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Pokročilé systémy řízení pro flexibilní velkokapacitní dopravní letoun typu BWB

Advanced control algorithms for flexible high-capacity passenger BWB aircraft

Summary

The BWB concept (blended-wing-body) appears as highly promising in the area of high capacity airliners of near future. Without a distinct boarder between the fuselage and wings, the aircraft construction presents a compact lifting body with significantly increased lift-to-drag ratio, with obvious environmental and economic consequences. The lightweight BWB structure shall suffer however from reduced stiffness compared to the classical boxed-wing concept, which is a challenge for feedback active damping and gust load attenuation systems exposed and detailed in this lecture.

Souhrn

Koncept BWB (blended-wing-body) se jeví jako velice slibná cesta pro vývoj dopravních velkokapacitních letadel blízké budoucnosti. Díky optimalizované konstrukci letounu coby kompaktního vztlakového tělesa bez tradičního dělení na křídlo a trup lze dosáhnout výrazně lepšího poměru vztlak-odpor, výrazné redukce strukturální hmotnosti díky absenci centroplánu a většího vnitřního prostoru pro větší kapacitu a delší dolet. Negativem se tak jeví pouze nižší tuhost tohoto řešení, kterou lze ovšem zvýšit systémy aktivního tlumení. Přednáška se zabývá souvisejícími novými algoritmy přímovazebního i zpětnovazebního řízení.

Klíčová slova: aktivní tlumení; systémy řízení letu; robustní řízení

Keywords: active damping; flight control systems; robust control

Contents

1. Introduction

For near future high capacity airliners, the BWB concept (blended-wing-body) appears as highly promising. The aircraft mechanical configuration presents a compact lifting body with significantly increased lift-to-drag ratio, with obvious environmental (lower noise levels and emissions) and economic (lower fuel consumption, increase operational economy) consequences. The lightweight BWB structure shall suffer however from reduced stiffness compared to the classical boxed-wing concept, which is a challenge for feedback active damping and gust load attenuation systems exposed and detailed in this lecture.

The transport aircraft BWB research and design efforts can be traced back to the 1980's. A comprehensive documentation of US research effort on the design of BWB subsonic transport aircraft, corresponding design issues and constraints, advantages and drawbacks given by such configuration, as well as results from windtunnel tests are presented in [1]. Thereby, the research progress is demonstrated starting from a preliminary design study in 1988 for novel configurations up to the highly efficient Boeing BWB-450 baseline aircraft. Basically, three generations of BWB configurations are documented which were successively improved. Starting from the design requirements definition, the disciplines aerodynamics, structure, stability and control, propulsion, and performance are discussed. Thereby, the importance of the shape of the airfoil for the center body and the outer wings for longitudinal static stability as well as aerodynamic performance is clearly outlined. Moreover, the attainable benefits in structural loads are shown in comparison to conventional configurations. Additionally, the overall performance improvement in terms of fuel burn per seat mile is denoted as 27%.

A detailed aerodynamic analysis of a BWB configuration is considered in the European project MOB and relevant results are presented in [2]. Therein, starting from a baseline configuration, the effects of different spanwise loading distributions, sectional airfoil profile adaptation, local twist variation and three dimensional shaping are investigated and the effects on aerodynamic performance concerning lift to drag ratio are determined. A noticeable outcome from this study is that a triangular-elliptic spanwise lift distribution outperforms the elliptic distribution. At the same time it is important to find a trade-off between induced drag and wave drag for optimized aerodynamic performance.

