ACFA 2020 Summary of Achievements

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1. Introduction

Blended wing body type aircraft are promising high fuel efficiency due to a smaller wetted area compared to classical tube/wing configuration and also due to a lower structural weight. The BWB configuration also offers a great potential for the minimization of noise signature through integration of the engine over the rear fuselage or in the airframe and also due to the generally higher wing area/weight ratio, which allows for a simplified high-lift system. The structural weight can be further minimized thanks to implementation of active loads control developed in ACFA 2020. Active control is also applied to improve the ride comfort by minimising the structural response to turbulence and of course has to provide appropriate handling qualities. Due to the unconventional placement of control surfaces, BWB type aircrafts require new design methods and architectures in particular for active loads and vibration control. Moreover new promising active control concepts such as adaptive feed-forward control and neural network control are investigated in ACFA 2020. The adaptive feed-forward control concept to control turbulence induced structural vibrations has been even validated by flight tests on the DLR ATTAS experimental aircraft. The control concepts are applied to two aircraft models. In a first step a large flying wing aircraft for 750 passengers designed in the VELA and NACRE project [21] is used. For that purpose an aero-elastic model has been generated based on the geometry and structural design as performed in the NACRE project. Main application case is a newly designed ultra-efficient 450 passenger aircraft. For this 450 passenger aircraft a pre-design for a flying wing and an ultra-wide body fuselage aircraft with carry-through wing box have been performed and both designs have been compared in particular with respect to fuel efficiency. Due to the significant better fuel efficiency, the Blended Wing Body design has been retained for the further work in the project. In the final phase of the project the structure of this new 450 passenger aircraft has been resized taking into account the attained loads reduction by active control. This led to further weight saving and improvement of fuel efficiency. More detailed technical results can be found in the references [7] to [20] and the papers belonging to the special sessions dedicated to ACFA 2020 of the EUCASS 2011 conference [22] to [31]. This report is partly based on [32].

2. ACFA 2020 Workplan and partnership

As outlined in Figure 1 the main drivers for the ACFA 2020 project were defined by the ACARE vision 2020, which targets for a strong reduction of the fuel consumption and noise emissions of aircraft. In the meantime ACARE presented the new “Flightpath 2050” as updated Europe’s Vision for Aviation with even more challenging targets for fuel efficiency and reduced noise emissions until 2050. CO_2 emissions should go down by 75% and perceived noise emissions should be reduced by 65% compared to a typical new aircraft in year 2000.

ACFA 2020 is focussed on two major challenges. First of all, European research on highly efficient aircraft configurations in the projects VELA and NACRE [21] was concentrated on very large aircrafts for more than 700 passengers but the biggest market share in long haul flights is taken by smaller mid-size aircraft. Therefore ACFA 2020 deals with the design of an ultra-efficient mid-size aircraft. Hereby, a blended wing body configuration (BWB) has been compared to a more conventional aircraft with ultra wide body and carry through wing box (CWB). The second and major challenge addressed in ACFA 2020 is the complex flight control and structural control system required for such aircraft configurations.

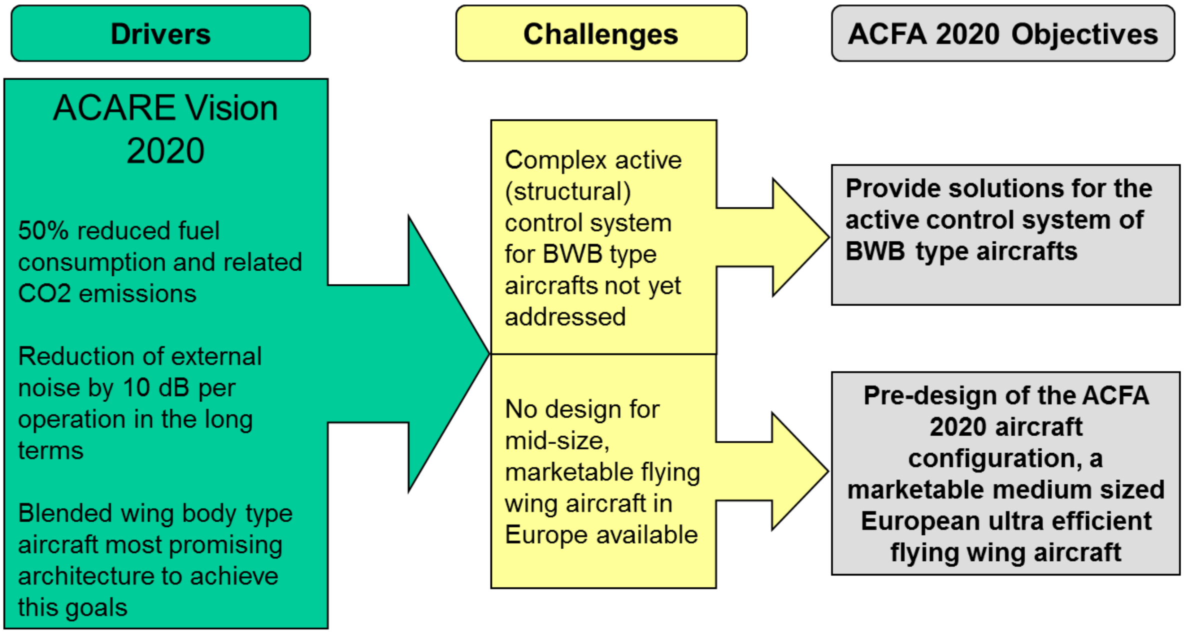


Figure 1: Main Drivers and Goals for ACFA 2020

As shown in Figure 2 the work is organised in 4 technical subsequent work packages. An additional work package WP0 is dedicated to the management of the project and the dissemination as well as exploitation of results.

