L_∞ Optimization of an Open Loop Gust Load Alleviation System for a large Blended Wing Body Airliner

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I. Introduction

For a significant fuel efficiency improvement on long-range transport aircraft, the transition to BWB (Blended Wing Body) configurations offers a promising long term solution. The advantage of higher lift to drag ratio is opposed by technical challenges such as the design of a flat pressurized cabin, specific demands on the control system due to the high coupling between flap deflections and aircraft movements in all three axes, handling asymmetric engine failure without tail as discussed in WILDSCHEK ET AL. [1] as well as handling gust loads. The idea of aircraft consisting only of a wing dates back to the 1930s, when the German Horten Brothers built their first flying wing airplanes [2]. Lack of active control technology made those airplanes almost non flyable. In LIEBECK [3] some of the problems listed above are discussed based on a design of a BWB subsonic civil transport aircraft however not mentioning handling gust loads. HILEMAN ET AL. [4] show environmental advantages of the BWB configuration such as lower noise signature with buried engines. Buried engines would also ease the problem of handling asymmetric engine failure without a tail. The strategic B-2 bomber, the only flying wing aircraft in service today combines efficient aerodynamics for long range transport with a low radar cross section. As explained in BRITT ET AL. [5] this aircraft requires a quite sophisticated control system in order to handle gust loads. The weight penalty imposed by the B2's large high bandwidth control surfaces including structural reinforcement in order to be able to transmit the high actuator forces are impractical for a civil BWB airliner where the main focus is on fuel efficiency.

Due to the low wing loading BWB aircraft are generally more sensitive to gust loads than conventional wing tube aircraft. This paper investigates the gust load response of a large 450 passenger BWB airliner (designed in the European ACFA2020 project, see Figure 1) by numeric simulation. The structural concept is based on these simulations considering also the gust load alleviation system. For some fuel configurations the BWB airliner is statically unstable, thus requiring artificial stabilization, i.e. an inner feedback loop from load factor to the elevators. Taking into account maneuver load alleviation, gust loads become the dominant sizing factor.

Figure 1. ACFA BWB airliner (courtesy of the ACFA consortium).

For efficient gust load alleviation L_∞ norms of the responses of wing bending moment, load factor, sheer force, etc. need to be minimized for gusts of different scale lengths throughout the whole flight envelope [6]. This paper will provide an optimization procedure for these minimization constraints. The BWB model used for this investigation is parameterized in Mach, dynamic pressure, fuel mass, and CG position. Three discrete CG positions are considered. The CG variation is achieved by fuel redistribution which is important on a BWB airplane for trim without too large control surface deflections in order to achieve optimum cruise performance. The other three model parameters are defined on a much finer grid. The model has spoilers on the upper wing surface, as well as a number of trailing edge flaps, rudders on the winglets, and split flaps for yaw moment balance in cross wind landings or asymmetric engine failures.

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II. Control Laws Design and Optimization

A. Flight Control Laws Design

The BWB aircraft is controlled via C*, i.e.:

$$C^* = -\frac{V_\infty \cdot \dot{\alpha}}{g} + \frac{V_\infty \cdot \dot{\theta}}{g} + \frac{27 \cdot \dot{q}_{CG}}{g} + \frac{122 \cdot q_{CG}}{g} \quad \text{with} \quad g = 9.81 \tag{1}$$

Artificial pitch stiffness is achieved by feedback of the vertical CG load factor n_z to the elevators. In order to achieve neutral pitch stability this feedback is done via a PI controller [7]. An additional pitch damper (i.e. feedback from pitch rate q to the elevators) allows placement of the poles of the angle of attack mode. In order to take into account handling qualities requirements the Control Anticipation Parameter (CAP) criteria is used, which provides boundaries for damping and frequency of the angle of attack mode [8]

$$CAP = \frac{\dot{q}(t=0)}{n_z(t=\infty)} \approx \frac{\left|\omega_0^2\right|_{shortperiod}}{n_\alpha} \tag{2}$$

with:

$$n_\alpha = \frac{n_z(t=\infty)}{\alpha(t=\infty)} \approx \frac{V_\infty}{g} \cdot \frac{1}{T_\mu} \tag{3}$$

Thereby, V_∞ denotes the free stream velocity, α is the angle of attack, and T_μ is the numerator time constant of the elevator to pitch rate zero, and thus strongly depends on the mass variant. The flight control law is scheduled with regards to inverse of dynamic pressure, Mach number, mass estimate and CG estimate. Robustness is investigated based on Nichols diagrams, compare Figure 2.