The relevance of a multidisciplinary design optimization (MDO), including the active control principles and methodologies, is emphasized in order to maximize overall aircraft performance. The preliminary multi-disciplinary design optimization for a BWB configuration is the topic of [3]. In this work, a numerical design tool is presented which was adapted to the needs of this unconventional configuration in order to provide meaningful results. Various structural solutions for a 700 passenger BWB aircraft are obtained with special emphasis on the design disciplines geometry, aerodynamics, propulsion, flight mission requirements, structural sizing, and component mass. For load prediction, both maneuver loads as well as gust loads are evaluated at different aircraft mass and center of gravity positions. Finally, the effectiveness of the design tool is demonstrated based on the design of three BWB configurations, where the same design requirements were assumed, however, the number of ribs in the fuselage differs. A tool for the generation of a nonlinear flight mechanics model of a BWB configuration within the MDO process is presented in [4]. The aim of this tool is to evaluate the rigid body dynamical behavior of the aircraft as well as the effectiveness of various control surface locations in an early design phase. While in this work only a rigid body aircraft model is considered, the necessity for a more complex, coupled aeroelastic model is discussed.

In this lecture, three novel research results are presented. First, a new approach to optimal placement of sensors (OSP) in mechanical structures is presented. In contrast to existing methods, the presented procedure enables a designer to seek for a trade-off between the presence of desirable modes in captured measurements, and the elimination of influence of those mode shapes that are not of interest in a given situation. An efficient numerical algorithm is presented, developed from an existing routine based on the Fischer information matrix analysis. We consider two requirements in the optimal sensor placement procedure. On top of the classical EFI approach, the sensors configuration should also minimize spillover of unwanted higher modes. We use the information approach to OSP, based on the effective independent method (EFI), and modify the underlying criterion to meet both of our requirements - to maximize useful signals and minimize spillover of unwanted modes at the same time.

The results of sensor optimization are directly used further for robust feedback control. Advanced non-convex non-smooth optimization techniques for fixed-order H infinity robust control are proposed to design flight control systems (FCS) with prescribed structure. Compared to classical techniques - tuning of and successive closures of particular single-input single-output (SISO) loops like dampers, attitude stabilizers etc. - all loops are designed simultaneously by means of quite intuitive weighting filters selection. In contrast to standard optimization techniques, though (H2, H1 optimization), the resulting controller respects the prescribed structure in terms of engaged channels and orders (e.g. P, PI, PID controllers). In addition, robustness w.r.t. multi model uncertainty is also addressed which is of most importance for aerospace applications as well. Such a way, robust controllers for various Mach numbers, altitudes, or mass cases can be obtained directly, based only on particular mathematical models for respective combinations of the flight parameters.

Finally, a new feedforward gust load attenuation system is presented. Compared to previous attempts, the measured alpha (angle-of-attack) signal is considered as a trigger only to activate the aerodynamic surfaces, namely ailerons and spoilers, in order to reduce the wing cut forces and moments caused by the “1-cos” gust and related excitation of wing flexible modes. The convex synthesis approach was selected and gives rise to 20-50% reduction of the first peak (in the time domain), which is otherwise regarded as impossible by standard active damping feedback techniques.

All results are developed and verified on a high-fidelity linearized simulation model, with coupled flight mechanics part and aeroelastic modes, for a 450 airliner concept developed within the ACFA 2020 FP7 project (www.acfa2020.eu).

2. Optimal sensor placement

Optimal sensor placement (OSP) in mechanical systems and structures has become a popular and frequently discussed research topic during last ten years. Applications cover modeling, identification, fault detection, and active control of such systems as bridges [5], rail wagons [6], large space structures [7]. The goal is to tell the designers of the whole mechanical system where displacement, force, inertial acceleration, or other sensors are to be installed so that they are as informative as possible.

Various approaches have been developed. We will mention two in brief. The former, information based approach, is based on the analysis of the output shape matrix. An iterative elimination algorithm, denoted as EFI (for "Effective Independence") has been developed that repeatedly deletes the lines of the initial, full output shape matrix with lowest amount of information, measured by either the trace or determinant of an underlying

Fischer information matrix. See [8] for a more detailed treatment and [5,7] for some case studies.

An alternative approach is based on the idea of maximizing the energy of the underlying modes in the optimally placed sensors. Related procedures lead to optimization problems over output Gramians of the system. Reference [9].

