Analysis of a multi-functional high-lift system driven by an active differential gear box

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Abstract A flight dynamics evaluation was performed in order to analyse the ability to use the outer flap for roll control as well. Based on the Airbus A350 flap system architecture, where the outer flap can be deployed independently from the inner flap by using a so called active differential gear box (ADGB), two different concepts were identified as potentially benefitial for the desired purpose. In both concepts the inner ailerons were removed in order to save weight and system complexity and the outer flap performs (all speed) roll control together with the outer (low speed) aileron. Concept 1 comprises the usual flap geometry and the outer aileron, whereas concept 2 comprises an outer flap, which is extended in spanwise direction by the length of the inner aileron. Roll spoilers were not considered in the presented analyses. The flight dynamics evaluation revealed that a flap deflection rate of at least 16°/s is necessary in order to fulfill requirements from certification specification CS-25 and handling quality criteria. A system analysis showed that the existing ADGB is only able to deflect the flap with a maximum rate of 0.43°/s or 1.4°/s with slight modifications of the existing ADGB. These values showed to be insufficient for regular roll control. Nevertheless, in case of a dual loss of hydraulic power the only available roll control could be performed by one remaining pair of ailerons, which are driven by an electrical back-up hydraulic actuator at the A350. In order to enable roll control, if these electrical back-up hydraulic actuators fail additionally, it was analysed whether the outer flap could be used as emergency roll control with the aforementioned feasible flap dynamics. The results showed that the handling qualities with this flap system ensuring roll control are barely controllable. However, it appears feasible to reach degraded but acceptable handling qualities if the system dynamics could be slightly increased.

Keywords multi-functional flap system · active differential gear box · roll control · handling qualities

Abreviations

ADGB	Active Differential Gar Box
AMC	Acceptable Means of Compliance
CPACS	Common Parametric Aircraft Configuration Schema
CS	Certification Specification
DAMIP	Dynamic Aircraft Model Integration Process
DLM	Doublet Lattice Method
EBHA	Electrical Back-up Hydraulic Actuator
EHA	Electrical Hydraulic Actuator
FH	Flight Hour
FTA	Failure Tree Analysis
IAS	Indicated Air Speed
ISA	International Standard Atmosphere
MCE	Motor Control Electronic
PFC	Primary Flight Control
PIO	Pilot Involved Oscillations
VLM	Vortex Lattice Method
WGS	World Geodetic System

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List of symbols

P	Probability (-)
T_R	Roll Time Constant (s)
$\dot{p}$	Roll Acceleration (°/s^2)

1. Introduction

Latest aircraft like the Airbus A350 or B787 comprise systems which enable differential deployment of the inner and outer high-lift flaps. In case of the A350 differential flap settings are used amongst others for drag and loads control in cruise [1]. In order to allow independent movement of the inner and outer flaps the A350 is equipped with an Active Differential Gear Box (ADGB).

The system architecture of the A350 high-lift system is shown in Fig. 1. The ADGB connects the transmission shafts of the inner and outer flaps via a special differential gear box. It further comprises a DC-brushless motor, a power-off-brake, the motor control electronic and all harnesses. It is powered electrically by the 230V AC system. A more detailed system description is given in section 4.

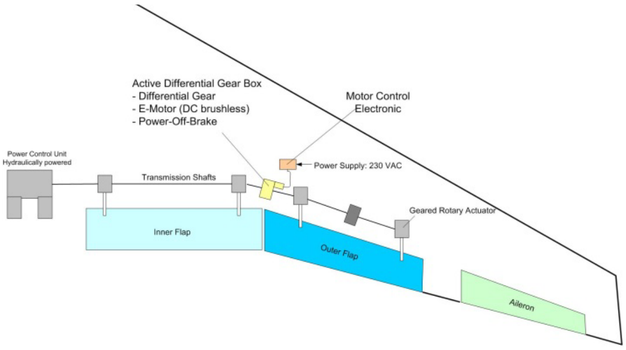

Fig. 1 System Architecture

The current architecture of the ADGB subsystem was developed based on three basic functional requirements:

- Variable camber function in order to increase the aircraft efficiency
- Spanwise lift variation in order to reduce the wing loads under gust conditions
- High lift operation of outer flaps under emergency conditions (loss of two hydraulic systems).

