Model Based Automatic Control Design for the T-FLEX Demonstrator Using RCE Environment

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The main goal of the paper is to develop automatic control design methods for flexible aircraft. The motivation for the research is that such automatic control generation enables the inclusion of the control design algorithms into the multidisciplinary design optimization (MDO) of aircraft design. In such an extended MDO framework, called co-design, the sizing, structural dynamics, aerodynamics and the controllers of the aircraft are optimized in one single step. This way control technologies can be included early-on in the preliminary design stage of aircraft design. Since the control design is model based, first a control oriented aeroservoelastic model needs to be developed. The modeling is done via the bottom-up modelling approach. The model generation also needs to be automatic due to parameter changes resulting from the MDO process. The research focuses on flexible aircraft, therefore, the control algorithms include baseline, manoeuvre load alleviation, gust load alleviation and flutter suppression controllers. All of these algorithms needs to be developed in such way that they can automatically executed in the MDO process. The overall MDO framework is based on the Remote Component Environment (RCE) environment and the aircraft investigated is the T-Flex demonstrator of the FLIPASED project. The paper presents the main concepts of the modeling and control synthesis, analysis for the above mentioned four controllers and the most important aspects of integrating such automatic control design methods into the RCE environment.

I. Introduction

The main direction of future aircraft design is to achieve more lightweight and higher aspect ratio air-frames with the aim to improve performance and to reduce operating costs and harmful emissions. This promotes the development of flexible aircraft structures with enhanced aeroelastic behaviour that are often prone to instability. Control design for such vehicles is a greater challenge, due to the complexity of dynamic coupling resulting in aeroelastic phenomena such as flutter. There exist several recent research projects investigating control design methodologies for flexible aircraft. These are the Performance Adaptive Aeroelastic Wing (PAAW) project in the USA, [1] and the Flutter Free FLight Envelope eXpansion for ecOnomical Performance improvement (FLEXOP) and Flight Phase Adaptive Aero-Servo-Elastic Aircraft Design Methods (FLIPASED) projects in the EU, [2, 3]. A demonstrator aircraft T-Flex has been designed and built in the FLEXOP and FLIPASED projects. This aircraft serves as a test bed for load alleviation and active flutter suppression control mehtods. The T-Flex demonstrator UAV is shown in Figure 1.

FLIPASED aims to demonstrate the benefits of including activate-control technologies from early-on in the preliminary design stage of aircraft design. This goal can be achieved by including the control design into the multidisciplinary design optimization (MDO) process of aircraft design. Such approach, where the aerodynamics,

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Fig. 1 T-Flex demonstrator aircraft

structural dynamics and the control design are optimized in a common step is called co-design [4–7]. The control design is model based, therefore, a suitable control oriented aeroservoelastic (ASE) model for flexible aircraft is crucial. The ASE model of an aircraft is typically constructed based on the integration of aerodynamics, structural dynamics and flight dynamics subsystems, [8–11]. The models of the subsystems are developed separately which are then combined. This way the ASE model is formed. One of the challenges with such ASE models is that they are typically of too high order for control design. Therefore, low order control oriented model is required. The main approach for the control oriented model development is the "bottom-up" modeling [12]. The key idea of the bottom-up modeling is the following. The subsystems of the ASE model in general have simpler structure than the nonlinear ASE model. Therefore, the subsystems containing the structural dynamics and aerodynamics model can be reduced by simpler, more tractable reduction techniques. Creating the ASE model from the reduced subsystems leads to the control oriented model which is suitable for control design.

One of the main challenges of co-design is finding a suitable control structure that can be included into the MDO process. The control design for flexible aircraft typically involves a lot of manual tuning and trial and error steps until the controller with the highest performance and robustness is achieved. In addition, the control synthesis often has a high computational load. In order to include the control design step into the MDO, it needs to have small computational load and the algorithm needs to be robust against the aerodynamic and structural dynamic changes that occur during the optimization process. The whole MDO process needs to operate in an automatic fashion, without hand tuning. Therefore, the main goal of the paper is to develop automatic control design methodologies that can be used for co-design. The control design algorithms are developed for the T-Flex aircraft. Since the paper specifically focuses on flexible aircraft, there are four controllers developed: a baseline controller, a manoeuvre load alleviation (MLA) controller, a gust load alleviation (GLA) controller and a flutter suppression controller. The control designs utilize the linear parameter-varying (LPV) [13, 14] framework. In addition to the control synthesis, performance and robustness analysis of the resulting controllers needs to be carried out in an automated fashion as well. The automatic control design and analysis is implemented in the Remote Component Environment (RCE) environment [15].