The core of the ACFA 2020 project is work package 3 “Development & Evaluation of active control concepts”, where active control systems for BWB type aircraft are designed by a community of partners. The main objective of the designed control systems is to reduce structural vibrations and unwanted rigid body motions on the one hand, and gust and manoeuvre loads on the other. The reduced static and dynamic loads are the basis for a structural resizing performed in work package 4 of the ACFA 2020 aircraft configuration which is designed in work package 1.

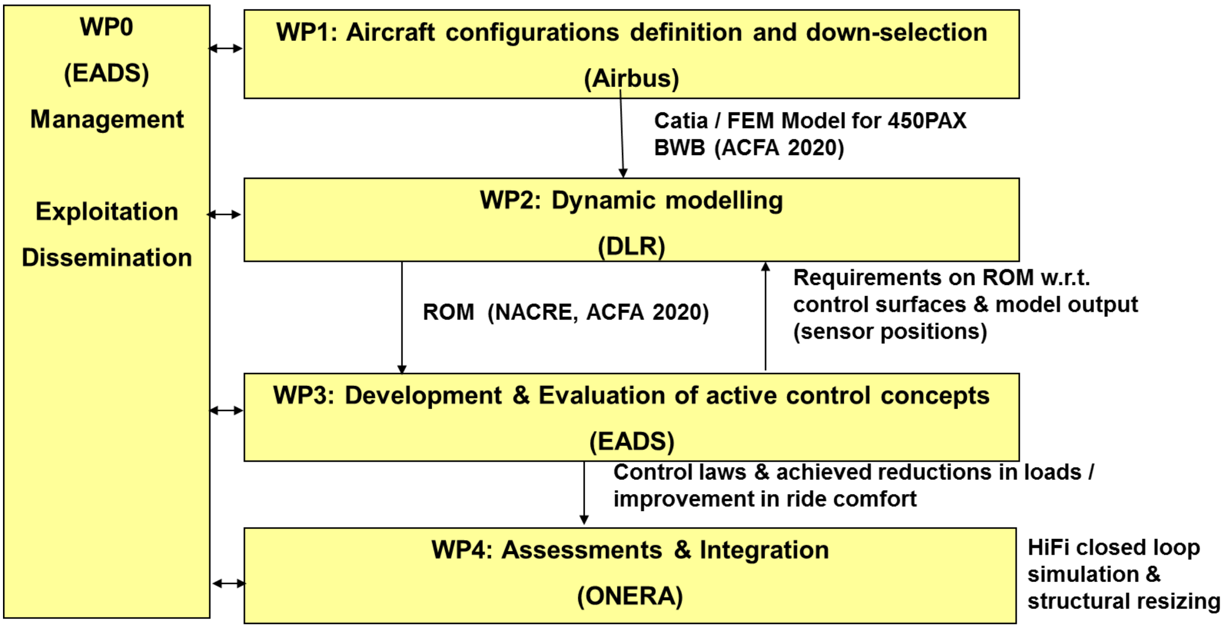


Figure 2: ACFA 2020 Work-package structure

Work package 2 deals with the generation of dynamic aircraft models which are required for the control design task. In order to be able to start with the investigations on control design as early as possible in the project in a first step models of the NACRE flying wing aircraft were created and after that in a second phase dynamic models of the ACFA 2020 have been generated. In both cases the aeroelastic models are linearised, parameterised and reduced to a reasonable order for the control design task. To be able to apply modern robust control design techniques the parameterised reduced order models (ROM) are transformed by DLR to linear fractional transformation (LFT) models to cover the uncertainties. The control design work in work package 3 is focussed on the application of modern robust control design techniques as well as adaptive control. Major goal of the work package 3 is to compare the different control concepts providing the required handling qualities with respect to complexity, robustness and by evaluating the best achievable reductions in loads and improvements in ride comfort. Finally in work package 4 the results are validated to some extent by performing higher fidelity simulations. Furthermore a structural resizing is performed based on the achieved loads alleviation.

The project consortium comprises 13 partners from 9 countries who are listed with their major activities and acronyms used within this paper in the following:

- EADS Innovation Works (EADS), project coordinator, lead and technical contributions in WP3

- Airbus Operations (AIRBUS), lead of WP 1
- Alenia Aeronautica S.p.A. (ALENIA), flutter analysis and structural modelling(WP2 and WP4)
- HELLENIC AEROSPACE INDUSTRY S.A. (HAI), aerodynamics (WP2 and WP4)
- Israel Aerospace Industries (IAI), adaptive, neural network control (WP3)
- Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), lead of WP2, technical contributions to all WPs
- Office National d'Etudes et Recherches Aérospatiales (ONERA), lead of workpackage 4, technical contributions to all WPs
- Swedish Defence Research Agency (FOI) , aerodynamics and HiFi simulations, task leader (WP2 and WP4)
- Technical University Munich (TUM), conceptual aircraft design (Institute for Aerospace Systems), dynamic modelling, structural sizing, task lead in WP2 and WP3 (Institute of Lightweight Structures and unsteady aerodynamics (Institute of Aerodynamics and Fluid Mechanics)
- Vienna University of Technology (TUV), Robust control design techniques, task lead in WP3
- Czech Technical University (CTU), Dynamic modelling (Order reduction, comfort modelling - Faculty of Mechanical Engineering) and robust control design (Institute of Information Theory and Automation)
- National Technical University Athens (NTUA), Aerodynamics and HiFi simulation (WP2 and WP4)
- Bialystok Technical University (BTU), Stability and convergence analysis for adaptive feedforward control concept (WP3)