Unlike other flap systems for commercial aircraft, the A350 ADGB subsystem is required to operate the outer flaps independently. The unit’s architecture comprises an electric motor and motor control electronic which is commanded by the high lift control computer.

This independency led to the initial question of this work: “What else can be done with this independant system and could it be used for roll control?”

The need for additional roll control can be justified by two sub-needs:

- Searching for possibilities to develop multifunctional systems and units in order to save weight and costs
- Having a back-up roll control provision available for failure case conditions (i.e. loss of two hydraulic systems)

In order to analyse the potential benefit of the ADGB used for roll control DLR was subcontracted by Liebherr. The flight control capability of a flap system driven by an ADGB was to be analysed through simulations from the flight dynamics perspective.

In absence of an A350 simulation model or any other suitable model of an aircraft of comparable size (e.g. A330), it was decided to use an existing model of the A320 instead. It was assumed that the results of the flight dynamics evaluation, especially in terms of necessary flap deflection rate, can be transferred to aircraft like the A350. For this reason the A320 simulation model had to be adapted to the A350 in terms of the flap system kinematics and aileron layout. In order to allow comparison with the A350 the flap kinematics of the A320 simulation were changed to dropped-hinge and the single ailerons of the A320 were split into to two ailerons at each wing (s. Fig. 2). This simulation model of the adapted A320 is chosen as reference. Besides this reference two different concepts in terms of roll control layout, which appeared most promising for the desired purpose, were investigated. Fig. 2 gives an overview on the analysed concepts and the specific flap and aileron layout of each concept.

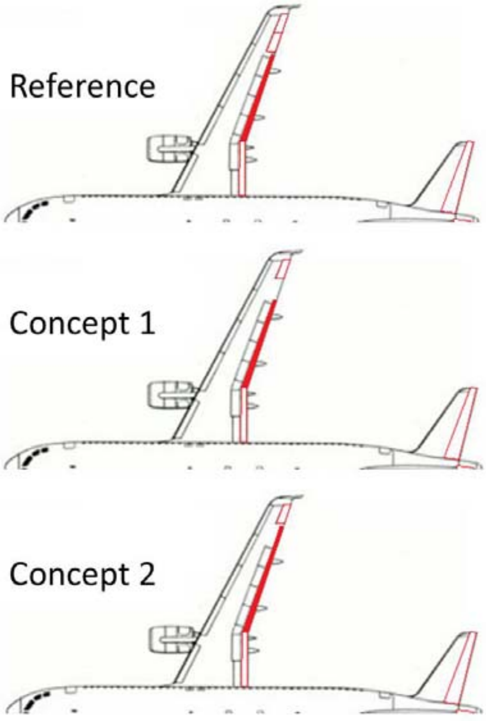

Fig. 2 Analysed flap and aileron layout concepts

Concept 1 comprises the same outboard flap as the reference as well as the outboard aileron for roll control. Differing from this, Concept 2 comprises the outboard aileron as well as an adapted outboard flap which is extended in spanwise direction by the length of the former inner aileron. The inboard aileron was removed for roll control in both concepts. Both the inner flap and the outer aileron remained unchanged in all roll control layouts.

It should be mentioned that roll spoilers were not considered at any concept. Due to the specific method used for aerodynamic modelling, namely the vortex lattice method (VLM), spoilers could not be modelled. However, this lack of roll control power is identical for each of the analysed concepts, for which reason the roll spoilers are disregarded here.

Another factor neglected here is aeroelastic bending of the outer flaps. The aircraft is modelled as rigid body. For analysis of a possible bending of the outer flap when it is deployed for primary flight control a more detailed modelling would be necessary.

2. Simulation modelling

Analyses of roll controllability involve extensive nonlinear simulations of specified rolling manoeuvres over the full aircraft operating envelope (s. section 3.1). For this reason, the first step of this work was the development of suitable nonlinear simulation models that incorporate the various adapted devices for roll control. The main requirements for the models included:

- Possibility to easily adapt flap geometry for studying various high-lift design configurations,
- Sufficient expected accuracy (e.g. 10-20% for aerodynamic stability derivatives over the normal operating regime),
- Loop capability (due to large numbers of simulations required),
- Inclusion of a stall model,
- Hinge moment computation for relevant control surfaces and flaps and associated kinematics.