The paper is organised as follows. Section II describes the main concepts of the RCE framework, followed by Section III presenting the T-Flex demonstrator aircraft. Section IV gives the details of the control oriented modeling, while Sections V and VI describes the algorithms of the control design and analysis steps respectively. Finally, the results of the paper are summarized in Section VII.

II. RCE Environment

DLR's Remote Component Environment (RCE) [15] is an open-source software environment for defining and executing workflows containing distributed simulation tools by integrating them into a peer-to-peer network. The following description has been taken from the related publication by the main developers, Boden et al. [15]. RCE is being developed primarily by DLR and has been used in various engineering projects, including several aerospace projects dealing with MDO and multidisciplinary analysis (MDA). RCE has several advantages that can help to achieve more reusable multidisciplinary processes. The workflow is composed of built-in and user-defined components. Disciplinary tools are integrated as standalone components, with defined inputs and outputs, and then distributed over the network. While executing the workflow, data dependencies between the components are automatically detected, and a component is executed as soon as all its input data is available. Thus, multiple components can run at the same time. The components of a multidisciplinary process can also be executed in a distributed manner, where the tools are located on different machines with possibly different operating systems. Once configured, the peer-to-peer network is automatically established between the RCE instances running on different machines, making components visible and executable even between instances that are only connected indirectly. The distributed execution capability alleviates tool deployment issues, Figure 2, including those related to the protection of intellectual property.

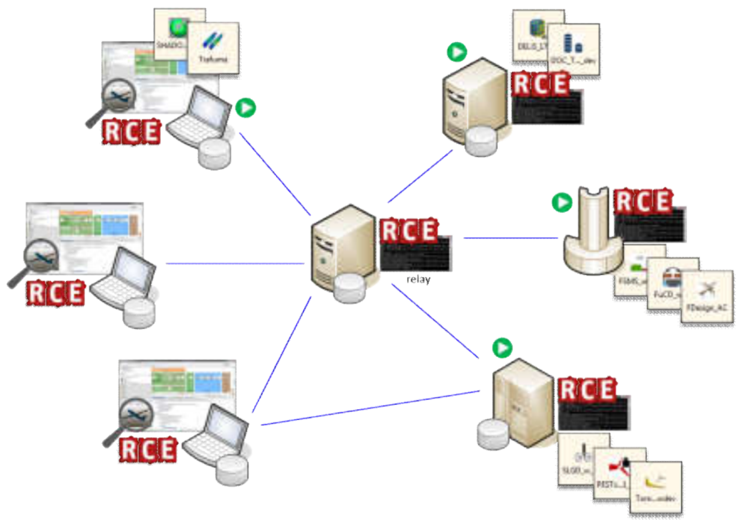

Fig. 2 Distributed RCE workflow

RCE supplies a graphical editor for creation of workflows, using the built-in components to control the data flow. Some built-in components can be used to perform optimization tasks within the workflow, including nested loops, using built-in or user integrated optimization algorithms. After integrating the tools required for the execution of the workflow, the user may compose them into a workflow. To this end, RCE offers a graphical editor allowing the user to construct a workflow by first dragging and dropping the required components into the editor and subsequently connecting their respective inputs and outputs. After constructing such a workflow, the user can execute it. The data model Common Parametric Aircraft Configuration Schema (CPACS) has been introduced and developed at the German Aerospace Center (DLR) since 2005. CPACS is implemented in XML. The data of the aircraft and the resulting controllers are stored and shared between the blocks via CPACS.

III. T-Flex Demonstrator Aircraft

The aircraft has a wingspan of 7 m and aspect ratio of 20. The aircraft has a 300 N jet engine. The empennage is configured as a V-tail and each wing has 4 control surfaces, [16]. The outer control surfaces are used for flutter suppression, see Figure 3.

The aircraft has two unstable aeroelastic modes. The first aeroelastic mode (symmetric) goes unstable at 52 m/s and 50.2 rad/s and the second (asymmetric) at 55 m/s and 45.8 rad/s. In order to have sufficient bandwidth, custom made actuators are designed for the aircraft. In addition to the GPS and air data probe, the aircraft has inertial measurement units (IMUs) at the center of gravity and in the wings as shown in Figure 4.

IV. Control Oriented Modelling of Flexible Aircraft

The controllers for the T-Flex demonstrator are designed based on a suitable model. Such model is called the control oriented model and the reminder of this section will describe the main steps of the automated control oriented model development.