3. Major results

3.1 Aircraft design

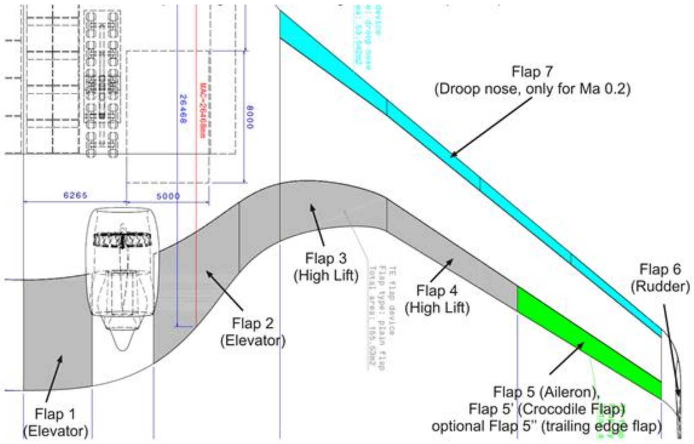
Conceptual designs for two configurations, a 450 passenger blended wing body (BWB) and an ultra-wide-body aircraft with carry through wingbox (CWB), were performed by Technical University of Munich and AIRBUS. Both aircrafts were designed for the same mission roughly defined by the following parameters:

Long Range Cruise Mach number: 0.85
Maximum range at Max Pax Payload: 7200nm
Approach speed should be < 150kt
Maximum operating Mach number MMO: 0.89
Maximum operating speed VMO: 340kts CAS
Max cruise altitude: 43100ft

The concurrent design was mainly done to compare the BWB configuration to a more conventional design in particular with respect to fuel efficiency. It turned out that the BWB aircraft shows about 13% better fuel efficiency compared to the CWB aircraft which is mainly due to lower weight of the BWB and better aerodynamic performance. Therefore the BWB configuration was retained for the further work on active control concepts..

Figure 3: ACFA 2020 aircraft configurations (BWB and CWB)

The final BWB configuration has a very blended shape between the centre body and the outer wing in order to get a smooth load & lift distribution along the blended wing span. A quite high sweep and aft position of the wing is important to make the aircraft stable. The BWB provides a lot of space underneath the cabin for the centre tank and so it can be efficiently used to trim the aircraft during cruise. However, this makes the fuel system safety critical because it must be operational to keep the aircraft centre of gravity within an acceptable range. More details about fuel management concepts can be found in [22].The longitudinal control is done by rear elevons located both on the centre body and on the wing (except aft of the engine pylons). The area dedicated to those movables is rather high in order to provide sufficient control authority. The lateral control is critical on this aircraft, especially in the one engine out case, and is achieved by split ailerons and rather high winglets equipped with a rudder. A detailed description of the design can be found in [22]. Figure 4 illustrates the main control surfaces available at the ACFA 2020 BWB.



Source: Technical University of Munich

Figure 4: ACFA 2020 BWB control surfaces

Two engines are located on the upper side of the centre body so it is expected to provide efficient shielding for the fan noise. Unfortunately in the frame of the ACFA 2020 project, it was not possible to assess the exterior noise benefit of this configuration vs. a classic aircraft of the same size but the noise benefit is revisited in the FP7 project OpenAir [6] which is dealing with novel noise reduction technologies.

However, a small study on interior noise comfort was performed with respect to turbulent boundary layer noise, which is the major noise source in cruise condition. Statistical energy analysis was applied for a portion of the cargo/cabin area, whereby some optimisation of the cabin treatment was performed. As shown in Figure 5 the BWB shows significant lower noise levels than the CWB and both aircrafts are quieter than a generic conventional single aisle aircraft configuration which was used as an additional reference. The mean overall sound pressure level of the BWB is about 3dB below the sound pressure level of the CWB configuration which is quite significant. The main reason behind is the large distance between the cabin and the outer skin which leads to a high transmission loss already at low frequencies. With respect to cabin noise one can conclude that the BWB configuration is quite favourable.

