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Lateral control for flexible BWB high-capacity passenger aircraft

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Abstract: Presence and coupling of rigid-body dynamics and flexible modes is a challenge for the flight control systems (FCS) design of a large blended-wing-body aircraft (BWB). We present and asses two approaches for a BWB's lateral FCS in this paper. First, a more classical approach is employed giving rise to separate flight dynamics controller (H_2 optimal, with sufficient roll-off) and an active damper for most prominent lateral flexible modes on top of that (mixed-sensitivity H_∞ design). This approach proves successful and has obvious advantages related to the design process complexity, or implementation and testing issues. On the other hand, there is always a risk of potentially significant performance loss compared to a fully integrated design. For this reason, fully integrated design is also presented in the form of a fixed-order MIMO H_∞ optimal FCS controller, obtained by means of direct non-convex non-smooth optimization package HIFOO. Performance of both approaches is assessed.

Keywords: Lateral control; Fixed order optimization; BWB aircraft

1. INTRODUCTION

Large aircraft structures and novel concepts, such as Blended Wing Body (BWB) aircraft configurations, can lead to higher fuel-efficiency and reduced emissions. However, this also leads to low frequency structure vibration modes, and coupling of those to the flight mechanic modes may occur. Also, BWB concepts are expected to show coupling between longitudinal and lateral dynamics. This and significant parameter dependency of the aircraft dynamics pose significant design challenges for developing robust and well-performing flight control laws. Traditional methods for flight control design typically use nested SISO control loops and strongly structured control architectures (6). These methods are based on detailed aircraft system analysis and exploit paths with weak coupling to obtain good results for conventional flight control design. However, multivariate methods, such as optimal control and particularly robust control design methods are state of the art for more complex flight control tasks under coupled and/or uncertain system dynamics. Two large groups of control design methodologies are optimal control design methods (e.g., LQG control and the Kalman estimator (4), (3)), as well as robust control design methods (see (8) and (5) for fundamentals, or (2) for an aerospace-specific overview). This work reports first findings from ongoing research connected to the control design for a large BWB passenger aircraft.

Two different approaches to lateral MIMO feedback Control Augmentation System (CAS) for NACRE BWB aircraft are presented in the following. They are namely a robust MIMO H_2/H_∞ mixed sensitivity controller and a low-order robust MIMO H_∞ optimal controller designed by direct fixed-order control design techniques. All controllers are designed to assure for desired closed-loop rigid-body response (namely rise time and no-overshoot behavior to the reference change of the bank angle set point, attenuation of beta disturbance, and required damping ratio of the DR mode) and to damp first two antisymmetric wings flexible modes. Performance and robustness of all controllers is demonstrated by means of MATLAB/Simulink simulations, and their advantages and drawbacks are discussed to arrive at conclusions. More details about BWB aircraft control issues can by found in (9), (10), (11), (12) and (13).

2. BLENDED WING BODY AIRCRAFT

ACFA 2020 is a collaborative research project funded by the European Commission under the seventh research framework programme (FP7). The project deals with innovative active control concepts for ultra efficient 2020 aircraft configurations like the blended wing body (BWB) aircraft (see Fig. 1 and 2). The Advisory Council for Aeronautics Research in Europe (ACARE) formulated the "ACARE vision 2020", which aims for 50% reduced fuel consumption and related CO_2 emissions per passenger-kilometre and reduction of external noise. To meet these goals is very important to minimize the environmental impact of air traffic but also of vital interest for the aircraft industry to enable future growth. Blended Wing Body type aircraft configurations are seen as the most promising future concept to fulfill the ACARE vision 2020 goals because aircraft efficiency can be dramatically increased through minimization of the wetted area and reducing of structural load and vibration by active damping in a integrated control law design (addopted from (1)).

