirement was introduced during the course of the project in such a way that the aircraft should have a stability margin of -10% MAC at cruising Mach number at combat altitude, i.e. the aircraft should be longitudinally unstable. This constraint was an input parameter during the initiation process of the investigated aircraft configuration.

In a first step, the aircraft simulation framework was used to check the stability margin at cruising Mach number at combat altitude. It turned out that the stability margin reads nearly -14% MAC which means that the longitudinal instability is greater than planned. The reason for this deviation is expected to originate in the simplified aerodynamic model being available during conceptual design. The effects on the pitch recovery moment were investigated next.

As described in subsection 2.1.1, the calibrated stall speed V_{s1g} was determined for an altitude of 10 000 feet. One altitude is sufficient since the calibrated stall speed is not directly affected by density altitude changes and therefore stays the same. The required pitch down acceleration was calculated for the obtained stall speed at 10 000 feet. For the first analysis, a short period damping of $\zeta_{sp} = 0.7$ was chosen from the Level 1-parameter range in TAB 1. The damping should not be chosen too high since an aircraft must be able to demonstrate a certain agility in this flight range with high angles of attack. The short period frequency ω_{sp} was determined as a function of $n_{z\alpha}$ which is recalculated for each altitude/airspeed. For the initial assessment it was decided to derive the short period frequency ω_{sp} from the centre line of the Level 1-area shown in FIG 2. The result plot of the simulation run of the reference model considering the described aircraft dynamics is shown in FIG 13.

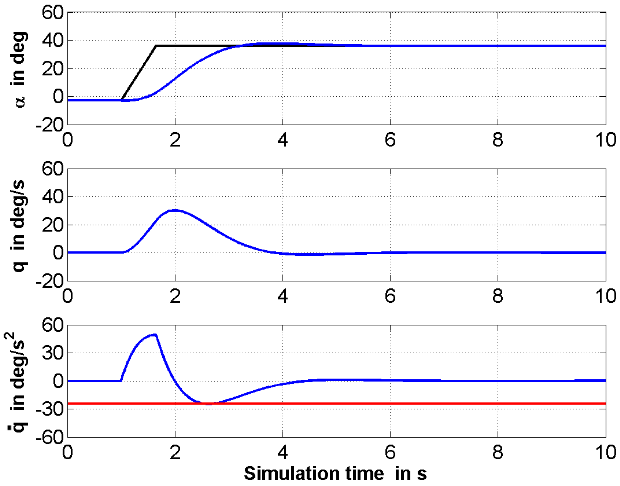

FIG 13. Longitudinal aircraft response (blue) due to an alpha-command (black) indicating the required pitch down acceleration (red)

The first time series shows the α-command (black) up to the target authority (angle of attack at maximum lift) and the model response (blue). Due to the desired agility of the aircraft, the observable small overshoot is accepted. The red line in the bottom time series indicates the lowest values of the pitch acceleration during the simulation run and represents the required pitch down acceleration. This value is used to calculate the required pitch recovery moment by means of Eq. (8) which is shown in FIG 14 versus the angle of attack together with the available pitching moment obtained for a full pitch down command.

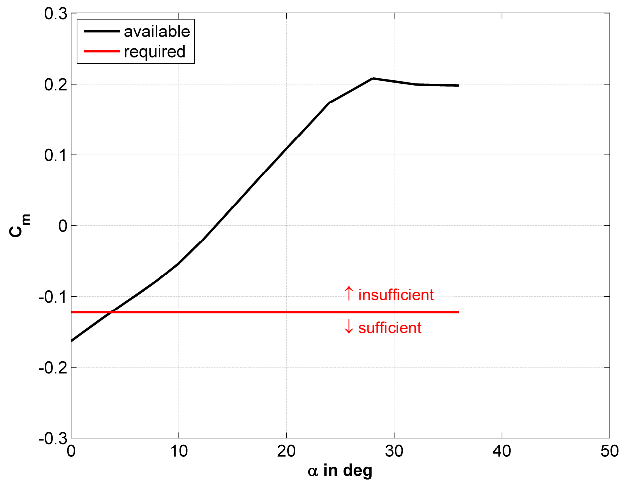

FIG 14. Required pitch recovery moment (red) and available pitching moment versus angle of attack at full pitch down (black)

The figure shows, that the curve of the available pitching moment is mostly not below the required pitch recovery moment line as outlined in FIG 5 above. The maximum allowable angle of attack would be around three degrees which is not sufficient for a highly agile fighter configuration.