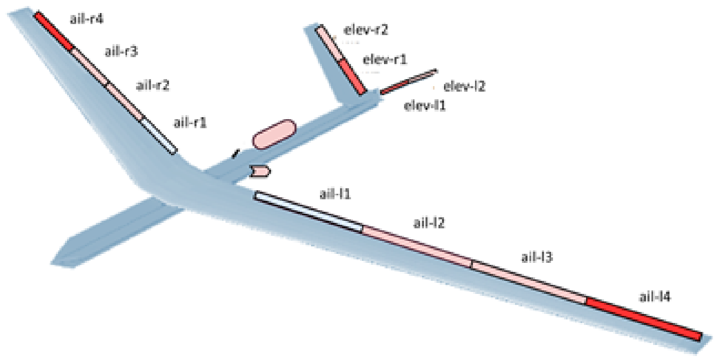

Fig. 3 T-Flex aircraft control surface configuration

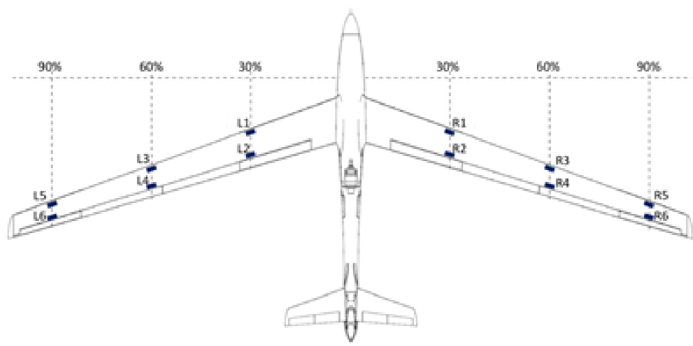

Fig. 4 T-Flex aircraft sensor configuration

Flexible aircraft are typically modelled using subsystems. The structural dynamics model, the aerodynamics model and the flight mechanics model are combined to form the aeroservoelastic (ASE) model. Such subsystem interconnection is depicted in Figure 5. These ASE models in general are of too high order for control design, therefore, model order reduction is required. One approach applied for the MDO process is the bottom-up modeling approach, [11, 12, 17].

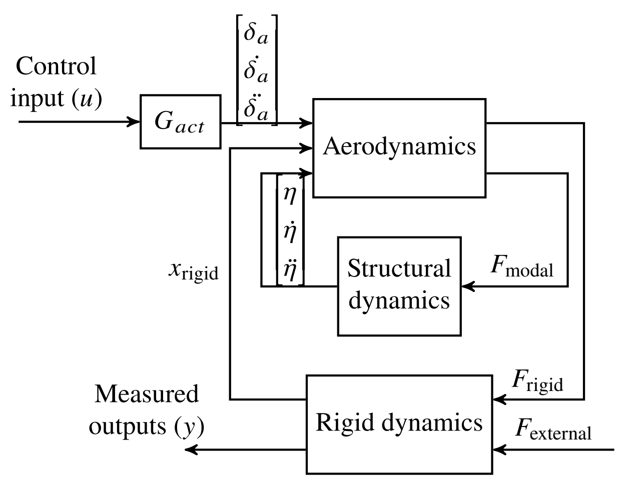

Fig. 5 ASE subsystem interconnection.

The key idea of the bottom-up modeling is the following. The subsystems of the ASE model in general have simpler structure than the nonlinear ASE model. Therefore, the subsystems containing the structural dynamics and aerodynamics model can be reduced by simpler, more tractable reduction techniques. Combining these reduced order subsystems results in a low order nonlinear ASE model upon which a nominal, low order, control oriented models can be obtained. The control oriented models are based on the LPV framework, [13, 14]. The LPV framework can serve as a good approach to model ASE systems for control design. The benefits of utilizing the LPV framework are the following; it can capture the parameter varying dynamics of the aircraft and many of the linear time-invariant (LTI) control design techniques have been extended to LPV systems. An LPV system is described by the state space model [13, 18]