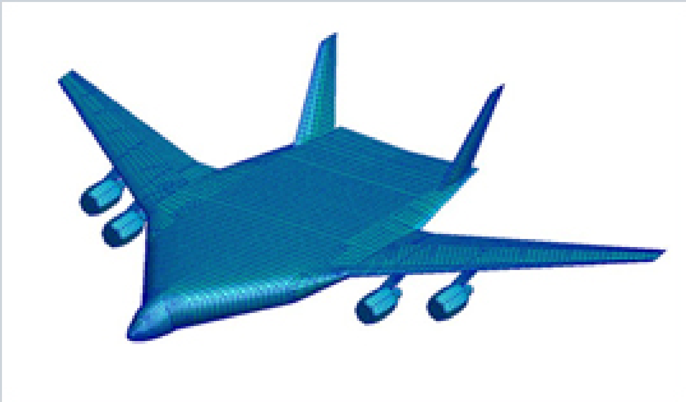

Fig. 1. BWB FEM structure.

Fig. 2. BWB visualization.

3. BLENDED WING BODY AIRCRAFT MATHEMATICAL MODEL

Mathematical model of BWB aircraft used for control law design consist of aircraft model itself, model of actuators and sensors. Actuators models are considered as 2^{nd} order linear models augmented by saturations and rate limiters. Sensors are modeled as 2^{nd} order Butterworth filters with time delays approximated by 2^{nd} order Padde approximation. Mathematical model of aircraft consist of rigid body description (modeled as a 12^{th} order linear system separated to longitudinal and lateral dynamics), flexible modes (for design purposes just four modes are considered, with rise to 8^{th} order linear model) and lag states. Overall model used for control law design is of order 52.

4. H2/H_∞ MIXED SENSITIVITY CONTROLLER

A two-stage control law is devised - separate control augmentation system (CAS) taking care of the flight-dynamics (robust H_2 optimal roll autopilot, with roll-off at higher frequencies), and an active damper for selected flexible modes (H_∞ optimal mixed-sensitivity controller tuned to first two antisymmetric wing bending modes). Such an arrangement has obvious advantages - regarding tuning (both parts are designed/tuned independently), future flight testing (the active damper can be tested after the roll autopilot is implemented and approved, and it can be turned on/off at any time while keeping the aircraft well controlled), safety (loss of the damper's functionality, e.g. due to sensors failure, does not take the airplane out of control). The drawback is potential reduction of performance compared to a fully integrated design where both flight dynamics and vibrational issues are handled by a single large multiple input multiple output (MIMO) controller.

4.1 design method

The lateral CAS (roll autopilot) is designed by H_2 norm minimization of the generalized plant, encompassing the lateral rigid body dynamics itself (4 states/outputs), 2 integrators (to assure for perfect steady-state tracking of roll angle set point command and for perfect steady-state attenuation of beta disturbance), and two low-pass filters (for required roll-off at higher frequencies - so that the flexible modes are left untouched, not excited by the controller). As all the rigid body (RB) states are measured, the observer needs not be implemented in fact and the resulting order of this CAS can be kept quite small (six states). Resulting controller features robust stability/performance for all considered mass cases (3 passengers and 5 fuel cases).

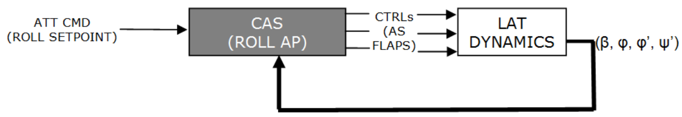

Fig. 3. Control augmentation system for H_2 controller design. Where control surfaces are considered as anti-symmetrically driven wings ailerons.

On top of that, a robust MIMO controller is built by minimization of the H_∞ norm of the frequency weighted mixed-sensitivity function. Wings modal antisymmetric sensor and antisymmetric flaps make up the input/output groups. Loosely speaking, the closed loop sensitivity function is kept small at selected frequency regions (in our case covering the wing antisymmetric modes) to assure for good performance (disturbance attenuation) while the complementary sensitivity function is kept small everywhere else (to assure for robustness - the design model becomes invalid outside the selected frequency region). A simple design model of 8th order was constructed (modeling accurately the two modes and close region in the I/O channels). Two resonant weighting filters of 2^{nd} order are tuned to the frequencies and dampings of the antisymmetric wing bending modes of a selected representative case for this purpose. Resulting H_∞ controller has 20 states.