As already mentioned, the longitudinal instability is higher than intended. In order to investigate the influence of the stability margin on the pitch recovery moment, the centre of gravity was shifted forward by about 30 cm. Now, the stability margin at cruise Mach number and at combat altitude is approximately -9% MAC and therefore slightly below the original planned stability margin. The figure showing the required and available pitching moment against angle of attack now looks as follows.

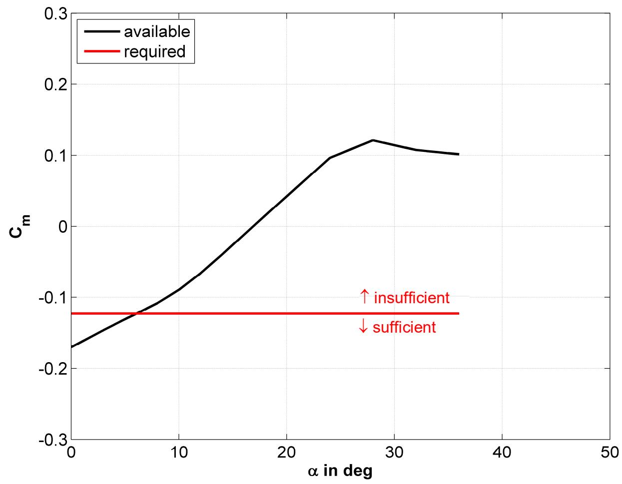

FIG 15. Required and available pitching moment versus angle of attack – shifted centre of gravity

While the required pitching moment remained unchanged, the available pitching moment slope decreases and the curve moved downwards for higher angles of attack. But the maximum of the pitch moment coefficient is still well above the required pitching moment coefficient.

The analysis has shown that controllability requirements are not yet fulfilled. A possible reason could be a too high instability of the aircraft, which is currently under discussion within the project. Aerodynamic studies revealed a strong movement of the neutral point with the angle of attack which increases the instability as well. Additional measures to solve this issue are considered and assessed by the relevant disciplines. e.g. an improved aerodynamic wing design in combination with LEVCONs, slats, and rudder deflections, an increased size of the horizontal tailplanes, and an adjustment of the mass distribution to further reduce the instability.

5.3. Analysis of Lateral/Directional Motion

The catalogue of requirements [27] includes information on required roll authorities to be considered in the preliminary design process. At four Mach number/equivalent airspeed combinations, different roll rates to be achieved are specified for a range of angles of attack varying from 10 to 50 degrees. In addition, factors are provided to obtain the associated demanded roll accelerations by multiplying the roll rates. They have been developed in discussions with the project partners. In total, 14 controllability requirements with respect to lateral/directional motion were set up and incorporated into the CPACS file.

FIG 16 presents exemplarily the results for a controllability requirement at medium subsonic Mach number, low angle of attack, and roll onset. Full roll input is applied in order to achieve full roll performance.

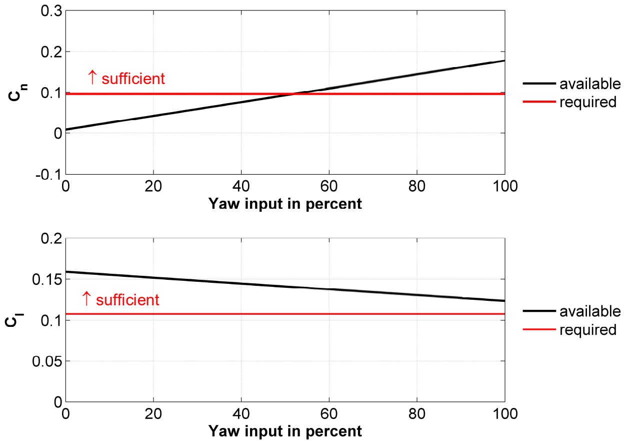

FIG 16. Yaw input dependent yawing and rolling moment coefficient – roll onset

The upper plot shows that about 50 percent yaw input is needed to account for the yawing moments due to the full roll input. The bottom plot shows that the available rolling moment decreases due to the yaw input but is still well above the required rolling moment. Although this controllability requirement is fulfilled it has to be discussed if a rudder deflection of nearly 50 percent is feasible for instance from structural perspective. The stability derivatives at this flight point without any control input read $C_{n\beta,dyn} = 0.7312$ and $LCDP = 0.3737$, respectively. Both derivatives are above the limits outlined in subsection 2.1.2 and are therefore satisfactory.