$$\dot{x}(t) = A(\rho(t))\ x(t) + B(\rho(t))\ u(t) \tag{1a}$$

$$y(t) = C(\rho(t))\ x(t) + D(\rho(t))\ u(t) \tag{1b}$$

with the continuous matrix functions $A\colon \mathcal{P} \to R^{n_x \times n_x}$, $B\colon \mathcal{P} \to R^{n_x \times n_u}$, $C\colon \mathcal{P} \to R^{n_y \times n_x}$, $D\colon \mathcal{P} \to R^{n_y \times n_u}$, the state $x\colon R \to R^{n_x}$, output $y\colon R \to R^{n_y}$ input $u\colon R \to R^{n_u}$, and a time-varying scheduling signal $\rho\colon R \to \mathcal{P}$, where $\mathcal{P}$ is a compact subset of R^N. The system is called quasi LPV model if the parameter vector ρ includes elements of the state vector x. The system matrix $S(\rho(t))$ is defined as

$$S(\rho(t)) = \begin{bmatrix} A(\rho(t)) & B(\rho(t)) \\ C(\rho(t)) & D(\rho(t)) \end{bmatrix} \tag{2}$$

In a grid-based LPV representation ([18]), the system is described as a collection of LTI models (A_k, B_k, C_k, D_k) = $(A(\rho_k), B(\rho_k), C(\rho_k), D(\rho_k))$ obtained from evaluating the LPV model at a finite number of parameter values $\{\rho_k\}_1^{n_{\text{grid}}} = \mathcal{P}_{\text{grid}} \subset \mathcal{P}$.

The main measure of the accuracy of the low order model is the ν-gap metric, [19].

1. Modeling block inputs

The modeling block takes the structural dynamics (M_{hh}, K_{hh}, B_{hh}) and aerodynamics data (Q_{hh}) as input via CPACS.

2. Reduction of the structural dynamics model

The structural dynamics of the aircraft are of the form

$$\mathcal{M}\ddot{\eta} + \mathcal{C}\dot{\eta} + \mathcal{K}\eta = F_{\text{modal}} \tag{3}$$

where F_{modal} is the force acting on the structure in modal coordinates, $\mathcal{M}$, $\mathcal{C}$ and $\mathcal{K}$ are the modal mass, damping and stiffness matrices respectively. The structural dynamics model is an LTI system, thus state truncation can be applied.

3. Reduction of the aerodynamics model

The aerodynamic lag terms take the state-space form

$$\begin{aligned} \dot{x}_{\text{aero}} &= \frac{2V_{\text{TAS}}}{\bar{c}} A_{\text{lag}} x_{\text{aero}} + B_{\text{lag}} \begin{bmatrix} \dot{x}_{\text{rigid}} \\ \dot{\eta} \\ \dot{\delta}_{\text{cs}} \end{bmatrix} \\ y_{\text{aero}} &= C_{\text{lag}} x_{\text{aero}} \end{aligned} \tag{4}$$

where V_{TAS} is the true airspeed, x_{rigid} is the rigid body state, η is the modal state of the structural dynamics, δ_{cs} is the control surface deflection and $\bar{c}$ is the reference chord. Using the aerodynamics model given by A_{lag}, B_{lag} and C_{lag} in (4) an LTI balancing transformation matrix T_{b} is computed. The balanced states of the aerodynamic model with the smallest Hankel singular values are residualized, leading to a reduced order aerodynamics model.

The initial model order reduction produced the following results. The structural dynamics model can be reduced in the following way. In order to keep the ν-gap between the high fidelity and the low order model low the first six structural modes and modes 19, 20, 21 are retained for the reference aircraft model. Te removal of the latter results in a large increase in the ν-gap. This way, a 18 state structural dynamics model can be obtained from the 100$^{\text{th}}$ order model. In case of the aerodynamics model, retaining two lag states results in a low order model with acceptable accuracy. The resulting nonlinear ASE bottom-up model has 32 states that consists of 12 rigid body states, 18 structural dynamics states, 2 aerodynamic lag states. Note, that the actuator dynamics are not included in the control oriented model. The ν-gap between the nominal, high-fidelity and the reduced order model for different airspeed values is given in Figure 6.