Resulting damper (and also the overall CAS/damper combo) features robust stability for all mass cases, significant improvement regarding damping of structural vibrations for major part of mass cases (more than 5dB

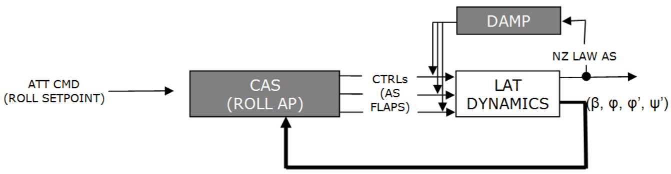

Fig. 4. Control augmentation system for H_2/H_∞ controller design. Where control surfaces are considered as anti-symmetrically driven wings ailerons.

attenuation), and no-effect on vibrations damping for the remaining cases. These findings, and the overall performance of the designed controller and its respective parts, are visualized in the Fig. 3 and Fig. 4.

4.2 H2/H_∞ control results

Brief assessment of the controller performance is given in the text above (regarding robustness and performance). A set of selected characteristics is now given to document those findings.

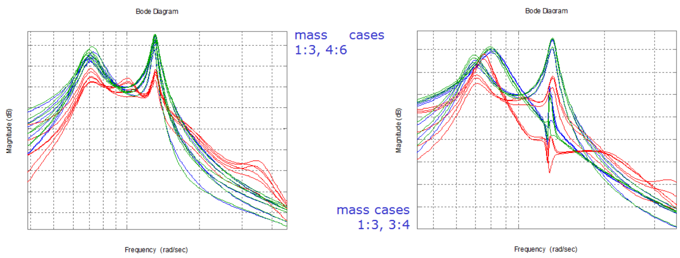

Fig. 5. Wing bending mode. Open loop (green), H_2 control (blue) and H_2/H_∞ control (red). All axis values are omitted from confidential reasons.

Note that very good performance is achieved for those cases that do not vary much in the frequency of the targeted modes (Fig. 5 left). However, even for the other cases (Fig. 5 right), some performance improvement is achieved, and robust closed loop stability is assured.

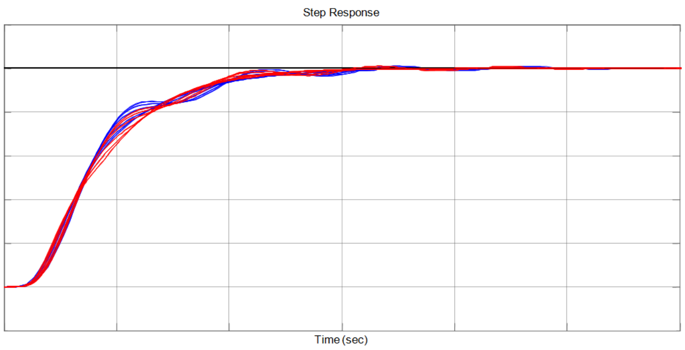

Fig. 6. Roll reference tracking. H2 control (blue) and H_2/H_∞ control (red).

Required response to a set point command is achieved. Note marginal improvement of the response when the damping system is connected (though it was not intended to influence the flight dynamics in fact). As stated above, the flight-dynamics part contains integrated yaw damper and beta compensator. Gain and phase margins for the complete designed controller have been evaluated. Robust closed loop stability for all mass cases is achieved. For simultaneous, independent, worst-case variations in the individual channels the gain margin ranges 1.9-3.7dB, phase margin 12-23 degrees, depending on the mass case (MATLAB/Robust Control Toolbox command *loopmargin*).

