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FUEL MANAGEMENT SYSTEM FOR CRUISE PERFORMANCE OPTIMIZATION ON A LARGE BLENDED WING BODY AIRLINER

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Blended Wing Body (BWB) aircraft configurations have been proposed for significant fuel efficiency improvement on commercial transport. In order to fly with the optimum lift-to-drag ratio throughout most of the mission, an adaptation of the center of gravity (CG) by fuel redistribution is proposed. The most aft location of the CG which still is controllable is mainly limited by actuator bandwidth whereas the front CG location is limited by control authority of the trailing edge control surfaces. This paper provides an optimization of the CG position with regards to minimization of fuel consumption. Layout of the fuel tank system is illustrated. Moreover, active stabilization of faulty CG positions is discussed.

1 INTRODUCTION

Blended wing body aircraft configurations have been proposed for significant fuel efficiency improvement on commercial transport [1]. The idea to this radical airframe design dates back to the 1930s [2]. The investigations in this paper are based on the ACFA BWB (Active Control of Flexible BWB Aircraft), a 450-passenger configuration with two rear-mounted turbofan engines, which originates from the European project ACFA2020 (Active Control of Flexible 2020 Aircraft). In order to fly with the optimum lift-to-drag ratio throughout most of the mission, an adaptation of the CG by fuel redistribution is proposed. The idea of adjusting the CG by variation of fuel distribution for improved cruise performance is not new [3, 4]. For BWB airplanes, however, it is essential in order to be able to exploit the potential advantages of this radical airframe design. The scenario is similar to the Concord supersonic transport aircraft which would not have been able to exceed Mach 2 without relying heavily on a safety-critical fuel management system, handled by the flight engineer at that time [5]. At takeoff and landing, a forward CG position is aspired for more stable configuration. With increasing Mach number, however, the neutral point is continuously shifted backwards, increasing static stability and, unfortunately, also trim drag. Especially for BWB airplanes, this increase of trim drag, and thus reduction of lift-to-drag ratio, is immense due to the low lever arm of the wings' trailing edge flaps used for trimming the aircraft and due to the flaps' effect on the wings' camber, and thus on the lift. For improved lift-to-drag ratio, the CG, therefore, needs to be shifted backwards when increasing the Mach number. In the unlike event of a failure of the fuel redistribution system at cruise Mach number, deceleration of the BWB aircraft would lead to a statically unstable configuration. Thus, also active pitch stabilization in the event of a faulty CG positions is investigated in this paper. Active stabilization of statically unstable aircraft dates back to the 1970s [6]. On the investigated BWB airliner, however, the pitch control surfaces are required to be very large. Providing sufficient bandwidth for active pitch stabilization comes at the price of actuator size. Limiting the actuator mass and available energy supply, also the controllable range of aft CG position is rather limited. Unless pitch control surfaces of high bandwidth are introduced, the proposed fuel redistribution system has to be seen as a safety-critical component.

2 FUEL TANK LAYOUT FOR CENTER OF GRAVITY ADAPTATION

In the style of the Concord supersonic transport aircraft [7], the ACFA BWB is equipped with three different types of fuel tanks: trim tanks, main tanks, and collector tanks (Fig. 1). The collector tanks directly feed the 2 turbofan engines and are thus always considered 100% filled. The fuel is mainly stored in the main tanks. For wing deloading, the main tanks are emptied from center to wing tips. The CG variation is mainly achieved by transfer of fuel to and from the trim tanks.

2.1 Defueling Scenarios

For takeoff with maximum fuel, the most front CG position that can be achieved with available fuel tanks is at 23.6 m, i. e., front trim tanks full and rear trim

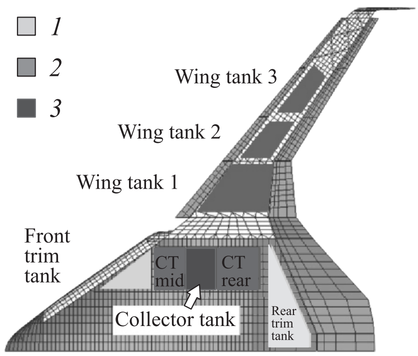

Figure 1 Fuel tank layout for the ACFA BWB: *1* — trim tanks for CG balance; *2* — main tanks (emptied from center to wing tips for wing deloading); and *3* — collector tanks (directly feed the 2 engines and are always 100% full)

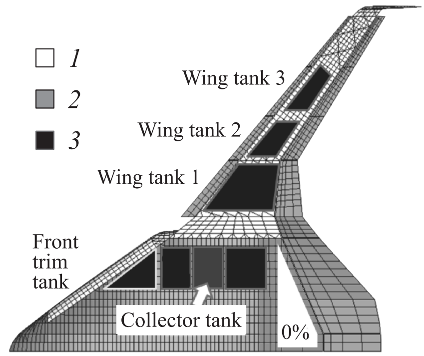

Figure 2 Representative takeoff configuration: *1* — empty; *2* — partly filled; and *3* — 100% full

tanks empty (Fig. 2). With this CG position, the aircraft is statically stable for a Mach number of 0.2.

After takeoff, the aircraft will generally start to climb and accelerate to the cruise Mach number, thus causing the neutral point to shift rearwards. Note that the following values given in terms of CG shift and thus static margins are potentially slightly overestimated due to the very preliminar aerodynamics of the model on which this investigation is based on. In the following, two cases at cruise Mach number at representative altitude are investigated, i.e., 75% remaining fuel and 50% remaining fuel. Part of the fuel is pumped to the rear trim tanks which is filled 50% in both cases. The front trim tanks are empty. The worst case scenario in both cases would be the complete failure of the fuel pump system (and thus, the inability to pump the fuel from the rear trim tank to the front) and, at the same time, the need to decelerate. In a first step, it is investigated if emergency jettison of the rear trim tank fuel can bring the CG back to a statically stable landing configuration. Note that due to the flat BWB centerbody, gravitational force cannot be used to bring back the fuel from rear to front trim tank, as it is possible with trim tanks integrated in the horizontal stabilizer of, for example, a conventional airplane [3, 4]:

– 75% fuel (Fig. 3*a*): the CG is at about 25 m, providing a static margin of 4.5% of the mean aerodynamic chord (MAC) at cruise Mach number. Emergency jettison of the rear trim tank fuel would result in a CG position of 24.3 m, and the aircraft would thus at least be statically stable above Mach 0.8. Further gravity driven defuelling of wing tank 3 (WT3) to front