Both these approaches are applied on pre-selected modes of interest. For instance, in an active damping application for a transport vehicle, see a recent report [7], the bandwidth and thus implied modes are defined according to some comfort standards and considerations regarding impact of particular modes on the loads induced in the structure. Typically, a few lower modes are selected as a result of such analysis. Resulting optimal sensors selection is subsequently called, with only those pre-selected modes in mind. However, also those not-considered, typically mid- or high-frequency modes are still present in the process and, if excited by disturbances or the control action, they can influence the active damping system behavior in an unexpected manner. This phenomenon, denoted as spillover, cannot be captured directly by the two existing approaches mentioned above. Although some procedures have been developed in the past that address these issues, they are based on advanced signal processing (filtering) of the measured signals and do not suggest how to modify the sensors positions themselves accordingly.

And it is exactly the problem we focus on. The aforementioned information approach is taken as the starting point. The underlying criterion is modified so that the influence of desirable modes is maximized, and those unwanted modes are minimized in the observations at the same time. The result is a compromise where suitably chosen simple weights serve as a tuning knob for the designer. A related numerical procedure is then developed, based on the EFI approach. Two examples are presented in section where one can appreciate the intuitively expected placements and study the influence of tuning. Further, a case study related to a large flexible BWB aircraft and its active vibration control system is presented.

Results of the described algorithm for the BWB aircraft are presented below. The ability to distinguish between particular modes in measurement simply by optimization of appropriate sensor configuration is critical in this application due to presence of more flexible modes in a narrow frequency range of 0-10 Hz. We cannot therefore rely on signal processing (filtering), and we have to think of a smart sensors configuration instead.

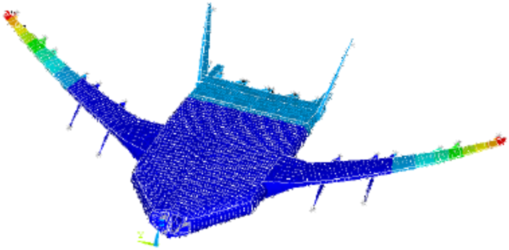


Figure 1: Shape of the 1st mode

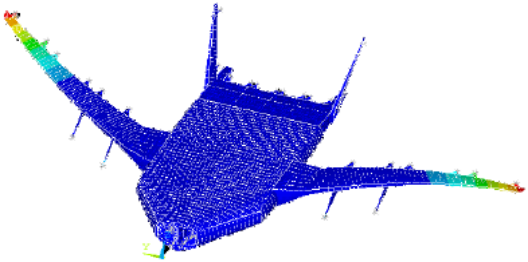


Figure 2: Shape of the 2nd mode

The most significant modes of the aircraft are first symmetrical and antisymmetrical wing bending modes (in frequency 1st and 2nd modes). Shape of the first and second aircraft mode modeled in ANSYS can be seen in the figures above. These modes are to be controlled and therefore we need to maximize information content of these modes in measurements.

The third and fourth modes on the contrary are to be rejected, see below for their respective shapes:

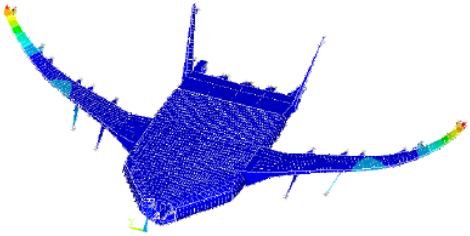


Figure 3: Shape of the 3rd mode

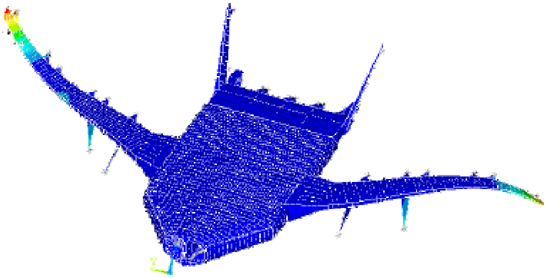


Figure 4: Shape of the 4th mode

The optimal sensor locations with respect to this problem formulation are depicted below.