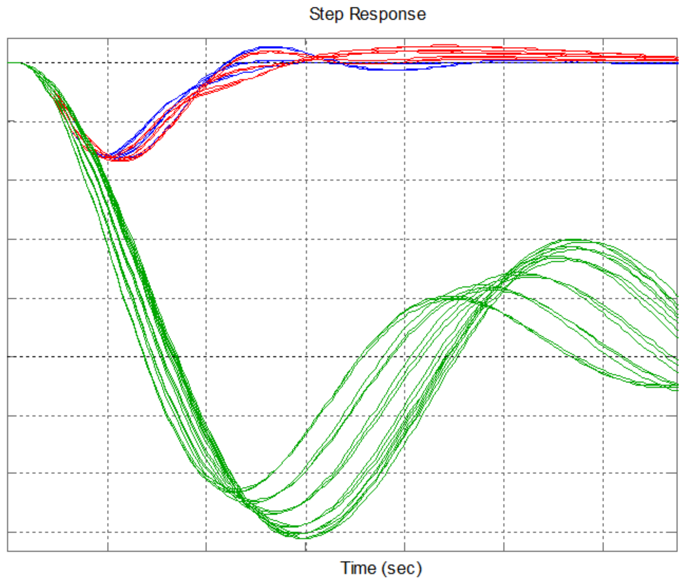

Fig. 7. Beta disturbance rejection. Open loop (green), H_2 control (blue) and H_2/H_∞ control (red).

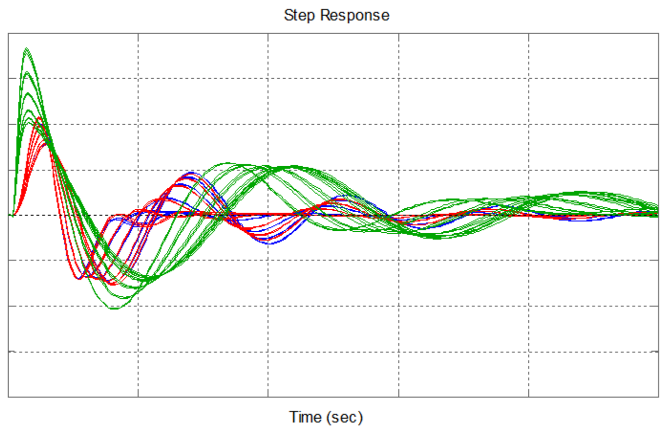

Fig. 8. Yaw rate damper. Open loop (green), H_2 control (blue) and H_2/H_∞ control (red).

5. FIXED ORDER H_∞ OPTIMAL MIMO ROBUST CONTROLLER

An integrated H_∞ optimal approach was used to design Lateral Control Augmentation System (CAS) for NACRE airliner. Similarly as in previous section two different control goals were aimed, but this time in one integrated version. One part of control law is to provide autopilot functionality. The autopilot consists of Stability Augmentation System (Dutch roll damper) and CAS (roll and beta angle reference signal tracking). Other part of control law takes care of vibration and load attenuation.

5.1 Design method

In order to directly obtain a robust feedback controller of pre-specified order, the H_∞ Fixed-Order Optimization (HIFOO) toolbox is used, outlined in detail in (7). The HIFOO control design method searches for locally optimal solutions of a non-smooth optimization problem that is built to incorporate minimization objectives and constraints for multiple plants. First, the controller order is fixed at the outset, allowing for low-order controller design. Second, no Lyapunov or lifting variables are introduced to deal with the conflicting specifications. The resulting optimization problem is formulated on the controller coefficients only, resulting in a typically small-dimensional non-smooth non-convex optimization problem that does not require the solution of large convex sub-problems, relieving the computational burden typical for Lyapunov LMI techniques. Because finding the global minimum of this optimization problem may be hard, an algorithm that searches only for local minimization is used. While no guarantee can be given on the result quality of this algorithm, in practice it is often possible to determine a satisfying controller efficiently.