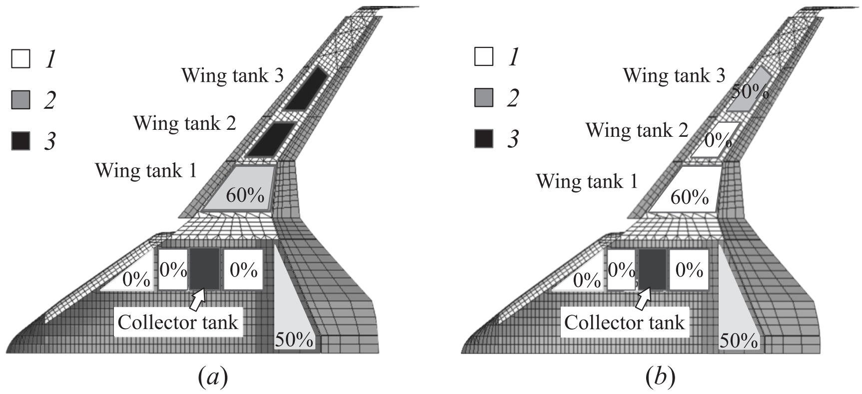

Figure 3 Representative cruise case: (*a*) 75% fuel remaining and (*b*) 50% fuel remaining (*1* — empty; *2* — partly filled; and *3* — 100% full)

trim tank (which is possible since the wing tips are elevated above the centerbody due to the high wing airplane configuration) would result in a CG position of 23.6 m, i. e., statically stable till landing. Such approach, however, reduces graviational wing deloading, and the aircraft structure would need to be designed in order to be able to handle said load case; and

– 50% fuel (Fig. 3*b*): the CG is at about 24.76 m, providing a static margin of 5.5% of MAC. Decrease of stability reserve for better cruise performance would only be possible by either deceleration or further filling of the rear trim tank. With 50% fuel left, emergency jettison of the rear trim tank fuel would result in a CG position of 23.7 m. It means that with this approach, the aircraft would be statically stable almost till landing, but would also loose almost 2/3 of the remaining fuel and, thus, range. On the other hand, gravity driven defueling of WT3 to front trim tank would result in a CG position of 24.5 m, i. e., statically stable only till Mach 0.8.

This investigation shows that either emergency jettison of the rear trim tank fuel and/or gravity driven defueling of WT3 to front trim tank in the event of complete fuel system failure at cruise Mach number can return the aircraft to a configuration which is statically stable till the landing Mach number. However, significant drawbacks such as loss of almost all fuel and, thus, range and/or increase of loads in the wing structure need to be considered. In order to avoid the said trade-off, either the probability of loss of the fuel system must be less than 10^{-9} per flight hour, or the aircraft needs to be equipped with control laws which actively stabilize the aircraft for a wide range of CG positions. Such control law design will be

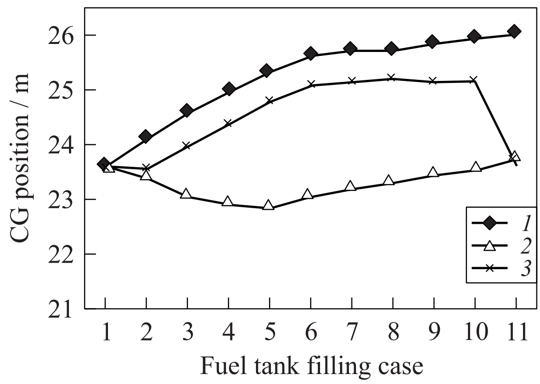

Figure 4 Front and rear limits of CG over fuel tank filling case: *1* — CG max rear; *2* — CG max front; and *3* — CG mission

discussed in section 3. Design of the proposed fuel management system is discussed in sections 4 and 5 based on investigations performed in [8].

2.2 Trim Computation for Cruise Performance Optimization

Figure 4 shows the maximum rearward CG position (*1*) and maximum forward CG position (*2*) achievable by fuel redistribution within the available fuel tanks. The optimum CG position is a trade-off of several parameters and depends on the phase of flight, e. g., for takeoff and landing, maximum static stability (i. e., forward CG position) is safer, but then also much higher upwards elevator deflection is required in order to counterbalance the pitching moment. Due to the resulting negative cambering, also a higher alpha is required, which brings the aircraft closer to stall. So, there definitely is a trade-off for the CG position. Table 1 illustrates the CG optimization procedure for cruise.

Generally speaking, if the altitude can be adapted without any constraints in order to achieve optimum angle of attack α_{trim} the elevator trim η_{trim} results with fixed CG position. An adjustable CG position, on the other hand, results from optimization of altitude, trim angle of attack α_{trim}, and elevators

Table 1 Center of gravity optimization for cruise

Angle of attack	Altitude	Elevators trim	CG position
$\alpha_{\mathrm{trim}_{\mathrm{opt}}}$	Adapted	Results	Fixed
$\alpha_{\mathrm{trim}_{\mathrm{opt}}}$	Adapted	$\eta_{\mathrm{trim}_{\mathrm{opt}}}$	Results
Trade-off	← Fixed to FL →	Trade-off	Results

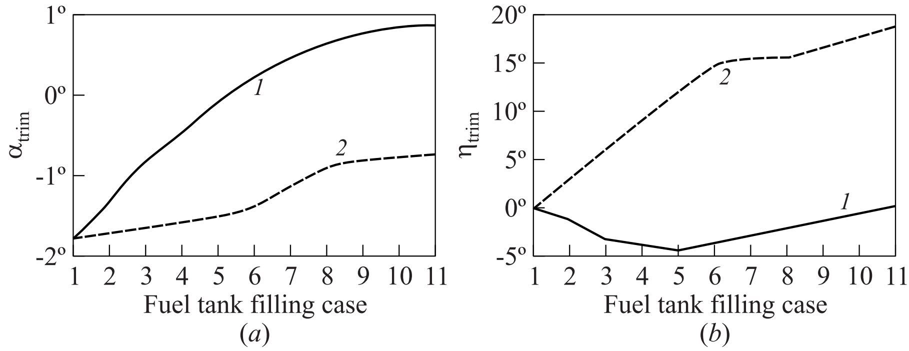

Figure 5 Center of gravity dependent range of α_{trim} (a) and η_{trim} (b) at cruise Mach number at flight level 390: *1* — maximum front CG and *2* — maximum rear CG

trim deflection η_{trim}. According to today's standards [9], however, the aircraft is assigned a certain flight level by air traffic control resulting in a trade-off between α_{trim} and η_{trim}. In cruise, generally optimum angle of attack is aspired at small elevators (i. e., trailing edge flaps) deflection in order to keep the design aerodynamic shape as undistorted as possible.