The Airbus A320 was selected as a baseline configuration due to the availability of the aircraft model, geometry, systems and operational data at DLR.

For modelling tasks like this, DLR has developed its dedicated “Dynamic Aircraft Model Integration Process” (DAMIP) [2]. This process involves integration of available data for a given airframe configuration into loop-capable models in a best-suited form for analysis of flight dynamics, loads, performance, flight missions or for flight control design analyses. If not readily or only partly available, an aerodynamic model is computed or augmented using lower-level methods, like the Vortex-Lattice Method (VLM), the Doublet Lattice Method (DLM, for flexible aircraft), or panel methods. Once input data has been prepared, DAMIP runs automatically.

2.1 Model structure

The model has been implemented using Modelica [3] and a DLR in-house developed Flight Dynamics Library [4] (s. Fig. 3).

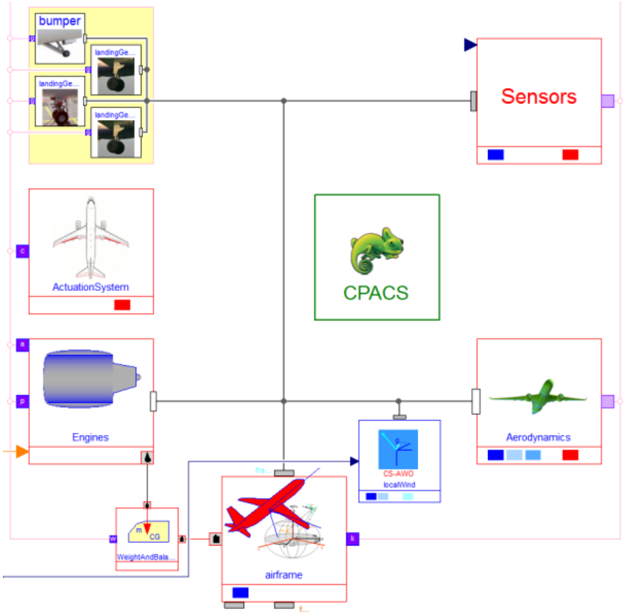

Fig. 3 Modelica object diagram of the aircraft model

The main strength of Modelica is multidisciplinary model implementation. To this end, Modelica allows model components to be coded and interconnected based on the original physical equations, rather than “sorted and solved” algorithms or signal flow diagrams as in traditional simulation tools. In this way, components can be constructed from discipline-specific libraries (multi-body, electronics, block diagrams, etc.) and integrated in a single model.

The aircraft model structure comprises an engine model, actuators, kinematics, weight and balance, aerodynamics, landing gears (optional), and sensors. Besides the aerodynamics, these components are based on available A320 model data. The actuation model includes parametrised allocation algorithms, e.g. for distributing roll commands over aileron and ADGB-driven outboard flaps. Control surfaces may of course be commanded directly as well. Environment models (gravity, inertial and WGS-84 coordinate systems and magnetic field), atmosphere (ISA, wind models) and terrain are at a higher model level and not depicted in Fig. 3.

All relevant data has been stored in an XML-based CPACS (Common Parametric Aircraft Configuration Schema) database [5]. This database is loaded during initialisation for simulation.

2.2 Aerodynamic model

The proposed geometrical changes to the outboard flaps and ailerons required most of the aerodynamic model to be newly developed (compared to the original A320). To this end, VLM was used. As forces in direction of flow are poorly covered by this method, the lift-drag polar of a reference model was used to estimate the overall drag. The local drag effects on the flaps, which considerably affect hinge moments at higher angles of deflection, are not covered. For this reason, the analyses address only changes in hinge moment levels from those of the baseline configuration. VLM requires the airframe to be represented by means of flat panels as depicted in Fig. 4.