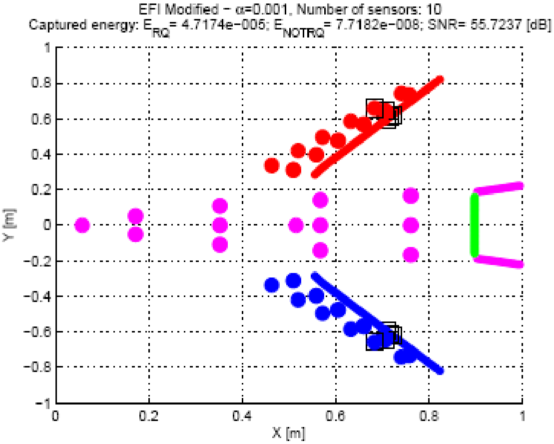


Figure 5: Optimal sensors locations

One can see that information content of required modes captured by this configuration of sensors is thousand times higher than information content of not-required modes (SNR is almost 56dB).

3. Fixed order robust controllers for BWB 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_{inf} mixed sensitivity controller and a low-order robust MIMO H_{inf} 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.

First, 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_{inf} 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.

The architecture of resulting controller is depicted in the figure below. Selected time-domain and frequency-domain characteristics then follow to demonstrate robustness (w.r.t. varying mass, CG position, altitude, airspeed and other parameters defining the flight envelope), and performance. Both the flight mechanics variables (attitude angles, angular rates, sideslip angle) and the flexible modes excitation indicators (accelerations at selected points) are inspected.

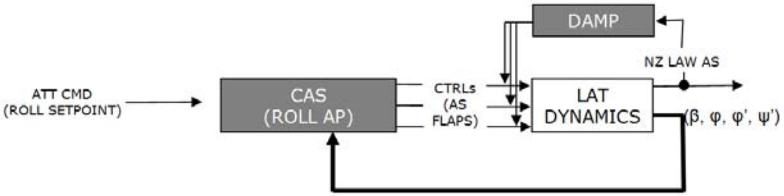


Figure 6: Control augmentation system design scheme. Anti-symmetrically actuated ailerons are considered as control surfaces.

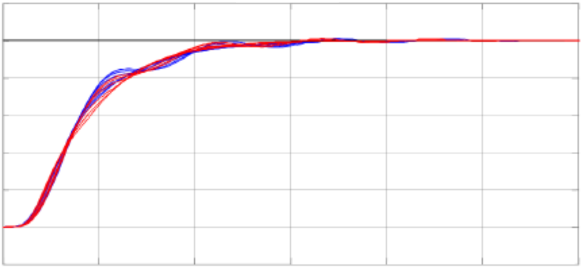


Figure 7: Bank angle setpoint response. With the damper circuit engaged (red) and disengaged (blue) respectively.

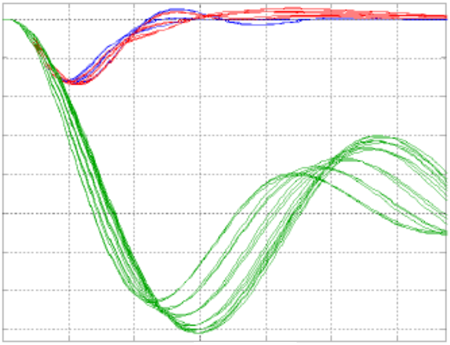


Figure 8: Sideslip angle setpoint response. With the damper circuit engaged (red) and disengaged(blue) respectively. Open loop response in green.

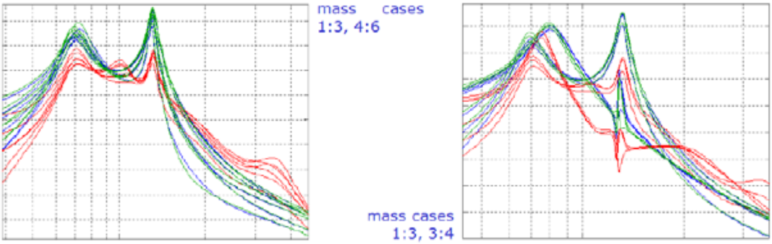


Figure 9: Wing bending mode damping improvement. Open loop (green), and controlled aircraft. Red – damper circuit switched on, blue – damper off.