Figure 5 illustrates the range of trim angle of attack and respective elevators trim deflection vs. fuel tank filling case computed with a flexible BWB aircraft model including nonlinear flight dynamics [10] for cruise Mach number at flight level (FL) 390. Note that for fixed aircraft mass, increased altitude allows higher α_{trim} due to the lower dynamic pressure. Thus, flight level should be increased for decreasing fuel filling during flight in order to be able to remain close to α_{trim} as is state-of-the-art.

The three unknowns trim angle of attack α_{trim}, trim elevators deflection η_{trim}, and required thrust $T_{A/C}$ are computed by the following three equations. A right-hand coordinate system is used with the origin in the fuselage nose and X-direction rearwards, Z-direction upwards. The force equations in body axes' Z-direction and X-direction for a selected Mach number give:

$$C_{L_{\text{req}}} = \frac{m_{A/C}(m_{\text{fuel}})g(H)\cos(\alpha_{\text{trim}} - \alpha_0)}{S_{\text{ref}}q} - \left(\frac{\partial C_L}{\partial \eta}\right)_{\alpha_{\text{trim}}} \eta_{\text{trim}} - \frac{\text{Fz}_{ae}}{S_{\text{ref}}q}\,; \quad (1)$$

$$T_{A/C} = \left(\frac{\partial C_D}{\partial \alpha}\right)_{\alpha_{\text{trim}}} \alpha_{\text{trim}} S_{\text{ref}} q + m_{A/C}(m_{\text{fuel}})g(H)\sin(\alpha_{\text{trim}} - \alpha_0) + \text{Fx}_{ae} + \left(\frac{\partial C_D}{\partial \eta}\right)_{\alpha_{\text{trim}}} \eta_{\text{trim}} S_{\text{ref}} q\,. \quad (2)$$

The moment equation is:

$$C_{M_{\mathrm{req}}} = \left(\frac{\partial C_M}{\partial \alpha}\right)_{\alpha_{\mathrm{trim}}} \alpha_{\mathrm{trim}} + \frac{x_{\mathrm{CG}}}{c_{\mathrm{ref}}} \left(\left(\frac{\partial C_L}{\partial \alpha}\right)_{\alpha_{\mathrm{trim}}} \alpha_{\mathrm{trim}} + \left(\frac{\partial C_L}{\partial \eta}\right)_{\alpha_{\mathrm{trim}}} \eta_{\mathrm{trim}} + \frac{\mathrm{Fz}_{ae}}{S_{\mathrm{ref}} q} \right) - T_{A/C} \frac{z_{\mathrm{eng}} - z_{\mathrm{CG}}}{c_{\mathrm{ref}} S_{\mathrm{ref}} q} + \frac{\mathrm{My}_{ae}}{c_{\mathrm{ref}} S_{\mathrm{ref}} q} \quad (3)$$

with auxiliary condition:

$$\eta_{\mathrm{trim}} = -\frac{C_{M_{\mathrm{req}}}}{(\partial C_M / \partial \eta)_{\alpha_{\mathrm{trim}}}} \,. \quad (4)$$

Equations (1) through (4) are solved iteratively for different settings of the CG position in X-direction x_{CG}. The CG position in Z-direction z_{CG} is considered in the equations but not varied. The offset of the engine in Z-direction

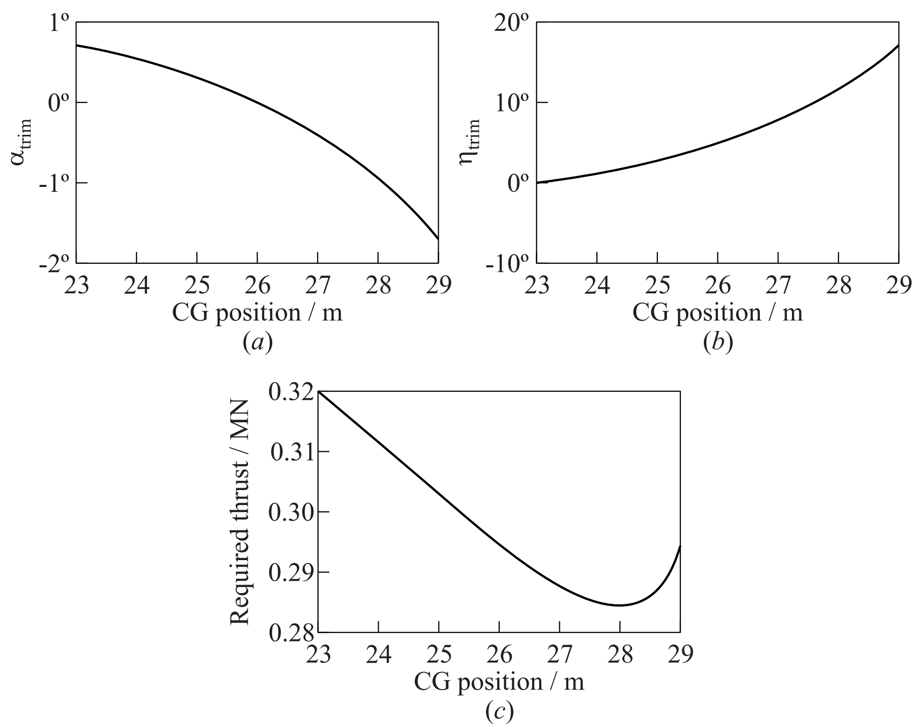

Figure 6 Trim angle of attack (a), elevators trim (b), and required thrust (c) over CG position in cruise with 75% fuel

is z_{eng} considering the nosedown pitch moment of the two turbofan engines mounted on top of the rear fuselage. The aircraft mass depends on the filling level of fuel tanks. Coefficient $C_{L_{\mathrm{req}}}$ is the required lift coefficient, and $C_{M_{\mathrm{req}}}$ is the pitch moment to be compensated by the elevators. The gravity constant $g(H)$ is considered to depend on the altitude H. Parameter S_{ref} is the reference area, c_{ref} is the mean aerodynamic chord (MAC), and q is the dynamic pressure, which depends on the altitude H and on the Mach number. The zero lift angle of attack is denoted α_0. All aerodynamic derivatives (i. e., derivatives of lift coefficient C_L, drag coefficient C_D, and pitch moment coefficient C_M with respect to either α or η) are the functions of the selected Mach number and the trim angle of attack. Equations (1)–(4) also consider global aeroelastic forces and moments due to aircraft flexibility. The forces Fz_{ae} and Fx_{ae} denote the additional lift force due to flexibility and additional drag force, respectively, and My_{ae} denotes the respective additional pitch moment. Exemplarily, Fig. 6 illustrates a result of such trim computation for cruise Mach number at a representative altitude. As expected, optimum lift-to-drag ratio (corresponding to minimum required thrust) is obtained for a far rear CG position, i. e., static unstable aircraft configuration. Interestingly enough, the computed elevators trim deflection η_{trim} for minimum drag at fixed flight level is far from zero, and computed α_{trim} is lower than α_{trim} estimated by previous aerodynamic computations. Note that in Fig. 6a, α_{trim} is related to a nominal design angle of attack.