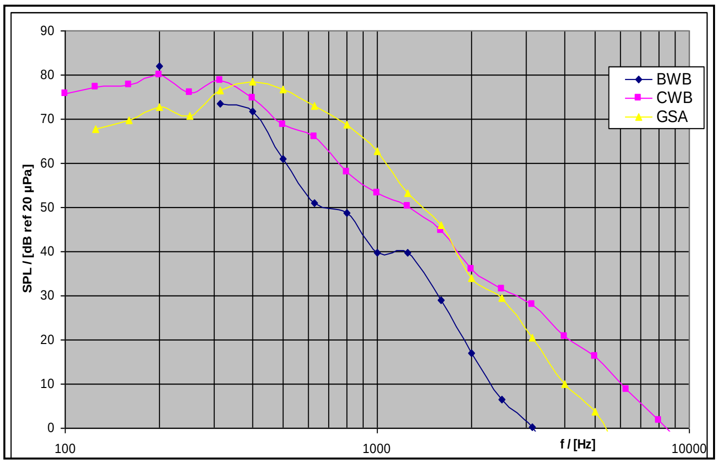
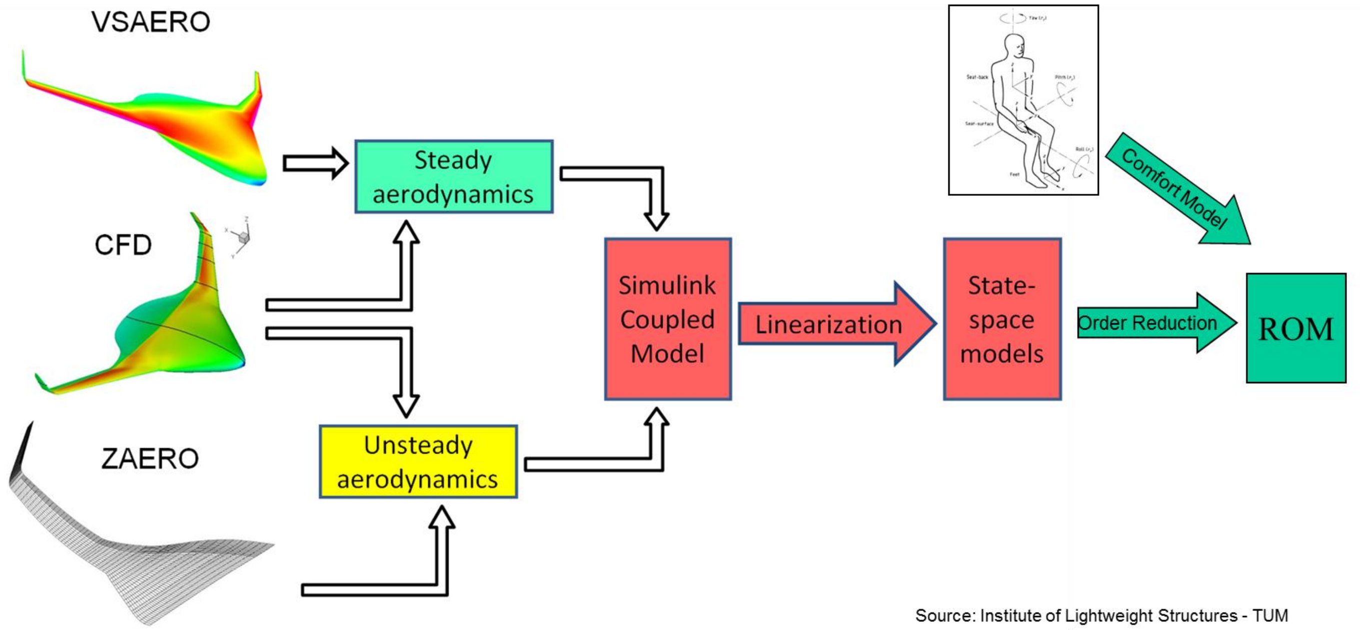


Figure 5: Comparison of interior noise levels for BWB, CWB and a conventional generic single aisle (GSA) aircraft

3.2 Dynamic modelling

The generation of aeroelastic parameterized reduced order models for the NACRE and ACFA 2020 BWB was a joint effort of numerous partners (DLR, FOI, ONERA, HAI, NTUA, TUM). In order to consider several fuel/payload cases, a set of structural models representing the various mass configurations were developed for both aircrafts. A structural model was provided by the NACRE consortium but was significantly refined to make it applicable for structural dynamics investigations. The steady and unsteady aerodynamics for the NACRE and the ACFA 2020 BWB have been calculated for a variety of flight conditions, i.e. Mach numbers, dynamic pressure, center of gravity positions and mass cases. In order to be able to use spoiler devices for the controller design, aerodynamic loads (lift, drag, pitching moment) were calculated by using an unsteady vertex blob code. The whole process and tool chain applied for the model generation is illustrated in Figure 6.



Source: Institute of Lightweight Structures - TUM

Figure 6: Model generation process

For the control system design low order models are used which comprises only 2-6 flexible modes and using simplified linear actuator and sensor models. By application of adequate order reduction methods (balanced truncation, singular perturbation approximation) it is assured that the input/output behavior is preserved in an optimal way. During the control design process higher order models comprising around 12 modes and also more detailed nonlinear actuator and sensor models are used to validate the robustness of the controller designs. Finally full order models (80 modes for the ACFA 2020 BWB) are used to evaluate the loads for the structural resizing.

Model inputs are the control surface deflections and engine thrust as well as gusts. For the modeling of the gust response a set of gust inputs have been considered whereby as inputs 2D von Karman turbulence models are used. By a Markovian representation of the vertical turbulence for a particular aircraft speed (TAS) at predefined locations ahead of the a/c and on the a/c signals are generated showing the theoretical spectra and cross spectra of 2D von Karman turbulence [3].

Model outputs are the rigid body motion, accelerations at preselected positions for vibration damping [10] as well as cut forces and moments (see Figure 7) for estimation of control performance and critical cases with respect to loads.

Regarding the comfort criteria CTU developed filters (e.g. sea sickness) delivering comfort outputs based on the states of the aeroelastic models [13].