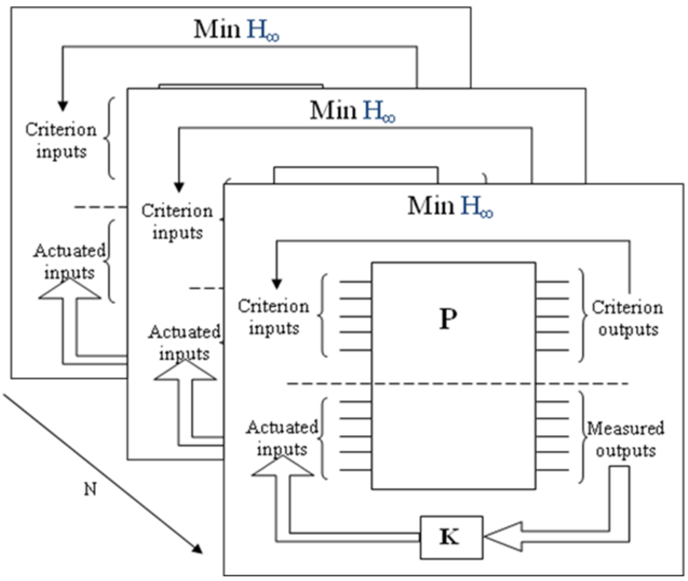

Fig. 9. H_∞ fixed order optimization setup.

The lateral integrated CAS was designed as a 2DoF architecture using fixed order optimization approach to keep control law order low. The resulting extremely low order (in this case 3^{rd} order control law was used) controller was built using HiFOO toolbox. Overall lateral CAS consist of Rigid Body autopilot (roll and beta tracker with Dutch roll damper) and structural modes control. The lateral CAS set up can be seen from Fig. 10. Two reference signals are used as inputs into feedforward part of controller (roll and beta set points). The beta reference signal is usually set to zero and then CAS provides coordinated turn functionality.

Control surfaces used by CAS are all ailerons (antisymmetricaly actuated FL1 - FL3), rudders (RU) and elevators (symmetrically actuated EL). Measured signals are lateral RB variables at CG (beta angle, roll angle, roll rate and yaw rate), for structural modes control we have selected

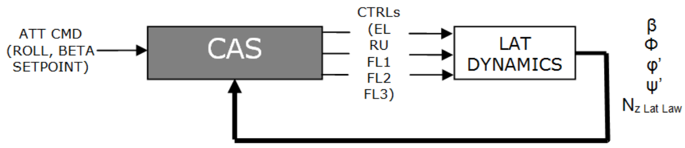

Fig. 10. Control augmentation system for HiFOO.

lateral wing acceleration modal sensor in antisymmetrical setup. Resulting control law (autopilot and structural modes controller) provides robust stability as well as robust performance for all 18 cruse conditions cases (6 fuel and 3 passenger cases).

5.2 HiFoo control results

Improvement of damping of 1^{st} and 2^{nd} wing bending modes can be seen form Fig. 11. Simultaneously DC gain is preserve for all cases. Robust performance property can be seen form Bank angle reference signal tracking response plotted in Fig. 12 (left). Response for series of two steps is involved here and one can see that handling qualities are satisfied with suitable amount of overshot.

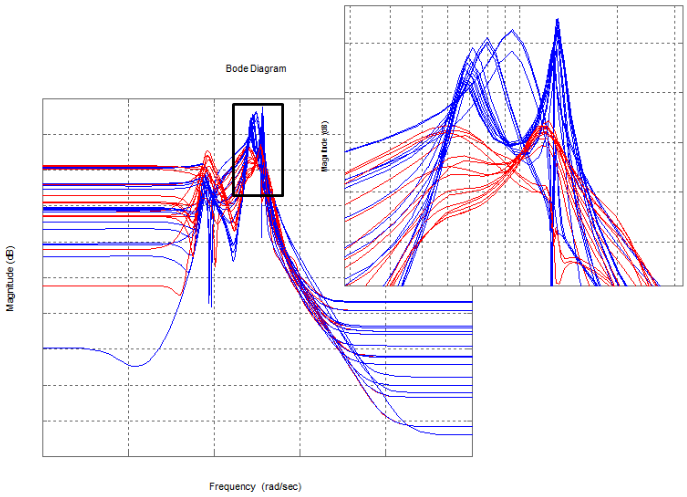

Fig. 11. Wing bending mode. Open loop (blue), closed loop (red).