3 CONTROLLER DESIGN CONSIDERING FAULTY CENTER OF GRAVITY POSITIONS

The motivation for investigating the ability to stabilize the ACFA BWB airliner for static unstable CG positions is the handling of faulty CG positions due to a failure in the proposed fuel redistribution system, on the one hand, and, on the other hand, the possibility of further fuel saving by flying with a static unstable configuration (as suggested by results of the previous section). Artificial pitch stiffness is basically achieved by feedback of the incremental vertical load factor Δn_z to the 4 elevators. In order to achieve similar characteristics as for an aircraft with neutral stability, this feedback is done via a PI (proportional-integral) controller.

The pitch damper (i. e., feedback from pitch rate q to the elevators) finally allows placement of the poles of the short period mode. A suitable amount of robustness as well as performance demands are required for such control law. The control laws are designed using the H_∞ Fixed Order Optimization (HiFOO) toolbox (for further details, see [11,12]). The design plant G is of order 36 containing Phygoid and short period mode, several flexible modes, linear approximations of the nonlinear actuators, and sensor delays. The augmented plant setup (i. e.,

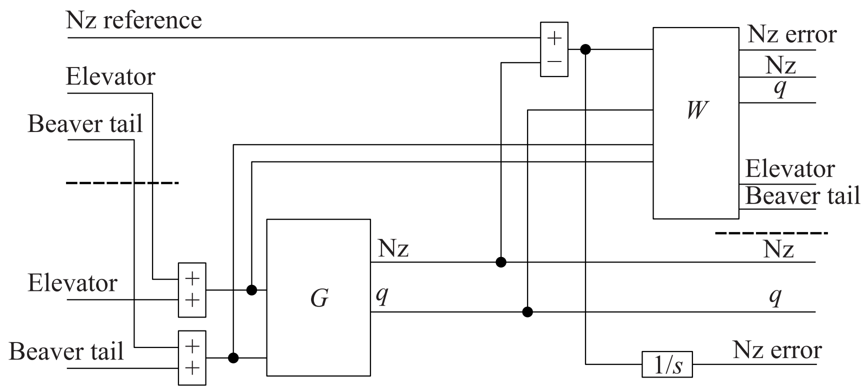

Figure 7 Augmented plant setup

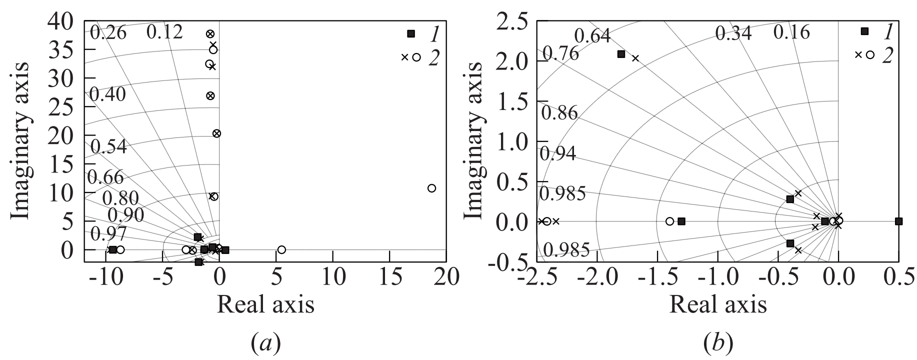

Figure 8 Pole-zero map of transfer function from elevators deflection to Δn_z: (a) overview; and (b) zoom (*1* — open loop and *2* — control law)

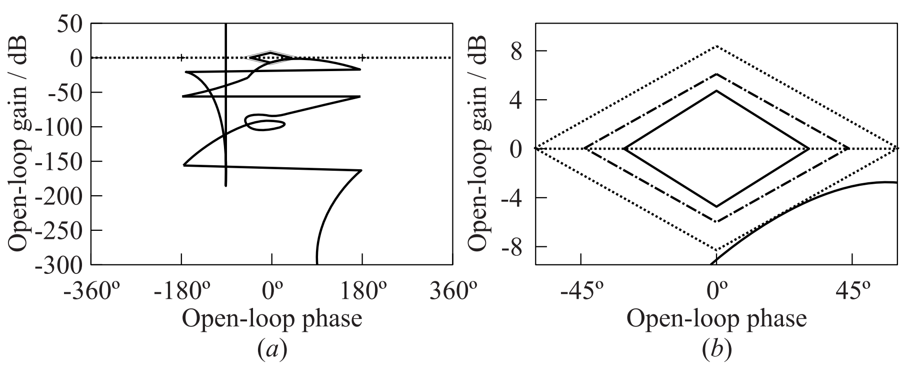

Figure 9 Nichols plot of actuator loop: (a) overview and (b) zoom

augmenting G with weighting matrix W) for H_∞ control law design is illustrated in Fig. 7 (for more details, see [13]).