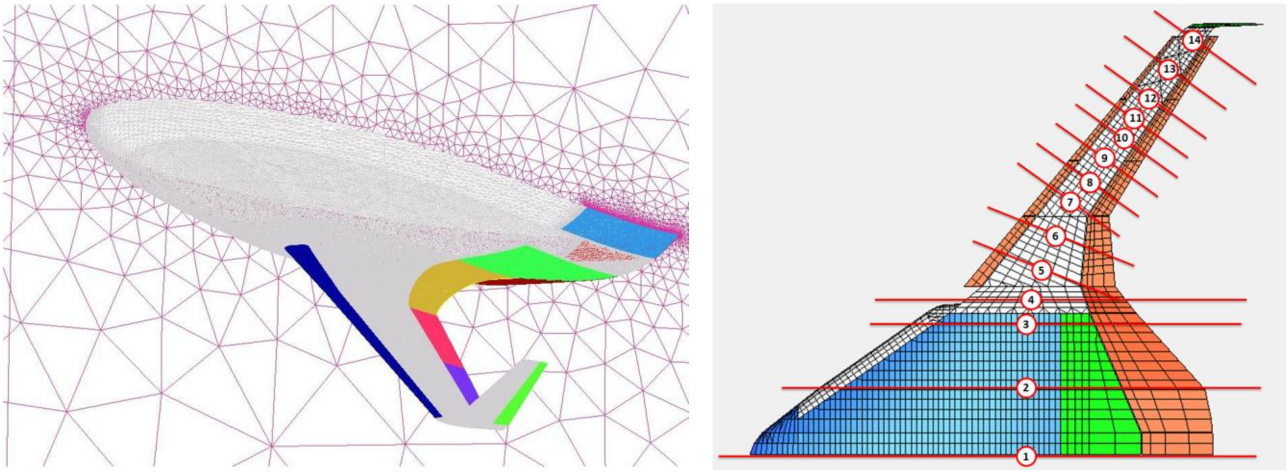


Figure 7: CFD mesh for the ACFA-BWB (FOI) and positions for cut forces and moments (TUM)

More details on the model generation process can be found in [24].

3.3. Control concepts

Control design for large flexible aircraft and in particular the BWB configuration is a quite challenging task due to numerous objectives and severe constraints which have to be taken simultaneously into account. Major goal of the ACFA 2020 project is to investigate and to combine various modern robust control and LPV design techniques as well as adaptive control concepts. As illustrated in Figure 8 basic feedback control is augmented by an additional feed-forward control path to alleviate the effect of turbulence and gusts. To achieve the desired handling qualities and to alleviate manoeuver loads also a feed-forward control path for pilot commands is used. Robust control concepts are investigated in particular by TUV and CTU. A large variety of design methods (H-infinity-, H2-optimal control design, H-infinity fixed-order optimization methods) and robust and scheduled extensions of these methods have been applied. Details can be found in [9], [11], [12], [14], [27], [29], [30]. Furthermore modern convex synthesis design techniques are investigated by ONERA [23]. An adaptive multiple input multiple output (MIMO) feed-forward control concept [20] is investigated by EADS Innovation Works to mitigate turbulence induced vibrations and related loads. To validate the real-time behaviour of the adaptation a flight test with the DLR Advanced Technologies Testing Aircraft (ATTAS) has been performed [8]. This aircraft is already equipped with sensors and actuators to flight test active feed-forward gust and vibration control concepts [2], [4]. A main result with control of engine pylon bending mode is shown in Figure 9. The power spectrum of the lateral engine acceleration is related to the spectrum of the nose boom alpha signal with and without control in order to get a performance measure which is independent from the excitation level. The alpha signal was the most suitable available reference for the turbulence strength. The signal power of the lateral engine acceleration was reduced by 40% by the converged feed-forward controller. This value is mainly determined by the correlation between the turbulence measurement with the alpha probe and the real excitation of the mode to be controlled. The adaptive feed-forward controller minimises the H_2-norm of the error signal, which is usually a modal sensor, i.e. an appropriate combination of accelerations measured at the structure to control. In principle the converged controller can be always active which provides robust performance of the feed-forward loop also in case of plant uncertainties or plant variations with time. Alternatively adaptation could be just used during flight testing and transformed into a fixed or scheduled controller for regular operation.