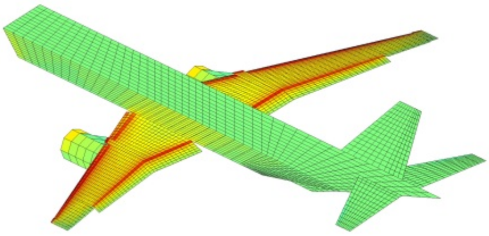

Fig. 4 Example panel geometry with VLM-computated pressure distribution

Control surfaces are defined by grouping appropriate panels and specifying their hinge lines. In order to cover the increase in wing surface area due to extension of the fowler-type flaps, three panel representations for flap settings clean (0), full (4), and in between (2) were generated. The aerodynamic derivatives were computed for the three configurations and various Mach numbers. Finally, the results were stored in multi-dimentional look-up tables for use in the simulation model. In DAMIP, this whole process, from VLM computation to coding of model equations in the model, is automated.
A stall model based on handbook formulae was included and parameters were calibrated to match stall speeds (as a function of weight and high-lift configuration) of the original A320 configuration.

2.3 Flap Kinematics

In order to enable transfering the results of the investigation from A320 to A350, the flap system of the A320-like aircraft model was assumed to comprise dropped-hinge kinematics. Thus, for the aerodynamic modelling the flap positions needed to be adjusted to the new positions of dropped-hinge flaps. A hinge point was estimated which should change the flap positions as less as possible in comparison to the A320 flap positions. Fig. 5 shows the estimation of the hinge point and the new flap positions based on the original A320 flap kinematics.

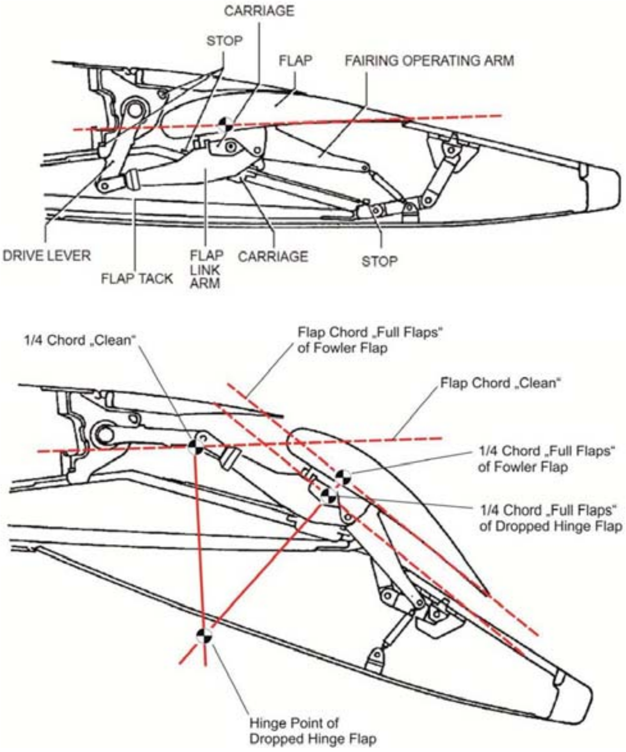

Fig. 5 Estimation of the hinge point and the new full flap position

The upper part of Fig. 5 shows the flap in retracted (“clean”) positions as well as the chord line of the flap (red dashed line) and the 25% point of the chord. The lower part of Fig. 5 shows the flap in fully extended position (“full flaps”). The chord line of the full flap position and the 25% chord point are drawn and for the retracted flap the chord line and the 25% chord point are transferred into the same drawing of the full flap position. The hinge point is constructed by drawing lines from the 25% chord point perpendicular to both chord lines. The intersection point of both lines is assumed to be a possible hinge point. Nevertheless, the length of both lever arms between this hinge point and both 25% chord points are different. For this reason the extended flap position needs to be adjusted in a way that both lever arms are identically long. It is obvious in Fig. 5 that the estimated flap position of the dropped-hinge flap is slightly lower and a little forward than the original A320 full flaps position. However, it is assumed that the changes of gap and overlap between flap and spoiler, which are of great importance for the aerodynamic efficiency of the high-lift system, can be adapted to the changed position of the flap, assuring the same aerodynamic efficiency. Indeed, the position of the hinge point might not be optimal as it is very low under the wing. However, it represents a possible solution with only minor changes of the flap positions with respect to the A320.