For simplicity, performance requirements are just expressed in terms of location of the closed loop poles. Except for the Phygoid mode, relative damping of all poles in the frequency range of the rigid body motion is required to be at least 0.5. Without additional autopilot loops, the Phygoid is even allowed to imply an unstable real pole as long as it is left of $\ln(2)/6\ \mathrm{s}^{-1}$, i. e., doubling time

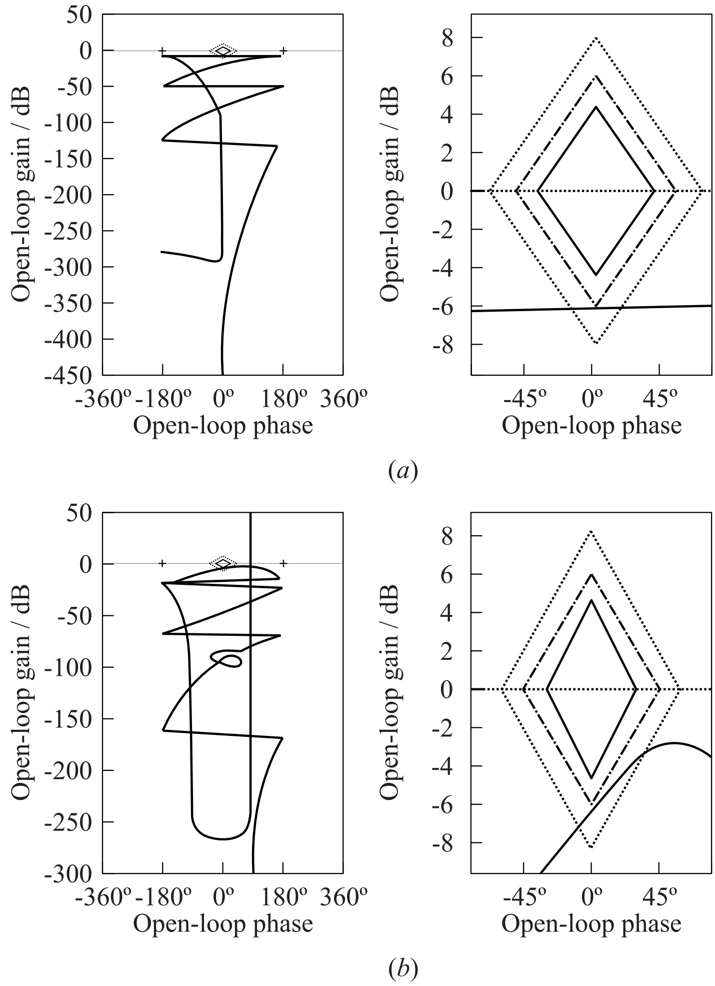

Figure 10 Nichols plot of sensor loops: (a) q and (b) Δn_z; left column — overview and right column — zoom

is > 6 s. See Fig. 8 for comparison between open and closed loop poles for fuel tank filling case 10 with CG optimized for cruise Mach number as illustrated in section 2, but with a 4% lower Mach number. One can see that the open loop unstable short period pole at 0.5 s^{-1} (black squares) is just stabilized by the control law (crosses).

The robustness requirements of the control law are described by exclusion regions in the Nichols chart, defining the gain and phase margins of the control law. Three regions and, therefore, three robustness criteria are considered for the frequency ranges bounded by frequencies of Phygoid mode and of the first wing bending mode (represented by solid, dash-dotted, and dotted lines of diamonds in the Nichols chart) [14]. Since multiple inputs single output control law is considered, the Nichols plots are investigated for each single loop (Figs. 9 and 10).

From section 3, it can be concluded that, with the available actuators, robust active stabilization for faulty CG positions is possible to some extent. Handling of landing Mach numbers with a CG position optimized for cruise performance, however, is far from realistic without availability of higher bandwidth surfaces for pitch control.

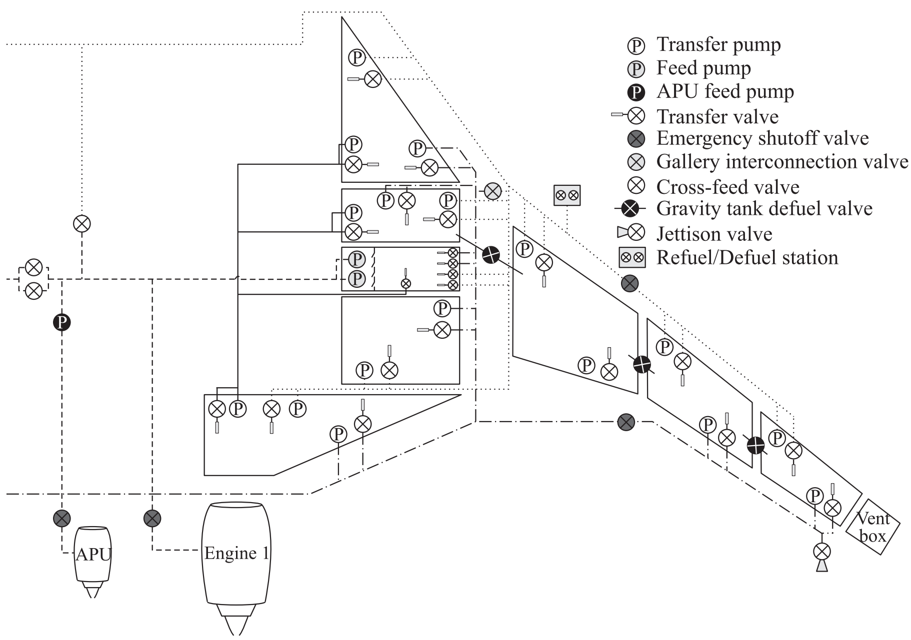

Figure 11 Fuel management system design, right side [8]

4 FUEL MANAGEMENT SYSTEM LAYOUT

As an alternative to the costly active stabilization of a highly unstable BWB configuration, the feasibility of a fuel management system design with probability of loss of said system of less than 10^{-9} per flight hour was investigated. This section summarizes subsequent work performed on the fuel management system in [8]. As illustrated in Fig. 11, the system is divided into four subsystems, the feed system (dashed lines) as well as the front (dotted lines), rear (dash-dotted lines), and center gallery (solid lines). For simplicity, design details such as internal tank compartments, tank inerting, water disposal, or secondary functions like heat exchangers are neglected in the following study.