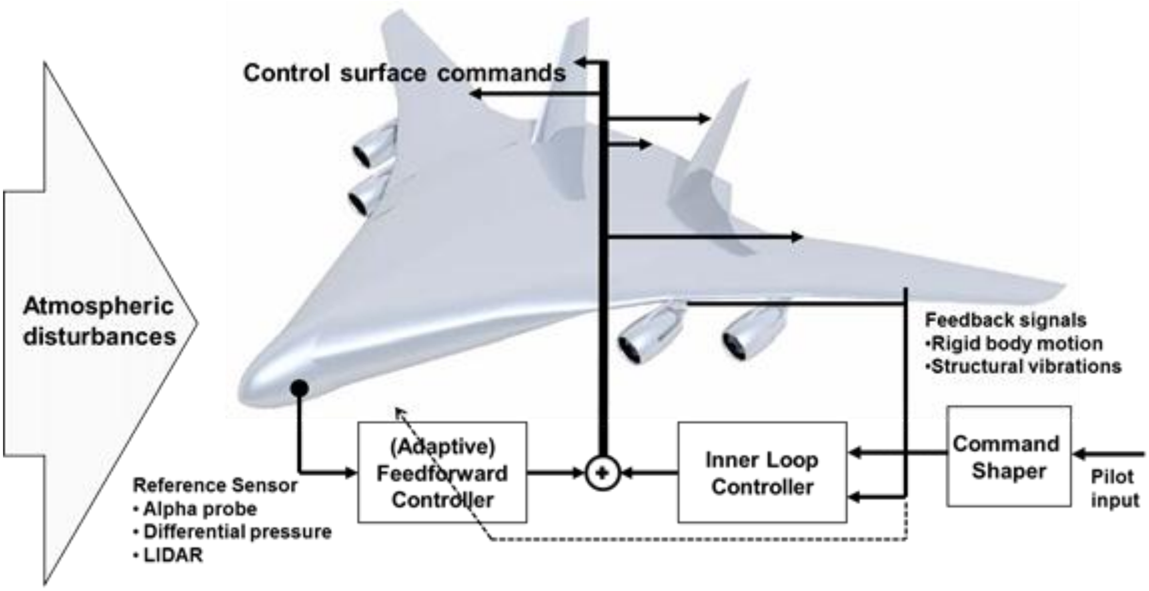


Figure 8: Basic outline of investigated control concepts

The adaptive feed-forward control concept has been also successfully applied to the NACRE BWB to control the 1st wing bending mode. This significantly improves the ride comfort but the effects on loads (wing root moments) were partially detrimental in particular for discrete gusts which are typically most important for the structural sizing. Therefore optimised, nonlinear feed-forward gust load alleviation concepts have been developed in addition. The basic concept and main results can be found in [8]. As illustrated in Figure 10 it can be very beneficial to add actively damping to the structure by feedback control and to combine this with a feed-forward gust load alleviation system deploying the spoilers when entering a gust. For the ACFA 2020 BWB an even more advanced gust loads alleviation system using optimisation techniques to determine the best sequence of control surface deployments has been developed. Details can be found in [31].

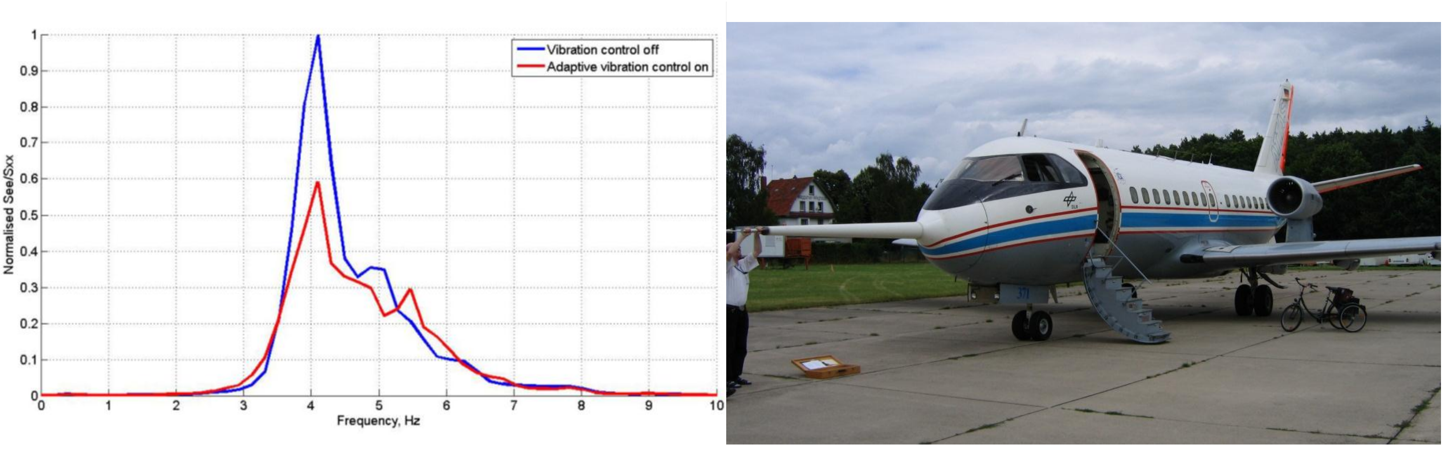


Figure 9: Vibration reduction for engine pylon mode with adaptive feed-forward control at ATTAS aircraft (right)

In addition adaptive feedback control has been successfully considered by IAI for the NACRE aircraft and is under evaluation for the ACFA 2020 BWB. A neural network controller is used to augment a classical controller, whereby the adaptive part is mainly directed to structural control.

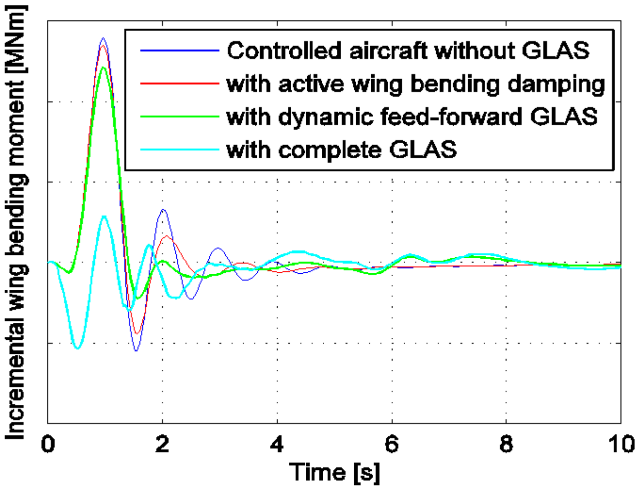


Figure 10: Example for the effect of gust load alleviation by combined feedback / feed-forward control for the NACRE aircraft

The comprehensive work on control design for the ACFA 2020 BWB has been presented in several papers at the EUCASS conference 2011. Robust and LPV control techniques ([26], [29], [30], Low complexity control system design 27] as well as adaptive Neural Network based control design have been investigated.

Each of the investigated control concepts delivered promising results with respect to the main goals and most of the methods are complementary. E.g., a feedforward gust load alleviation system was combined with an LPV controller designed [31].