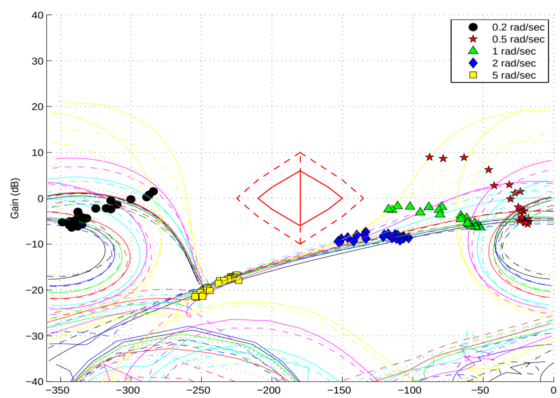

Figure 2. Nichols plot for n_z to elevator loop for a stable CG configuration

B. Optimum Gust Load Alleviation

Feed-forward information about the gust is acquired at the aircraft nose by a gust sensor in order to activate the control surfaces. The elevator pitches the BWB airliner into the gust in order to minimize the angle of attack increase due to the gust. This is probably the most efficient means because the source of the gust load is directly counteracted. However, especially for very short gusts the reaction time here becomes critical. The spoilers reduce the first peak of the wing bending load. Due to strong coupling between pitch and wing bending a modal wing bending acceleration signal is fed back to the flight control laws for active wing bending damping, as well as to avoid wing bending excitation due to spoiler deflections. Investigating maneuver loads, turbulence, and gust loads in numeric simulations with the controlled aircraft, the updraft gust was identified to be the sizing case for the BWB wing structure. Thus, the following investigations are performed with sizing 1-cos gusts of different scale length, well knowing that with gust load alleviation, other cases can become sizing. The updraft gust is identified by the alpha probe mounted at the pilot station. In a first step only the L_∞ norm of the incremental wing root bending moment Mx_{WR} is minimized.

Cost function: $$J_1 = \max(Mx_{WR}(t)) \tag{4}$$

The resulting open loop control law provides a 75% reduction of incremental Mx_{WR}, but also leads to high negative load factors Nz_{CG} (see plot in the right upper corner) which is to be avoided for safety of passenger reasons, see Figure 3:

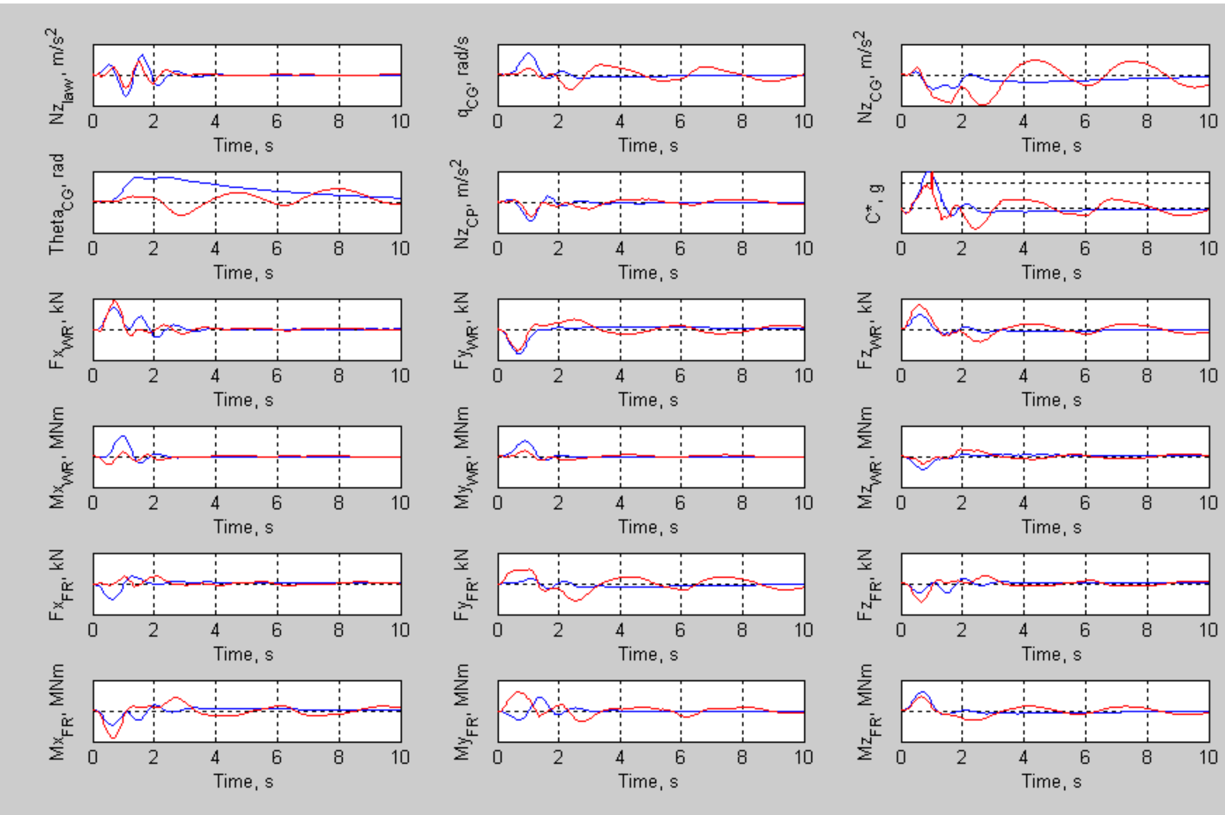

Figure 3. Gust load alleviation for cost function 1.

The respective control surface deflections are shown in Figure 4:

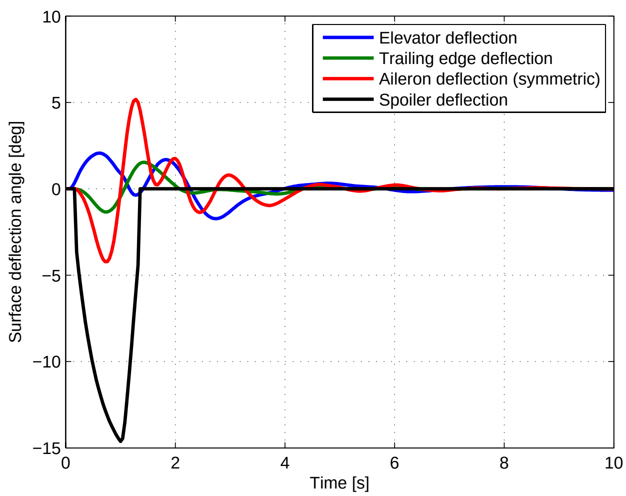

Figure 4. Control surface deflections for cost function 1.

Thus a new cost function is applied, i.e.:

$$J_2 = a \cdot \max(Mx_{WR}(t)) + b \cdot \left|\min\left(Nz_{CG}(t)\right)\right| \quad (5)$$