As a modern alternative to this fairly traditional approach, an integrated design is presented next. Recent concepts of non-convex non-smooth optimization applied for the feedback design principles make it possible to design, at one shot, a MIMO control structure, of fixed low order (in spite of the fact that the design model degree is very high), minimizing a selected criterion (the closed loop Hinf norm in our case), and assuring robustness with respect to multimodels (that define selected flight envelope points dynamics). Among the solvers available, we went for the HIFOO package, co-developed by our distinguished colleagues Didier Henrion. The presented results are arguably the first serious flight control results on these modern design techniques.

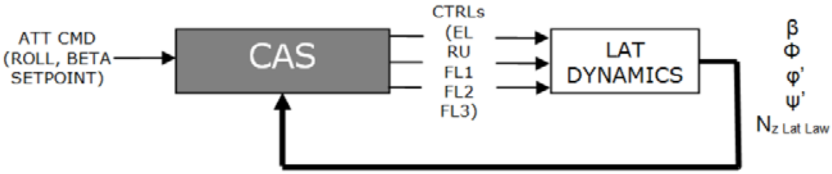


Figure 10: HIFOO control design setup.

Performance figures follow. One can appreciate nice transients in the observed variables (in time domain) as well as the increased damping of flexible modes. In this regard, the integrated design is indeed superior to the distributed structure presented above. As a matter of fact, the engaged controller is of order 5 (!) only.

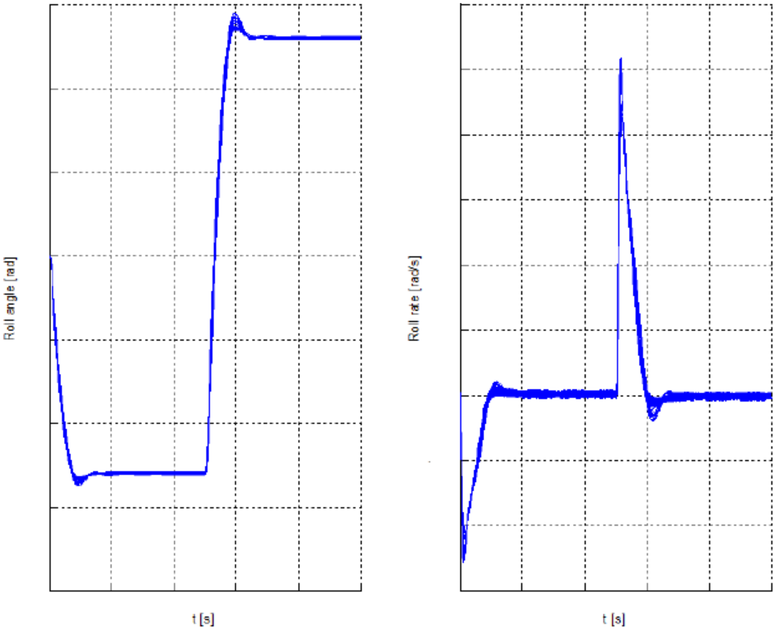


Figure 11: HIFOO – bank-angle and roll-rate setpoint responses.