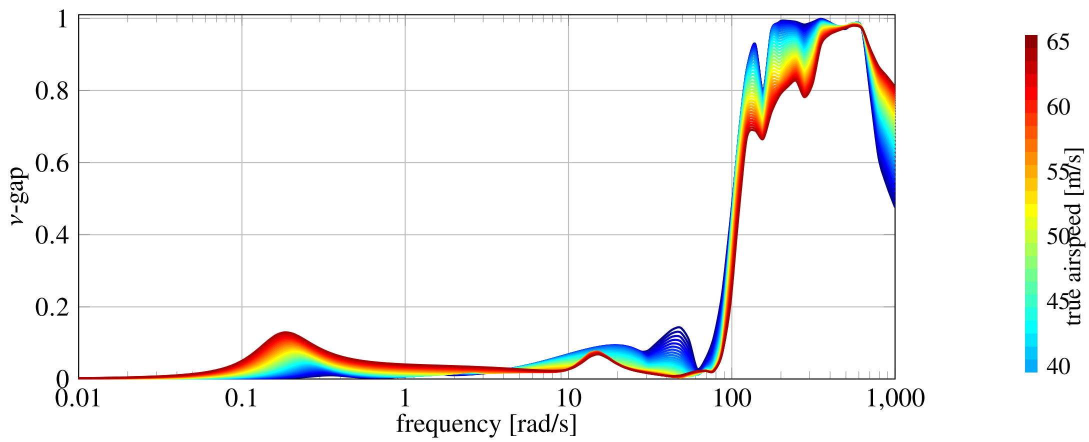

Fig. 6 **ν-gap values between the nominal low order and high-fidelity models.**

4. Uncertain low order model

The next step is to develop uncertain LPV models of the aircraft. Uncertain models can be developed by extending the structural dynamics model with the uncertain parameters. These uncertainties appear in the mass matrix $\mathcal{K}$ and in the damping matrix C in (3) of the nonlinear ASE model and are denoted by $\delta_{\mathcal{K}}$ and δ_C, respectively. Based on this uncertain, nonlinear model a grid-based uncertain LPV model is constructed. The grid-based uncertain LPV model is obtained over a 3 dimensional grid. The grid consists of 81 equidistant points of the airspeed between 30m/s and 70m/s, 3 points of the natural frequency in the structural dynamics between $\pm 1\%$ of the nominal value, and 3 points of the damping in the structural dynamics between $\pm 10\%$ of the nominal value. This results in a total of $81 \times 3 \times 3 = 729$ grid points. The scheduling parameter ρ can then be defined as

$$\rho = \begin{bmatrix} \rho_{V_{TAS}} \\ \delta_{\mathcal{K}} \\ \delta_C \end{bmatrix} \tag{5}$$

where $\rho_{V_{TAS}}$ is a measured parameter and $\delta_{\mathcal{K}}$ and δ_C are unmeasured. These uncertainties have a significant effect on the flutter speeds and frequencies. The nominal and uncertain flutter modes of the control oriented LPV model are shown in Figure 7.

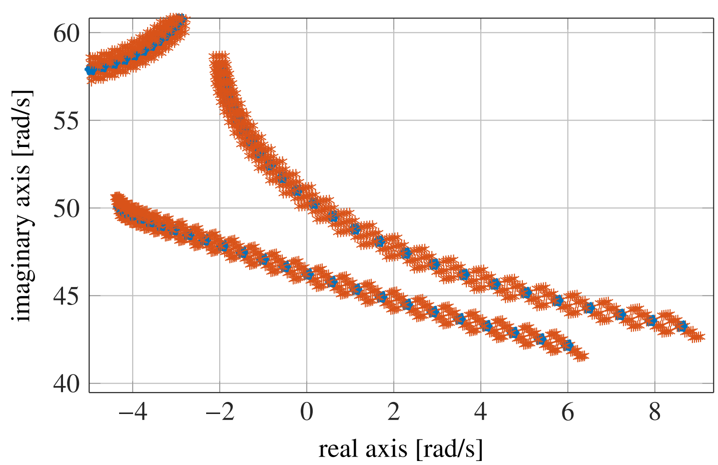

Fig. 7 **Uncertainty of the flutter modes: nominal model (blue), uncertain (red).**

5. Modeling block robustness

As it can be seen, the bottom-up modeling approach involves a certain degree of heuristics. These heuristic steps include the selection of the structural dynamics states to retain and setting the the number of retained aerodynamic lag states. These parameters are hand tuned for the initial, reference aircraft model. The modeling tool needs to be adopted to the collaborative design in this respect. This means that the retained the initial structural modes to be retained are the ones of the reference aircraft. However, it is crucial that after every MDO iteration, the ν-gap metric is analyzed and that it does not exceed a threshold value. If this value is exceeded, it means that the bottom up-model is not accurate enough. Therefore, at the expense of increasing the order ot the resulting model, additional structural modes need to be retained. The number of retained modes is increased until the ν-gap values are satisfactory. A similar approach is used for the order of the lag state aerodynamics model. In this case the number of the retained lag states is increased until a satisfactory ν-gap level is obtained.