2.4 Simulation model

Simulation code (C/C++) is generated automatically from Modelica models by means of a modelling environment like DYMOLA [6]. This allows different types of runtime models for various types of model analyses to be obtained from a single model implementation. In this case, a non-linear six-degrees-of-freedom simulation model and according trimming script were generated for use in Matlab^{TM} / Simulink^{TM}. Model inputs and outputs were automatically adapted for the tool to be used for simulation analyses (s. section 3). The trimming script was extended and parametrised to properly initialize all simulation scenarios in all relevant flight conditions, as specified in the CS-25. Most relevant in this case are turning in level flight with both engines operative or with a single engine failure.

The simulation model was extensively validated by means of comparison with a reference A320 model and with results from other aerodynamic codes. In case of modified airframe configurations, qualitative and quantitative sanity checks were performed.

3. Flight dynamics requirements

With the simulation model described above the necessary system dynamics were evaluated based on requirements from the certification specification (CS-25) and handling quality criteria. These system dynamics in terms of necessary flap deflection and flap deflection rate should allow the use of the outer flaps as regular primary flight controls. For the evaluation of the required flap system dynamics the flap deflection and rate were adjusted in a way that the roll control efficency of the analysed layout is the same as that of the reference aircraft.

3.1 Requirements from Certification Specification

For the design of roll controls the relevant paragraph of the CS-25 is 25.147 “Lateral control”. This paragraph generally states that with the critical engine inoperative as well as with the engines operating, *“roll response must allow normal manoeuvres (such as recovery from upsets produced by gusts and the initiation of evasive manoeuvres)”* [7].

A method to demonstrate that the aircraft fulfils this requirement is given in the respective Acceptable Means of Compliance AMC 25.147. This AMC requires that it should be possible to roll the aircraft from a steady 30° banked turn through an angle of 60° in not more than 7 seconds with all engines operating and in not more than 11 seconds with that engine inoperative, which is most critical for controllability [7].

First of all, this manoeuvre was simulated with the reference aircraft in order to evaluate the roll control power of the reference. The simulations showed that the time to accomplish the required manoeuvre is in the range of one to five seconds for the reference aircraft (s. Fig. 6).

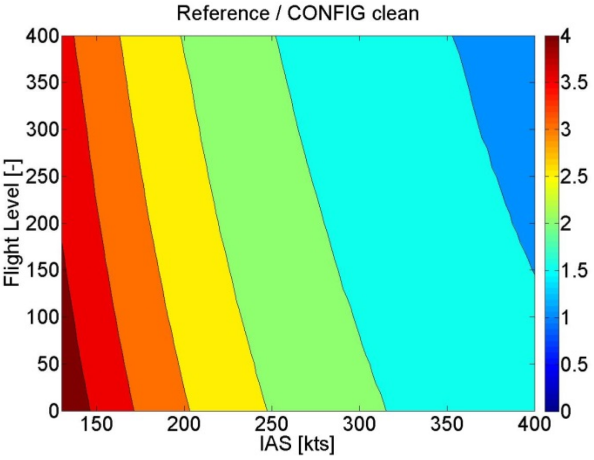

Fig. 6 Time to accomplish roll manoeuvre in seconds with reference aircraft in clean configuration

This is indeed extremely quick for an aircraft like the A320 especially as no roll spoilers are used. However, it must be emphasised here that in the simulation model the aircraft is modelled as a rigid body. Therefore, no damping effects due to wing bending or any other dynamic effects exist in the simulation. Regardless the actual roll power of the real A320 the flight dynamics evaluation for the analysed concepts 1 and 2 is performed relative to the roll control power of the reference aircraft simulation.

The flap deflection rate was adapted for concepts 1 and 2 in order to match the simulation results of the reference aircraft. As the flap area is larger at concept 2 the required flap deflection angles as well as the deflection rate are smaller than at concept 1. Table 1 shows the flap deflection angles and deflection rates of concepts 1 and 2 necessary to aquire the roll control power of the reference aircraft.