A second example shows the results for a controllability requirement at low subsonic Mach number, low angle of attack, and roll onset. Full roll input is applied in order to achieve full roll performance.

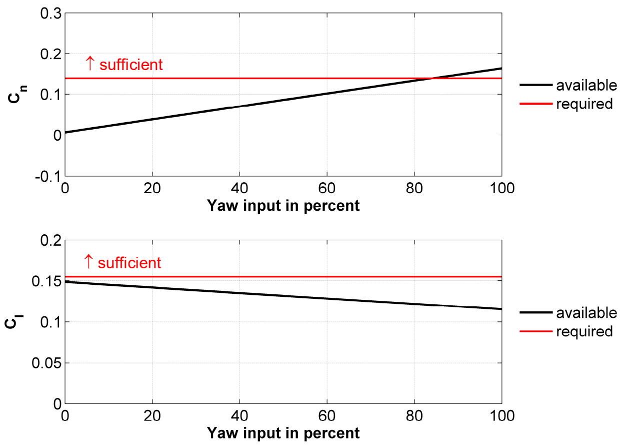

FIG 17. Yaw input dependent yawing and rolling moment coefficient – roll onset

More than 80 percent yaw input is required to achieve the required yawing moment at this flight condition. Furthermore, the reserve margin is not very large to generate an increased yawing moment if necessary. In addition, the required rolling moment cannot be achieved, even without yaw input.

The analysis of the lateral/directional motion revealed that the lower the Mach number, the less the controllability requirements are met. This mainly affects the yawing moment, but in some cases the required rolling moment cannot be applied. That means that in particular the design of the vertical tail has to be reviewed.

6. CONCLUSION AND OUTLOOK

This paper presents a methodology for the assessment of stability and controllability of combat aircraft in the early stage of aircraft design. The theoretical background on stability and controllability was outlined and prerequisites such as a multi-fidelity aerodynamic data set and a flight dynamics model were addressed.

The methodology was demonstrated for an aircraft configuration from the DLR project Diabolo. Within this project, a generic research configuration, a triple-delta combat aircraft named DLR-FFD, is developed and analysed. The initial control concept consisting of an all-movable elevator, a V-tail and ailerons was investigated regarding the stability and controllability requirements which were presented previously.

Aerodynamic data used for the stability and controllability assessment is provided by a workflow for aerodynamic multi-fidelity modelling. Building blocks of the workflow, which is applicable to early aircraft design stages, and examples of its application for the DLR-FFD data set generation were described. An automated coupling of geometry and CFD meshing capabilities is an essential part to obtain aerodynamic data of varying fidelity efficiently. Together with multi-fidelity surrogate models, that combine aerodynamic data in a hierarchical manner, these capabilities enable the generation of high-fidelity based aerodynamic data sets. The superposition principle of the aerodynamic data sets used by the CPACS data exchange format offers the flexibility to separate baseline performance data from the flight states requiring control effector deflections by using increment values. This allows to combine data obtained from different sources and models into a comprehensive data set.

The analysis revealed that the available pitching moment with full pitch down is not sufficient in order to recover the aircraft at high angles of attack. A shift forward of the centre of gravity resulted in an increased pitching moment at higher angles of attack, but the pitch recovery requirement was still not completely fulfilled. It seems that the instability of the aircraft is too high, therefore the aircraft configuration is currently under revision, starting with a modified wing design. In addition, increasing the fidelity of the aerodynamic data for the elevator or a sizing of the elevator could leverage its effectiveness. The impact of both measures will be investigated in the further course of the project.

In terms of the lateral/directional motion, the results show that the lower the Mach number, the less the controllability requirements are met. This mainly affects the yawing moment at low Mach number, but in some cases the required rolling moment cannot be met either. That means that in particular the design of the V-tail has to be reviewed.

Further discussions are being held if the differential use of the elevator would make a significant contribution to the rolling moment. In addition, a targeted use of the LEVCONs could have a positive effect on aerodynamics. Finally, the option to consider thrust vectoring is also still there, where both longitudinal and lateral/directional motion can be supported with a single control effector. The above-mentioned options would lead to a more complex control concept approach.

In the end the methodology presented was shown to work properly and as expected, as the results provided important findings for the aircraft design process which can now be considered during the next iteration.

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