6. Modeling block outputs

The modeling block provides two models, one for the baseline control design (RigACModel) and one for the flexible control design (FlexACModel). The FlexACModel is the low order, uncertain LPV model of the aircraft obtained by the steps described above. The RigACModel is obtained from the nominal low order aircraft model by rezidualizing the structural and lag state dynamics. This model serves for the baseline control design, containing only the 12 rigid body states. These resulting models are saved in the ToolSpecific section of CPACS.

V. Automated Control Design Algorithms

A. Expected closed-loop structure

Generally, aircraft manufacturer control design workflow follows what we can call a frequency grid approach. This approach consists in designing different controllers, through a frequency guideline. Each of them address a phenomena an aircraft is faced during its operation. With reference to Figure 8, one may notice that different phenomena (flight, loads...) usually occurs at different frequencies. These frequencies are dependent on the geometry and structure of the aircraft, and in the considered case, one may expect even more blending. Still the big picture remains.

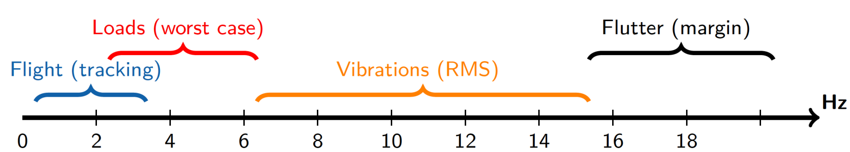

Fig. 8 Frequency grid of the physical phenomena occurring over an aircraft. Ranges and values are different from an aircraft to an other

As a matter of consequence, the closed-loops one is intended to develop is presented as in Figure 9, where each function in cascaded with the other.

As presented in Figures 8 and 9, the flight control system layout will gather a set of multiple functions. Each function should be independently designed without affecting the others. Moreover, as the functions are connected but somehow with different objectives, we will consider designing them with the following sequence:

1. Baseline flight control, a flight oriented control loop
2. MLA, a maneuver load alleviation control loop
3. GLA, a gust load alleviation control
4. Flutter, a flutter shield control

B. Baseline Control Design

The baseline control design is based on the LPV model obtained in the model integration block, that has 12 rigid body state and the actuator dynamics. The baseline control design takes the actuator dynamics and the baseline control

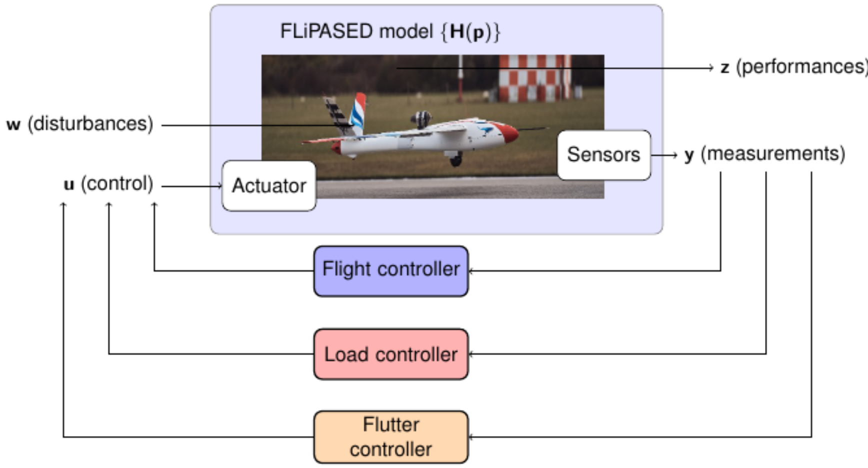

Fig. 9 Multiple control loops

design model RigACModel as inputs via CPACS. The baseline control system features a classical cascade flight control structure with scheduled control loops to augment the lateral and longitudinal axis of the aircraft, see Figure 10.