The simulations of concept 1 showed that the clean and full flaps configuration are the most critical cases as in both cases one flap is at its mechanical stop position. For this reason the other flap has to generate the rolling moment alone. In flap configurations 1+F to 3 the flaps are in such position that for roll control one flap can be deployed whereas the other flap can be retracted. This leads to a smaller required flap deflection angle and rate. As the intermediate flap positions are not the critical ones concept 2 was only analysed for the flap positions “clean” and “full” (s. Table 1).

The full flap position is also critical as roll control results in a loss of lift, hence an increase of the stall speed. This fact had to be counteracted by a larger approach speed, which is indeed a design issue. Concerning this issue concept 2 has a clear benefit due to the larger flap. As the flap generates more lift the deflection in full flaps position can be decreased compared to the reference and concept 1. The simulations showed that with the larger area the outer flap only needs to be deflected to 32° instead of 35° in order to aquire the same fligth state. This offers the possibility to further deflect the outer flap up to 35° for roll control and thus generate more rolling moment even in full flap configuration. Furthermore, the rolling moment is generated neutrally concerning lift, which would not have a negative effect on the stall speed, hence approach speed.

CONFIG	**0/1**	**1+F**	**2**	**3**	**4**
Concept 1					
deflection [°]	13	+/-5	+/-5	+/-5	-9
rate [°/s]	20	10	10	10	15
Concept 2					
deflection [°]	11	n.a.	n.a.	n.a.	-4 / 3
rate [°/s]	16	n.a.	n.a.	n.a.	10

Table 1 Necessary flap deflections and rates

3.2 Handling Quality Analysis

Besides the requirements given in the certification specification, handling qualities are another important factor for flight control design or for evaluation of flight control efficiency. For the definition of handling quality criteria three different handling quality levels were defined [8] in the following way:

- Level I: Flying qualities clearly adequate for the mission flight phase,
- Level II: Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists,
- Level III: Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both.

As limit values for handling quality criteria might differ between different classes of aircraft, four different aircraft classes were defined of which only one is applicable for this analysis, namely Class III: large, heavy, low-to-medium maneuverability airplanes such as heavy transport, cargo, tanker or heavy bomber airplanes [8].

For roll control a suitable handling quality criterion exists which rates the maximum roll acceleration and the roll time constant (s. Fig. 7).

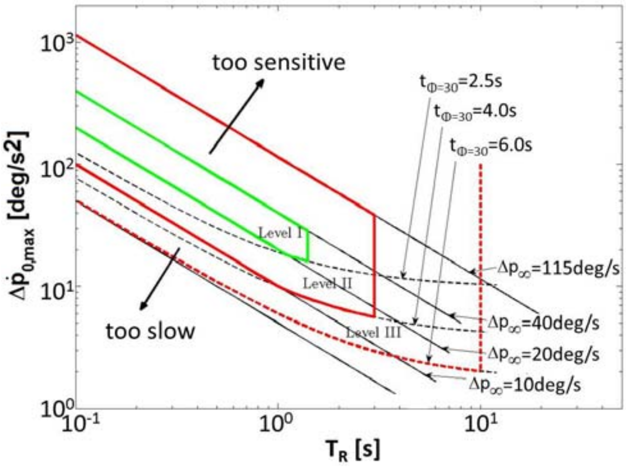

Fig. 7 Handling quality criterion for roll control

One can observe in Fig. 7 that in case of too high roll accelarations the roll control would be too sensitive (possibly causing pilot involved oscillations PIO), whereas for too low roll accelerations the aircraft response on a control input would be too slow (possibly causing overcontrol by the pilot).

For evaluation of the handling qualities the flap deflection angles and rates as depicted in Table 1 were applied. The maximum roll acceleration and the roll time constant were evaluated for all flap configurations within the whole flight envelope. It is not surprising that the handling qualities are exactly in the same area for all of the three analysed concepts. As the roll control power of concepts 1 and 2 were adapted to that of the reference aircraft the handling qualities should be the same as well. Fig. 8 shows the region of handling qualities for all analysed concepts.