4.1 Feed System

The feed system provides continuous pressurized fuel supply for the two turbofan engines and the Auxiliary Power Unit (APU). Considering CS 25.903 [15], two separate feed lines are necessary in order to ensure continuous operation of an engine if there is a malfunction in the other line. Therefore, the feed system is divided into a right and left side, each one with its own two feed pumps (compare CS 25.991). Both pumps must be capable of providing 100% pumping capacity for fail-safe functioning. The feed pumps are located in a collector cell within the feed tank (i. e., collector tank) in order to guarantee a continuing fuel reservoir even for short times of negative g accelerations. Any backflow is prevented by baffle check valves within the collector cell walls. CS 25.953 requires the ability of supplying the engine by the opposite feed line. Therefore, both lines are connected with cross-feed valves which are closed during normal operation and open in case of faulty pumps of one line. Their parallel alignment is based on ETOPS (Extended range Twin Operations Performance Standards) requirements for fuel system availability in [16]. Note that cross feed is only functional if both feed pumps of the supplying side and one cross-feed valve are operational because each feed pump is only designed for 100% pumping capacity. The APU draws its fuel from the right feed line and has a separate fuel pump driven by two 28VDC motors for start-up procedure and emergency 270VDC power supply (used for all other pumps). In order to enable the APU pump to suck fuel, the main feed pumps must either have a unidirectional bypass or an additional intake with a one-way valve must be available. The connection between the right feed line and front gallery is designated for maintenance defueling issues and, hence, is locked in a closed state during flight. Both engines and the APU are equipped with an emergency isolation valve near the corresponding power plant in order to be able to cut off the fuel supply in case of fire or other malfunctions like leakages. Since these valves are the final barrier between the fuel supply and the engines, they must provide a high level of integrity and reliability. Another important design criterion for the feed system is the strict segregation to the fuel jettison function in order to prevent any unsafe fuel condition.

4.2 Fuel Transfer System

The main task of the fuel transfer system is the symmetric defueling of the center and wing tanks in order to supply the feed system. Additional tasks are active CG control, wing deloading, and fuel jettison. The system is divided into three galleries in order to achieve sufficient safety margins through component redundancy and locally separated installations. Additionally, this segregation limits the consequences of comparatively rare but still possible uncommanded component behavior as well as any mechanical fractures. Each tank is fitted with a minimum of two transfer pumps and two transfer valves. For simplification, it is assumed that these components allow an unidirectional fuel flow only. So, the valves with their attached diffusers carry out the filling while the pumps are used for the defueling process. The transfer pumps and valves are supplied by power supply busses of 270VDC and 28VDC, respectively. Considering the failure rates of the said components and their attached power buses, the likelihood for losing the access to a tank is greater than 10^{-9} per flight hour. Such case is not catastrophic due to the relatively high number of separated tanks but it can affect the ETOPS ability.

As already mentioned in section 2, the worst-case scenario for defuel and trim strategy is 50% or less remaining fuel located in the rear trim tank and WT3 (i. e., CG optimized for cruise performance). In order to avoid emergency jettison, WT3 is directly connected to WT2 through a drainage valve. Since the wing tips are elevated during flight, their fuel can drain by gravity to WT2 and be further transferred to one of the galleries. The implementation of said drainage valve does not significantly increase systems complexity and weight. For this reason, it was decided to fit all three wing tanks with such a drainage valve, thereby increasing their availability to achieve an ETOPS-compliant range in all fuel cases. The drainage of WT1 is directed into the mid center tank.

Since the rear trim tank cannot be gravity defueled due to its low position within the aircraft's tail, an additional third fuel pump with a direct line to the collector tank, mid center tank and front trim tank (solid lines gallery) is added in order to fulfill fail-safe requirements. This extra pumping capacity allows a quicker trim process or a direct consumption of the fuel if the other pumps within the tank should have failed. The third fuel pumps in the front trim and mid center tank are not essential for emptying the rear trim tank but are needed for sufficient redundancy for CG adjustment.

In order to increase the fuel system's survivability in the event of a fractured wing tank, the front (dotted lines) and rear (dash-dotted lines) gallery are fitted with two emergency valves which seal off the pipes, affected by the engines' burst zone, in the outer wing section. The gallery interconnection valve is generally used for refuelling and defuelling process, allowing a faster tank filling. Another benefit is the application for system reconfigurations in the case of single component losses and thus increasing its availability.

The jettison function (i. e., dump fuel in the event of an emergency that forces the crew to land) is not necessarily safety critical because according to CS 25.473 landing with maximum takeoff weight must still be possible. However, overweight landing usually results in extensive maintenance workload. With respect to the failure rate of a jettison valve and the requirements in CS 25.1001 (i), two valves must be installed. The location at the wing tips was chosen in order to avoid any contact between the dumped fuel and the hot turbine exhaust gases.

4.3 Fuel Tank Venting

An aircraft is exposed to rough and opposed climate conditions on ground and during flight. This also affects the temperatures and pressures within the fuel tanks. In addition, there is a continuous change of the fuel levels due to refuelling or defuelling procedures. For these reasons, the fuel and tank system must be ventilated in both directions to induce a pressure equalization and thus unload the tank structures which again results in a weight reduction. With the implementation of more separate tanks also comes the need for an expanded vent line system. As stated in CS 25.975, the venting must be effective under any normal flight condition [15]. Therefore, two venting valves are fitted in each tank diagonally so that fuel swash due to varying pitch attitude is covered.

4.4 Management System and Power Supply

As the fuel systems control center, the fuel management system commands and monitors all implemented functions. Since the automatic fuel system shall provide a failure rate below 10^{-9} per flight hour, three dissimilar duplex fuel management computers (FMC) in a master/slave configuration are proposed. Fuel management includes the interpretation of all sensor data, the identification of overall system status, the control of actuators like pumps and valves, as well as failure and leakage detection. Additionally, the system's state has to be displayed for crew information on the flight deck. The selection of a specific gauging probe technology and placement of the sensors clearly depends on the tank shape and the exact fuelling and defuelling strategies. That is why this subsystem was not designed in more detail. Actuation control is carried out using an internal data bus connected to all actuators. In order to maintain the reliability of the system consisting of this component arrangement, it is mandatory to use distributed power-supply architecture as well. Since a functioning pump is useless