It is important to mention that the flightmechanics of the ACFA 2020 BWB is quite challenging mainly due to two facts:

- Actuator dynamics was chosen rather slow; e.g. elevator bandwidth is 0.5Hz due to the large size and weight of this control surface

- The aerodynamics of the ACFA 2020 BWB is in a predesign stage. In the transonic region strong non-linear effects are present due to a complex shock system which results in strong fluctuations also in the flight dynamic properties with variation of dynamic pressure and angle of attack.

All together the control design task was much more challenging as it would be for a more optimised aircraft design. Nevertheless the controlled ACFA 2020 BWB configuration fulfils handling quality requirements while showing significantly reduced loads and reasonable ride comfort. This illustrates the power of the applied modern control design techniques.

3.4. System Architecture for ACFA 2020 BWB

The control design investigations for the ACFA 2020 BWB were based on the assumption of a fully operational aircraft However, in reality faulty components and partly functional systems have to be considered as well. In particular the probability of a catastrophic event has to be below the limits stated in the certification specifications issued by the regulatory authorities.

Therefore, the first step in the system design process is the determination of a basic architecture which allows the investigation of relevant failure cases. Electro-mechanical actuators were utilised for the control surface actuation taking into account the trend towards a more-electric aircraft. Therefore also the power generation and distribution system was investigated and an adequate architecture is proposed. In a BWB active control of the center of gravity is quite important in order to exploit all the benefits of this configuration. Therefore also an architecture for the fuel management system has been investigated taking into account that center of gravity control is safety critical.

The investigations were based on the ACFA 2020 ROMS using also manoeuvre and gust load alleviation functions. Possible failures have been injected to acquire the aircraft’s model responses. For the system design only the criterion of stability has been used. The proposed system architecture is described in some detail in the report D3.21.

The initial control surface configuration did not provide an adequate failure tolerance. In particular, a jammed flap in deflected position significantly affects the aircraft’s attitude and control authority which results in a catastrophic event due to instability of the aircraft. A segmentation of the control surfaces was identified as the most promising approach to make actuation failures tolerable. The proposed control surface segmentation is shown in Figure 11.

In the next step, a basic flight control, fuel and power supply system was designed on the basis of the obtained results. Overall the jamming issue and the low failure tolerance compared to conventional aircraft configurations remains challenging. Studies showed that an aerodynamically favourable approach with an active stabilisation for unstable CG positions is only possible to a certain extent. A landing with a CG adjusted for cruise performance is impossible with the bandwidth of currently available actuators. For this reason, a safety critical fuel system was designed to allow the readjustment of the stability reserve in any flight condition. The criticality and the location of the trim tanks within the lower part of the fuselage resulted in a rather high complexity of the automatic fuel functions. As in any more electric aircraft high reliability and graceful degradation are mandatory also for the power supply system. An implementation of four power buses together with a duplex power supply is considered as the most promising approach.

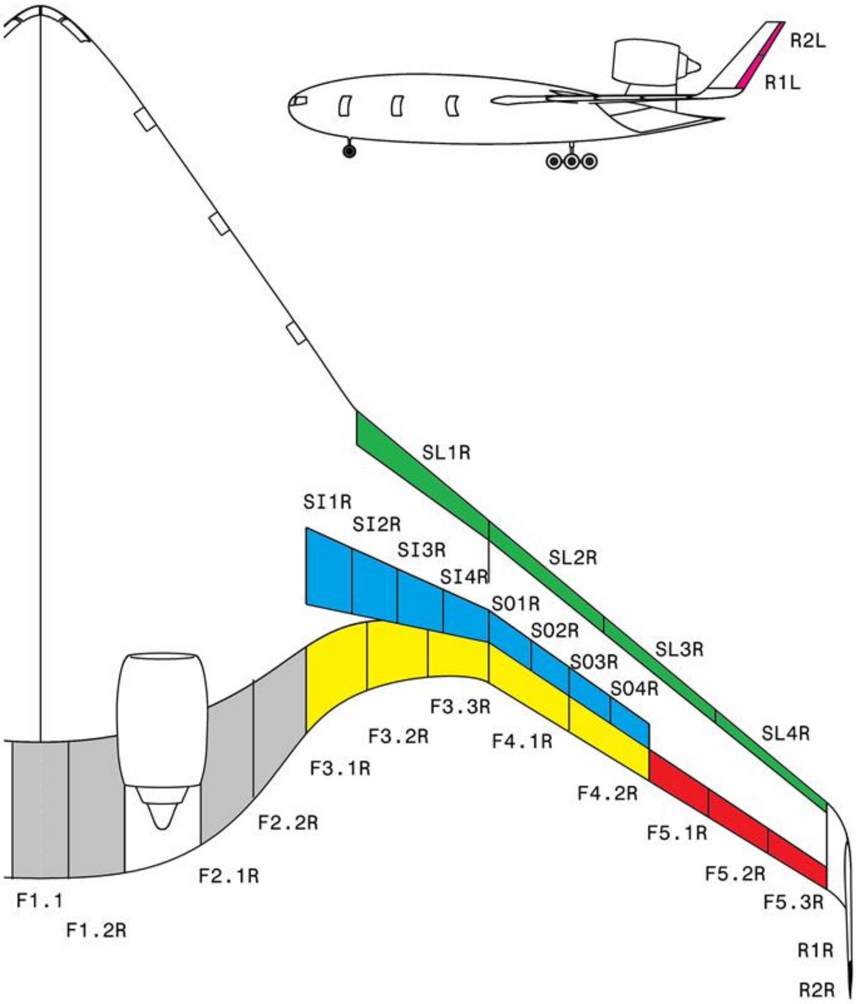
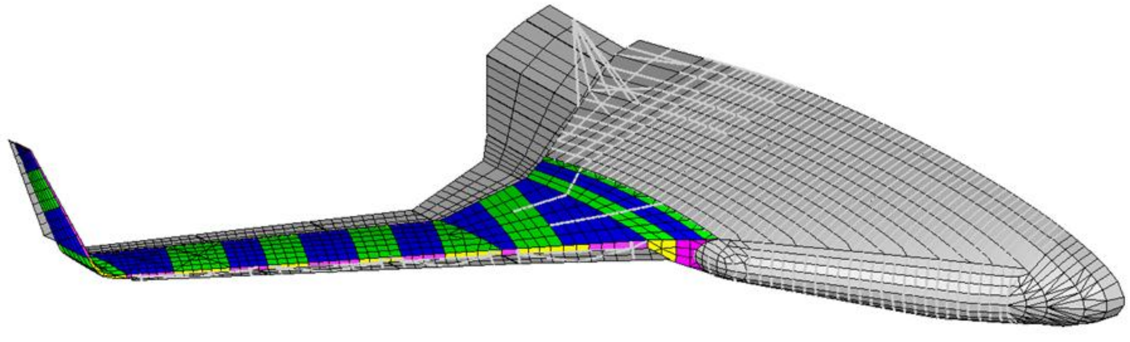