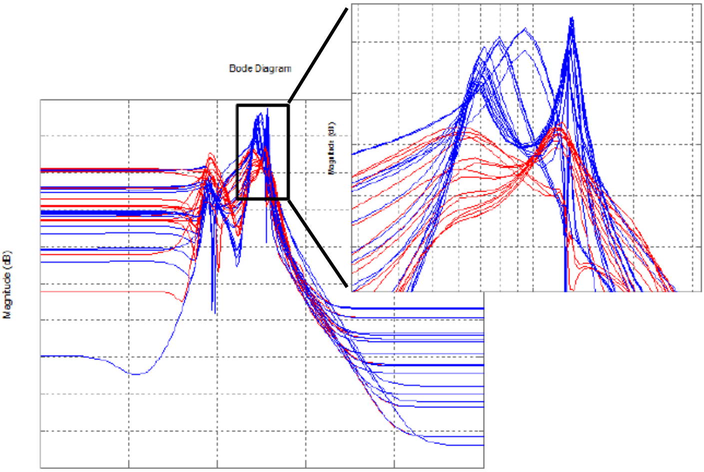
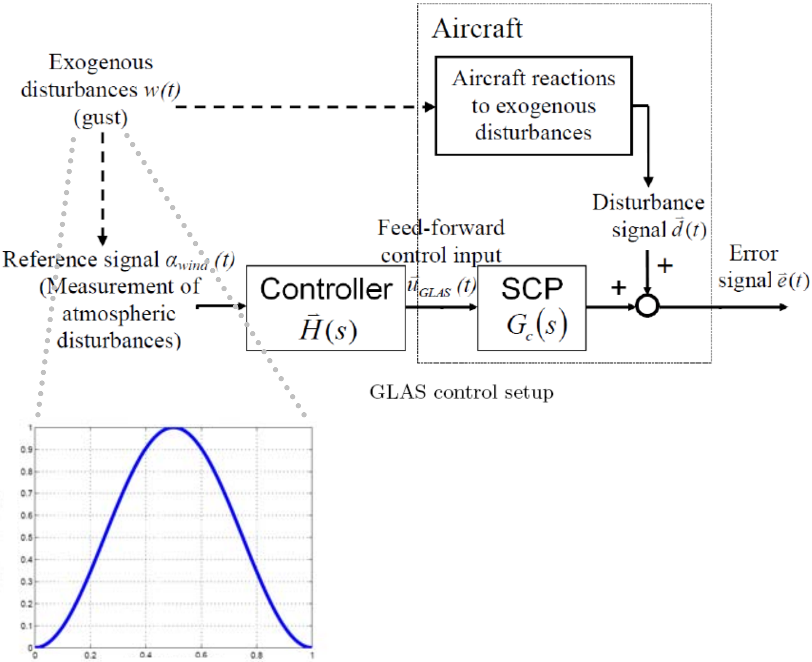


Figure 12: HiFOO – wing bending mode damping performance.
Open loop (blue) vs. controlled aircraft (red).

4. Gust load alleviation system

Next to the feedback control concepts, the feedforward ideas can be applied to achieve significant reduction of mechanical loads caused by flexibility of the airframe. One such case shall be presented now.

The Gust load alleviation system (GLAS) is based on triggered feedforward control system for attenuation of aircraft excitation by exogenous disturbance signal, in our case wind gust of „1-cos“ shape. Design of the wind gust detection system, the trigger, is not considered in detail here. It is assumed that it is possible to estimate upcoming wind gust and its direction with certain time delay needed for estimation. This signal is than the triggering signal used as a input for GLAS feed-forward controller H(s) and it is considered as a unit step signal. The GLAS H(s) can be realized as a finite response filter (FIR) shaping the input step command and producing the control signals.



GLAS control setup

The convex synthesis approach is charged to design feed-forward control system. This methodology described by [10][11] can easily address both time and frequency domain criterion and constraints. Nice overview and aircraft control system designed by convex synthesis was done in [12].

Performance graphs follow. What is of special concern is the 1st peak's reduction in wing cut forces / moments, which is regarded as non-achievable by purely feedback solutions. As the first peak, for the long gusts, is the sizing one (induces maximum loads in the construction), potential weight savings can be realized if the GLAS system becomes approved as the critical flight control system functionality.