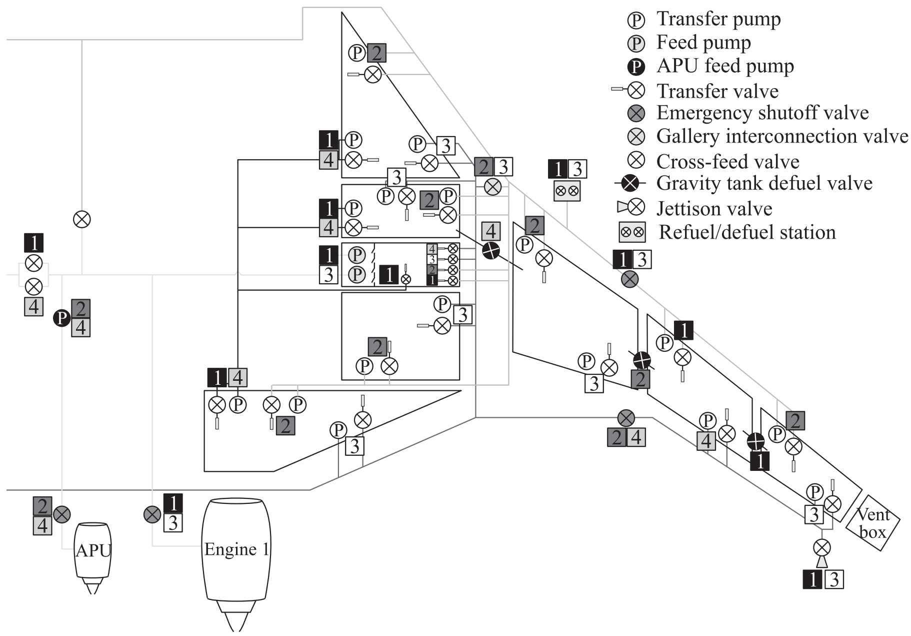

Figure 12 Power supply mapping for the fuel management system components, right side [8]

if the according valve in the other tank is passive, all attached trim, transfer and feed components of a gallery use the same power bus or buses, respectively. In addition, this arrangement supports the efforts to achieve adequate system segregation. In contrast to all other transfer pumps and valves within the fuel system, the three units connected to the center gallery are supplied by two power buses, i. e., 1 and 4. While the safety calculations indicate sufficient reliability for the forward and rearward trim capability even with a single power supply, a failure probability of approximately $7 \cdot 10^{-10}$ per flight hour would raise the requirements to be met by the other functions of the fuel system to an unrealistic level. Figure 12 describes the mapping of the four power supply buses to the components of the fuel management system — see numbers in squared boxes.

5 PRELIMINARY SAFETY ANALYSIS

In this section, the preliminary safety analysis of the previously proposed fuel management system is discussed in order to demonstrate that the required probability of failure per average flight hour (Q/T) is less than 10^{-9}. For this investigation duration of flight is assumed with 10 h. Applied failure rates are either taken from statistics, existing components or are derived from similar architectures. Due to the early design phase, the component failure rates are component requirements rather than approved values. It is assumed that a faulty component is directly transferred into a passive state and thus excludes the system state "Out Of Control." In addition, the probability of dormant faults is neglected. Furthermore, it is assumed that a faulty data processing component has no inconsistent failure effects possibly affecting its neighbors and that no failure propagation occurs beyond the boundaries of any containment area. The analysis of the fuel system covers the fuel management, the feed function, and the trim function which includes the transfer capability. The fuel gauging is considered with a safety budget because no detailed designs are performed on gauging. Additionally, the re- and defuel function as well as the fuel jettison are neglected since their loss is not safety critical. As already mentioned, 3 Fuel Management Computers (FMC 1, 2 and 3) are required (Fig. 13).

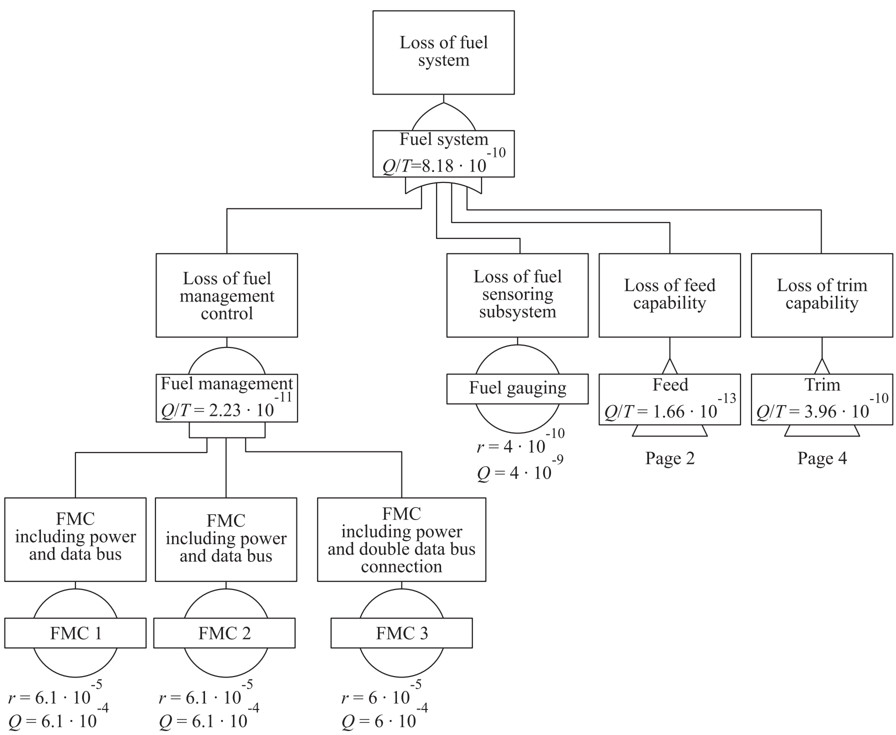

Figure 13 Fuel system fault tree [8]