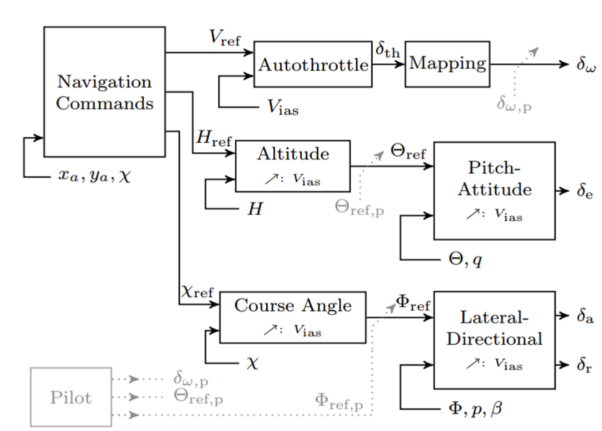

Fig. 10 Baseline control architecture

The main algorithms of the baseline control design are described in [20]. As the cross-coupling between longitudinal and lateral axis is negligible, longitudinal and lateral control design is separated. The control loops use scheduled elements of proportional-integral-derivative (PID) controller structures with additional roll-offs in the inner loops to ensure that no aeroelastic mode is excited by the baseline controller. Scheduling with indicated airspeed V_{ias} is used to ensure an adequate performance over the velocity range from 38 m/s to 64 m/s. Structurally the controller consists of several loops targeting different dynamical modes. Accordingly, intuitive design specification for the loops can be formulated by the user in terms of settling times, reference tracking or robustness margins. The control design itself automatically optimizes the corresponding gains, in order to satisfy the specified design goals. Once the optimization found a feasible solution it provides the corresponding control gains and control structure which is then used for the numerical analysis. However, a simple metric is also returned for the user which indicates the performance of the control loops. This allows the interaction with the automated design process: the user can formulate tighter or loser specifications according to the individual needs. A clear graphical representation is also provided which can be included in the reporting. In addition, the controller generation process adjust the speed-dependence of the control gains in order to achieve the best possible performance and the simplest scheduling function. Frequency and time domain results can be seen in Figure 11 and Figure 12.

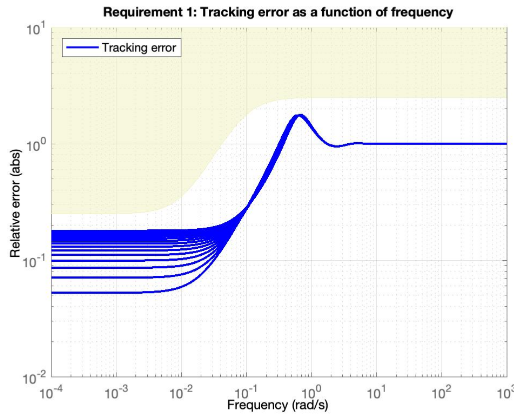

Fig. 11 Frequency domain results of the baseline control design

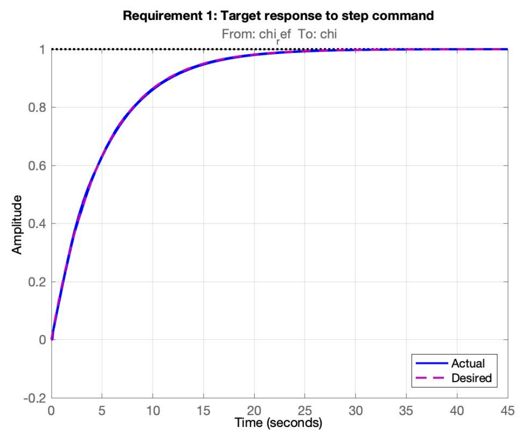

Fig. 12 Time domain results of the baseline control design

C. MLA and GLA Control Design Blocks

The MLA and GLA controllers both seek to reduce the wing root bending moment corresponding to manoeuvres and gust encounter. Their structure is predefined with specified inputs and outputs. The pitch angle and rate, the commanded and real vertical acceleration are needed for the manoeuvre load alleviation controller. Based on these measurements it calculates the necessary aileron and elevator deflections. The gust load alleviation controller takes the pitch rate, the vertical acceleration in the fuselage and on both wing tips as an input. It likewise provides aileron and elevator deflections. Both controllers are synthesized based on the structured H_∞ synthesis method with a full order model including unsteady aerodynamics, gust inputs and load outputs. Before the synthesis takes place, the order of the state-space model of the aircraft is reduced removing irrelevant dynamics. As an objective function for the MLA and GLA controller the weighted transfer function from gust input to wing root bending moment has to be reduced.
Output of the RCE blocks are state-space models of the controllers. The resulting controller state-space systems can then be fed to a closed loop model in order to analyse the overall aircraft performance.

D. Flutter Suppression Control Design

The flutter controller design is done based on the uncertain LPV ASE model of the aircraft. The flutter control design takes the outer aileron (denoted by L4 and R4) actuator dynamics and the flutter control design model FlexACModel as inputs via CPACS. The airspeed and the uncertainties in the structural dynamics model are treated at parametric uncertainties and dynamic uncertainty is added to account for the model reduction. In order to reduce the computational time of the control synthesis, structured H_∞ design is chosen that result in an LTI flutter suppression controller. Similarly to the baseline control design algorithm, the flutter suppression control design block needs to be augmented with basic analysis algorithms to verify if the resulting controller satisfies the control performance specifications. As a main measure, the multi-input multi-output (MIMO) disc margins are selected.