Property of beta disturbance attenuation is investigated in Fig. 13 (left). One can seen complete vanishing of side wing influence in few second and without inducing of oscillation for major part of cases. Dutch roll mode damping is investigate in Fig. 13 (right).

Gain and phase margins for the complete designed controller have been evaluated. Robust closed loop stability for all mass cases is achieved. For simultaneous, independent, worst-case variations in the individual channels the gain margin ranges 0.8-2.6dB, phase margin 5-16 degrees, depending on the mass case (MATLAB/Robust Control Toolbox command *loopmargin*).

6. CONCLUSIONS

Two efficient approaches to lateral control for the prospective BWB concept of large passenger aircraft are elaborated and assessed in this paper. First, a hierarchical

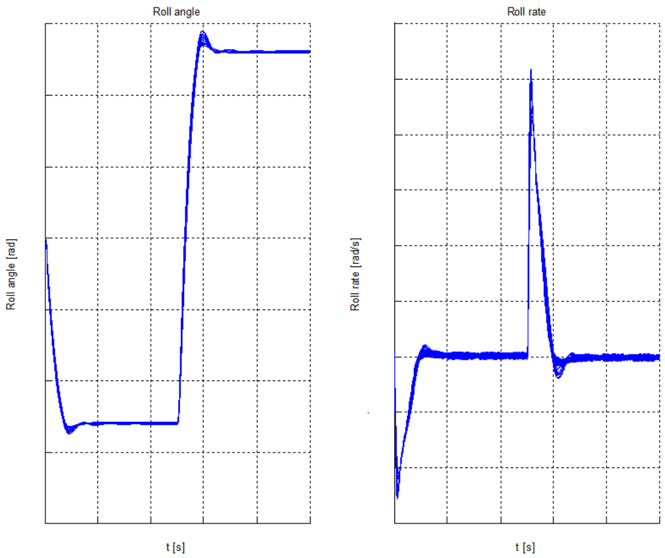

Fig. 12. Bank angle and Roll rate reference signal tracking.

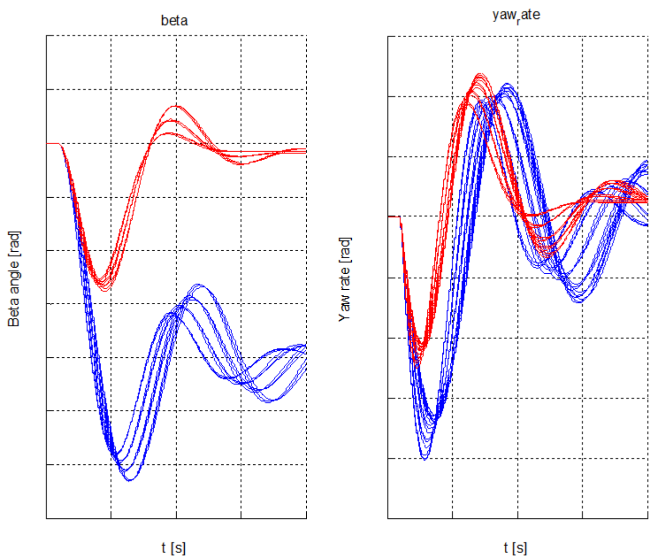

Fig. 13. Beta angle disturbance attenuation (left) and Yaw rate damping (right). Open loop (blue), closed loop (red)

approach is considered with separately designed control augmentation system (lateral autopilot with integrated beta-compensator and yaw damper) and the active damping system for structural vibrations on top of that. Main advantages of this approach are due to safety (the non-critical part - active damper - does not de-stabilize the plant if disengaged, e.g. due to a failure), easier process of tuning and certification (step-by-step), and the results look very good in fact. On the other hand, this approach is conservative by its nature and does not exploit fully the potential of active control as a true MIMO overall controller could do. Therefore, the second approach also presented in the paper is a fully integrated H_∞ optimal control law of low order designed by fixed order optimization. Performance of both control strategies is assessed, and the integrated design indeed features better closed loop characteristics in terms of robustness (more mass cases covered), rise times, or Dutch-roll damping.

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