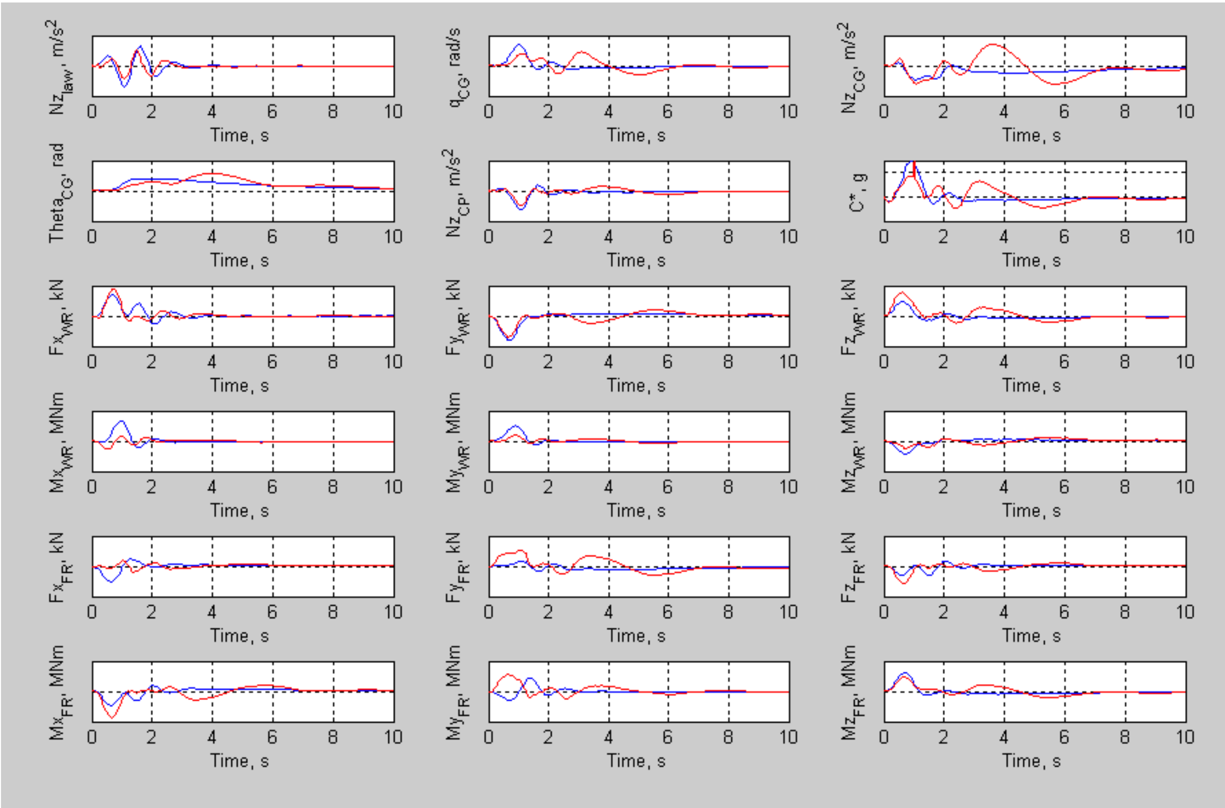

Figure 5. Gust load alleviation for cost function 2.

Still a 75% reduction of Mx_{WR} is achieved. The negative load factor is gone, but the positive load factor is increased. Furthermore, the increase of wing rot sheer force Fz_{WR} is not advantageously for structural resizing. The respective control surface deflections are shown in Figure 6:

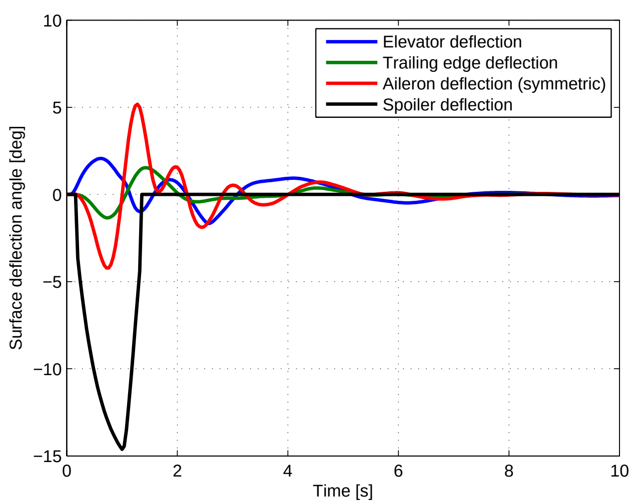

Figure 6. Control surface deflections for cost function 2.

Currently under investigation is the more complex cost function:

$$J_3 = a \cdot \max(Mx_{WR}(t)) + b \cdot \max(Fz_{WR}(t)) + c \cdot \left|\min\left(Nz_{CG}(t)\right)\right| + d \cdot \max\left(Nz_{CG}(t)\right) \quad (6)$$

III. Achievable Load Alleviation

Figure 7 shows a preliminary simulation result of a time response to a 1-cosine gust with (red line) and without (blue line) gust load alleviation. Artificial stabilization naturally is activated in both cases. The first peak can be reduced but the control laws have to be adjusted carefully in order not to increase the second peak. Simulations have to be performed for several fuel configurations and flight conditions as well as for different gust lengths in order to find the sizing cases and the achievable load reduction. The load reduction finally allows for a reduction of structural weight. Control laws however have to be optimized for the new aircraft structure as well as the critical flutter speed checked after each step of resizing. In order to reduce those iteration steps future investigations will be dedicated to the generation of an optimization tool for gust load alleviation design/structural resizing partial automation.

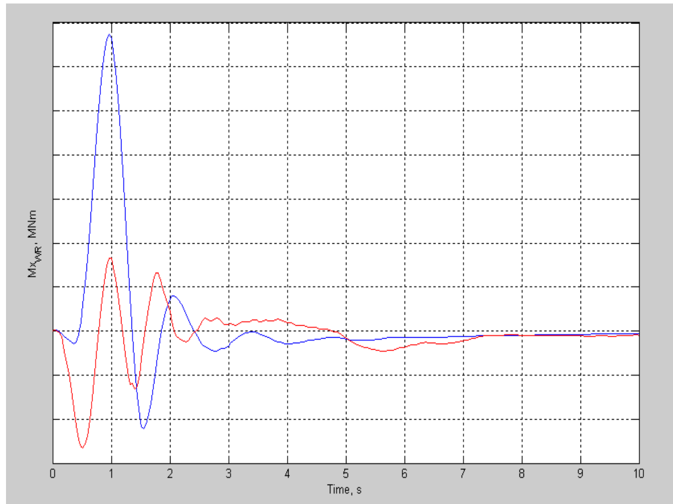

Figure 7. Achieved alleviation of incremental wing root bending moment.

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