The model generation, the control synthesis and the analysis of the resulting controllers for the baseline and flutter controllers is shown in the workflow presented in Figure 13.

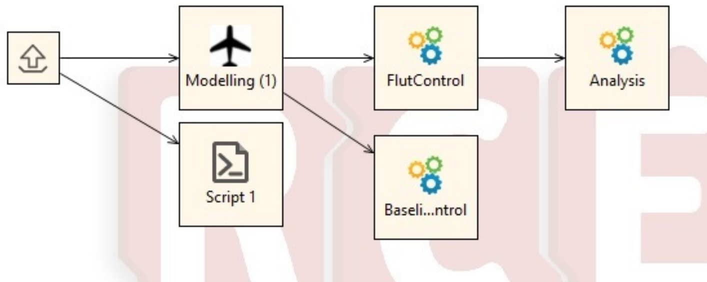

Fig. 13 RCE workflow for the aeroelastic model generation for baseline and flutter suppression control design

VI. Closed Loop Analysis

For the closed loop analysis the controllers are connected with the flexible aircraft model. Figure 14 shows the pole migration of the FlexACModel with (red) and without (blue) the baseline controller. The designed baseline controller is stable with the flexible model up to the flutter speeds.

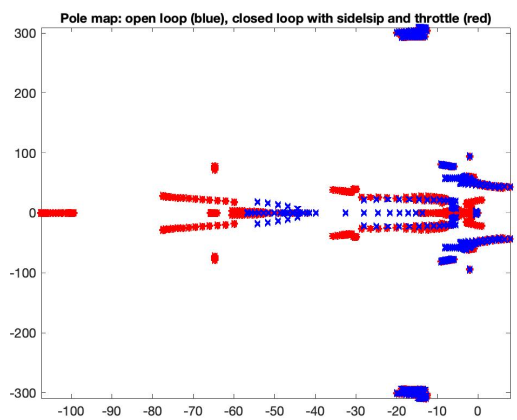

Fig. 14 Flexible aircraft dynamics with (red) and without (blue) the baseline controller

The analysis of the closed-loop is based on disk margin calculations. Complex scalar uncertainties are injected into the channels involved in the feedback loops and the phase and gain combination at which the closed-loop becomes unstable is computed in each channel, simultaneously. First, the robustness of the baseline controller is analyzed without the flutter controller. The speed at which the disk margins become zero is considered the open-loop flutter speed. In the next step, the flutter controller is also connected to the system and the margins are recaclulated. This step reveals how much the flutter controller is able to extend the safe flight envelope functioning simultaneously with the baseline controller. Figure 15 shows the disk margins obtained by this analysis.

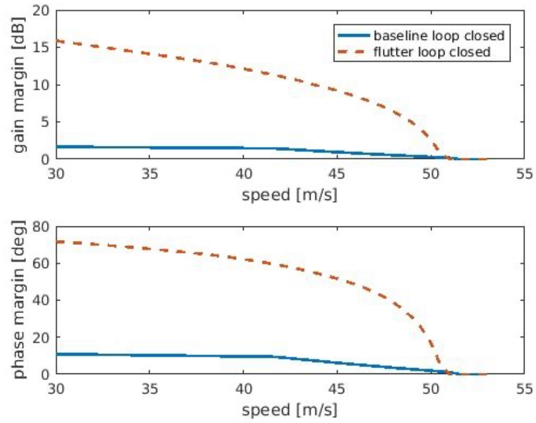

Fig. 15 Resulting disk margins

VII. Conclusion and outlook for full paper

In this paper, automatic control oriented model generation and automatic control synthesis and analysis steps for flexible aircraft are discussed. The goal of the automation is to achieve modeling and control design tools that enable co-design. In such way the control design step can be included into the MDO process. The paper focuses on the T-Flex demonstrator aircraft of the FLIPASED project. Four controllers are investigated for the T-Flex aircraft. These are the baseline controller, MLA, GLA and flutter suppression controllers. The main concepts of model generation and control design automation are presented in the paper. The resulting workflow is implemented in the RCE environment which enables seamless integration into a high level MDO workflow.

In the full paper, detailed steps of the automation with a qualitative and quantitative evaluation will be elaborated upon. Detailed results of each control design algorithm and analysis process will also be presented.

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