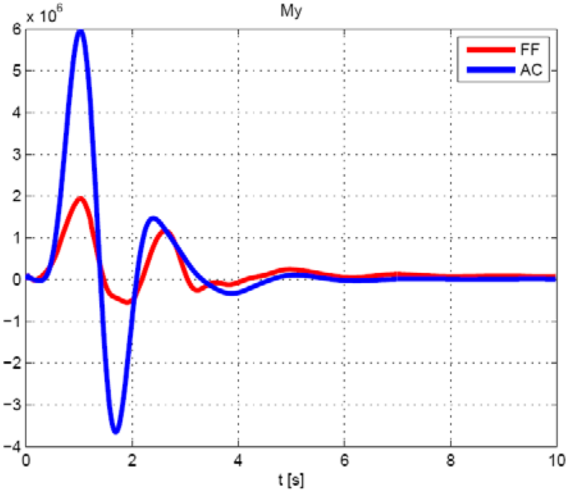


Figure 14: GLAS – torsional moment reduction.
Free (blue) vs. controlled aircraft.

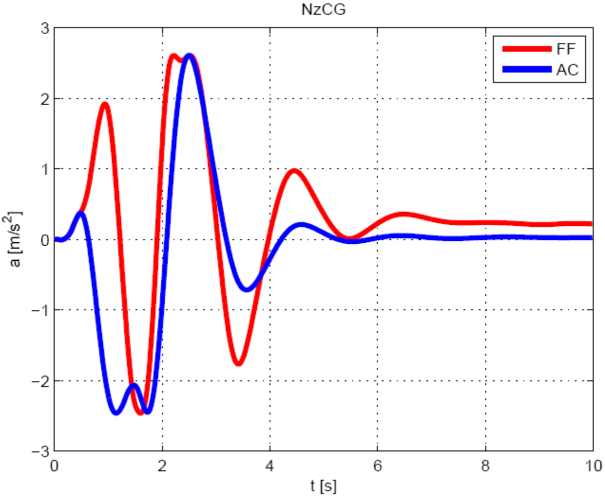


Figure 15: GLAS – vertical acceleration. Free (blue) vs. controlled aircraft.

5. Conclusions

Selected recent results related to design of the control laws for a blended-wing-body airliner concept have been presented. They cover various aspects of the overall design process that need to be considered in order to arrive at a working and reliable flight control system (FCS) architecture.

Prior to any control design attempts, the selection and location of sensors and actuators must be carefully considered. In case it is done improperly, no control laws will work well, no matter how sophisticated and advanced they are. In this field, our contribution lies in modification of an existing method, the EFI heuristic, as develped in section 2, so that the parasitic modes are explicitly eliminated by a smart sensors placement, and the spillover risk is reduced.

Feedback control loops are essential parts of the FCS. They are traditionally implemented to improve the dynamical properties of the aircraft (dampers, stabilizers), or enable automatic regimes (autopilots). For flexible aircraft, they are supposed in addition to suppress the vibrational modes of the airframe in order to reduce mechanical loads and fatigue and to increase passengers' comfort. We presented in section 3 two approaches leading to practically implementable controlled-complexity controllers, namely a distributed controller, and a fixed-order completely integrated MIMO design.

The feedback is essentially inevitable due to its ability to attenuate unmeasurable disturbances and cope with system's uncertainties. However, in the (rare) case the disturbance can be directly measured, the feedforward solution brings substantial benefits. There is no need to wait till the disturbance takes effect on the system so that it can be measured and compensated by the feedback controller; instead, the feedforward controller is informed in advance to avoid the disturbance from exciting the system by taking an instant compensating control action. These ideas are developed for the GLAS system (gust-load alleviation system) in section 4.

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Martin Hromčík, born on May 3, 1975 in Ledeč nad Sázavou, received the M.S. degree in technical cybernetics and Ph.D. degree in control engineering from Faculty of Electrical Engineering, Czech Technical University in Prague, in 1999 and 2005, respectively. The title of the doctoral thesis was "Advanced algorithms for polynomial factorizations".

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Teaching experience

At the Department of Control Engineering he lectures the courses on "Flight control systems" and "Automatic control", for the local Czech students as well as the international students of the SpaceMaster and Erasmus programs. He has been the supervisor or supervisor-specialist of three graduated Ph.D. students, is a supervisor of one finishing Ph.D. student (with thesis submitted), and has been a supervisor of more than 20 bachelor and diploma theses.

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