Figure 11. Final segmentation of control surfaces

3.4. Resizing of ACFA 2020 BWB

In a final step the wing of the ACFA 2020 BWB was resized taking into account the loads reduction achieved by active loads alleviation. The critical flight load cases for the resizing activity have been provided as time histories for all relevant states during manoeuvre or gust loads simulation. With given modal displacement histories together with the eigenvectors and stiffness matrix of the corresponding aircraft configuration an equivalent static load vector has been calculated for all timesteps by the mode displacement method. For manoeuvre and longitudinal gust load cases, the whole time histories have been considered. Within the considered time frame 30 time-steps have been selected for the extraction of equivalent static load cases. The min./max. wing bending moments at 14 positions along the wingspan, as well as min./max. wingtip vertical displacements were used as criteria to select the most critical time steps.

The resizing was formulated as a structural optimization problem for the wing area of the ACFA 2020 BWB. MSC Nastran SOL200 was used to solve the optimization problem. The considered region for sizing is the upper and lower panels of the wingbox, ranging from wingroot to the tip of the winglet. For the optimization the wingbox was subdivided into 18 design zones, as shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. For each of these areas the shell properties of skin panels, spars and ribs remain constant.



Courtesy of TU-Munich

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Figure 12. Areas for resizing the structure

The only objective is minimization of total mass whereby several constraints are considered, namely strain constraints depending on material strength, static stability (buckling) and flutter constraints. The flutter speed is assessed by the MSC Nastran dynamic aeroelastic analysis, SOL145. Former flutter investigation the ACFA 2020 BWB showed lowest flutter speed at MTOW configuration, with a combination of symmetric wing bending and symmetric torsion modes. Thus, the flutter check of the optimized configurations was performed for symmetric boundary conditions at MTOW configuration only.

The manoeuvre case is sizing without loads alleviation, whereas with loads alleviation gust and manoeuvre loads become equally important. The resizing process based on simulated load cases with and without active loads alleviation has been proven to be feasible and delivered significant weight savings. In total a structural weight saving of about 4t, out of ≈19t mass of a single wingbox has been achieved. About 25% of this weight saving is due to active loads alleviation. The flutter constraint was quite important and formed the main limitation for the possible weight saving. The separation of loads analysis and structural design limited the effectiveness and flexibility of the resizing process, i.e. load simulations could not be influenced, nor repeated with the updated structure. Ideal would be an integrated approach of loads and structural design. Of course this was out of scope of ACFA 2020 but would be a promising approach for future research.

4. Summary

The BWB concept proofed to be very efficient with respect to fuel burn also for medium sized transport aircraft (450PAX). Compared to a more conventional configuration by application of same engine technology more than 13% less fuel burn has been estimated for the BWB aircraft. The major part of the project dealt with the development of advanced active control concepts in particular to achieve a significant loads reduction and high ride comfort. Major results are published in [27], [28], [29], [30] and [31]. It was shown that the ride comfort can be largely improved by a combined feedback and adaptive feed-forward control concept. Nevertheless, the achieved values for ride comfort are at the lower levels of discomfort and particular attention should be paid to this area also in future studies on BWB type aircraft. The adaptive feed-forward control concept to reduce turbulence induced vibrations was in addition validated by flight tests with the ATTAS aircraft. Loads due to discrete gusts can be also significantly alleviated by combined feedback and feed-forward concepts.

In a final step the ACFA 2020 BWB has been resized according to the loads achieved with active loads alleviation resulting in additional weight savings.

The ACFA 2020 project showed that the BWB concept is quite attractive mainly with respect to fuel burn and that it can be further improved by enhanced active control. Nevertheless there is still a long way to go to bring such an unconventional configuration to reality. From aeromechanics point of view the next most interesting topics to investigate after the ACFA 2020 project are the low speed handling qualities. Also BWB sensitivity against gust and best suited control surface layout for gust load alleviation would be important topics not sufficiently addressed in ACFA 2020. In order to get a coordinated progress in the BWB knowledge the next step should be also in another direction e.g. pressurized centre body structural design and integrated approaches to optimise loads control and structure in a single step.

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