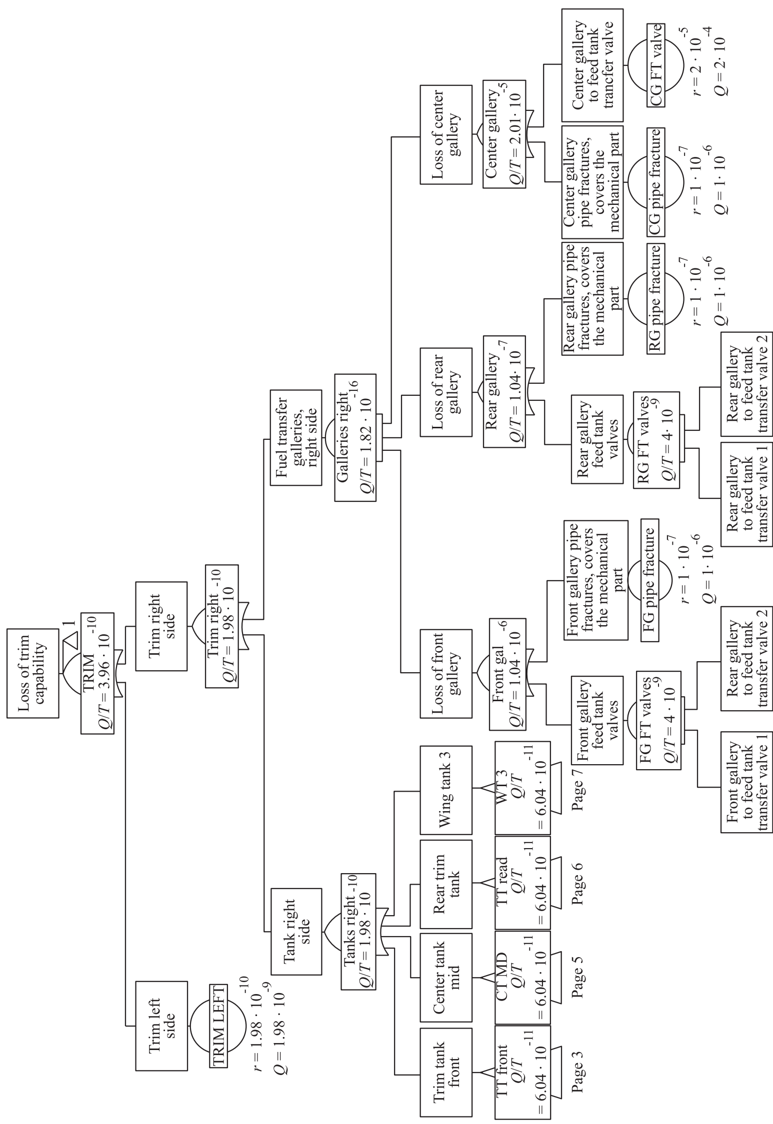

Figure 14 Fault tree for the trim by fuel redistribution function [8]

The small failure probability of the feed function of $1.66 \cdot 10^{-13}$ per flight hour results from the requirement for an emergency pump and for cross-feed capability which can only be performed if both feed pumps of the supplying side and one cross-feed valve are operational. The feed system thus does not have any significant influence on the system's overall failure rate. The safety analysis of the proposed fuel management system is detailed in [8]. Here, only the fault tree for the trim function is extended due to its significance for this paper (Fig. 14). The trim function is divided into a left and a right side reflecting the local separation within the aircraft. For simplification and the fact that both sides have the same configuration, only one side is further broken down to the component level. There, the two domains "access to tanks" and "fuel transfer" are grouped since both of them are safety critical for themselves. The limiting factor for the center gallery is the single valve to the feed tank, whereas for the other two, a pipe fracture is the most likely event. With respect to safety, one feed tank valve would be sufficient. But on the other hand, each one of these would become the bottleneck because a single failure would cause the loss of

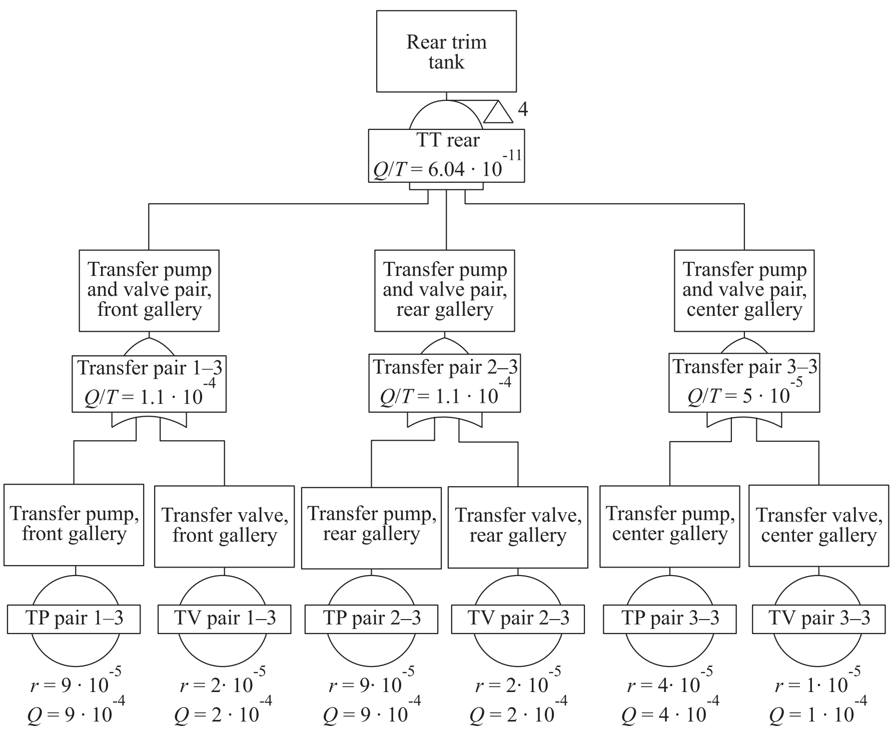

Figure 15 Fault tree for loss of rear trim tank [8]

the whole gallery's feed tank supply, justifying two valves. As expected, the relatively high importance of the trim function for the system's overall failure rate is mostly reasoned by the reliability of the transfer pumps and valves within the center, front, and rear trim tanks.

As an example, Fig. 15 shows the fault tree for loosing access to the fuel within the rear trim tank. Emptying WT3 is less challenging because of the drainage valve to WT2 where four transfer pumps powered by different power buses are available.

6 CONCLUDING REMARKS

The fuel tank layout for a fuel management system on a BWB airliner is introduced. It is shown that fuel redistribution during mission allows static stability at takeoff and landing while providing improved lift-to-drag ratio at cruise Mach number with minimum static stability. Numeric trim computations with a flexible model of the investigated BWB aircraft even suggest that optimum lift-to-drag ratio is achieved with an unstable configuration. Moreover, a failure in the proposed fuel redistribution system at cruise configuration is shown to cause static instability during deceleration. Thus, the feasibility of active stabilization of the BWB aircraft is investigated. The resulting ability to stabilize the airplane is very limited unless the bandwidth of the aircraft's pitch control surfaces is radically increased which would lead to a heavy and energy consuming actuation system which can jeopardize the efficiency improvement expected from the BWB configuration. Moreover, active stabilization increases the costs for the flight control system in terms of design, certification, maintenance, weight, energy consumption, etc. Thus, as an alternative, the feasibility of fuel management system design with a failure rate of less than 10^{-9} per flight hour is investigated. Said system requires a few more components and more complex management system and power supply than on a conventional airplane but is seen as a promising solution which is most probably less cost intense than active stabilization. Future investigations will be based on investigating (with respect to improved fuel efficiency due to reduced trim drag) the trade-off between CG adaptation by fuel redistribution and relaxed static stability enabled by active stabilization.

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