As can be seen in Fig. 8 the handling qualities are in a relatively good region. Indeed, the handling qualities are not only in the Level I area but also in Level II, but this fact might also be influenced by the level of accuracy of the simulation model. As mentioned before e.g. no roll spoilers are available in the model. Nevertheless, the simulation results show that the handling qualities of the reference aircraft are in an acceptable region, and that the roll control of the analysed concepts 1 and 2 can be adapted in a way that the handling qualities are comparable to the reference.

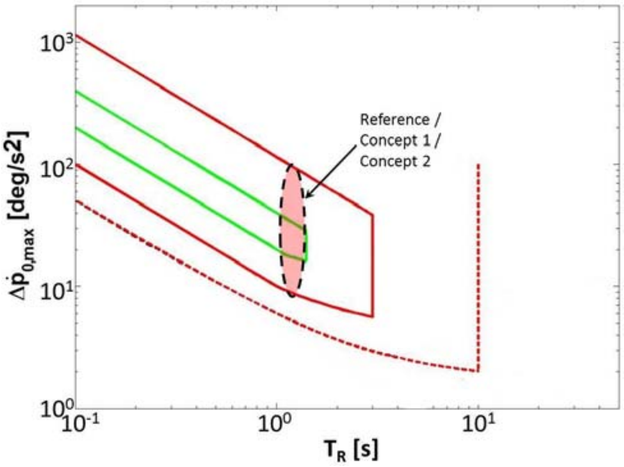

Fig. 8 Handling qualities for all analysed roll control concepts

3.3 Minimum Requirements Analysis

The flight dynamics analysis revealed an enormeous roll control power of all concepts. Therefore, the actual roll performance is much better than required. In order to judge whether the flap system performance necessary to match the reference is really necessary to fulfil the requirements from CS-25 or handling qualities, or whether the flap dynamics could be relaxed, a minimum requirements analysis was performed.

This minimum requirements analysis applies a much lower aircraft roll rate of 15°/s. This value is the maximum commandable roll rate under manual control at all Airbus aircraft. Although the relevant AMC from the CS-25 requires only an average roll rate of about 8.5°/s (60 degrees in 7 seconds) it was assumed that the maximum achievable roll rate should not be below 15°/s. Furthermore it was decided to use a flap deflection rate of 16°/s, which showed to be sufficient in the analysis described above. As the flap deflection rate mainly influences the roll acceleration, hence handling qualities, which were acceptable with this deflection rate, it was set and fixed to 16°/s for all flap configurations.

With a constant roll rate within the whole flight envelope a controller is necessary for controlling the outer flaps. Therefore, the roll rate was fed back into the outer flap controller, which was designed with proportional and integral part. Simulations showed that even with only the outer ailerons the roll rate is larger than 15°/s at high airspeeds. Therefore, the maximum deflection of the ailerons was limited as a function of the indicated airspeed (s. Fig. 9).

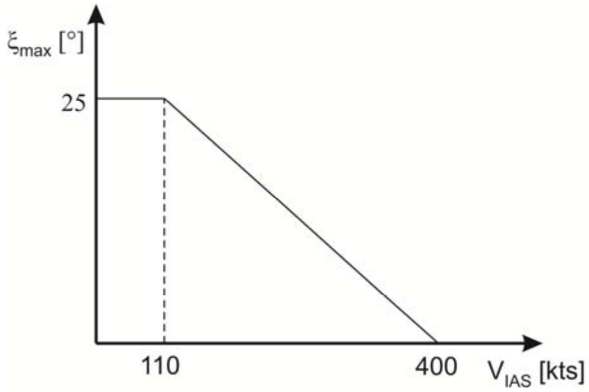

Fig. 9 Speed dependent limitation of the maximum aileron deflection

With this controller the roll requirement from CS-25 and the handling qualities were evaluated again. In addition the hinge moments were calculated in order to estimate the necessary actuation effort. The evaluation of the time to accomplish the roll manoeuvre defined in CS-25 reveales now a more or less constant duration of the manoeuvre of about 4 seconds. This value is ideed not surprising with a bank angle difference of 60° and a roll rate of 15°/s. Another issue is the handling quality evaluation, which showed very good results for this roll control concept (s. Fig. 10).

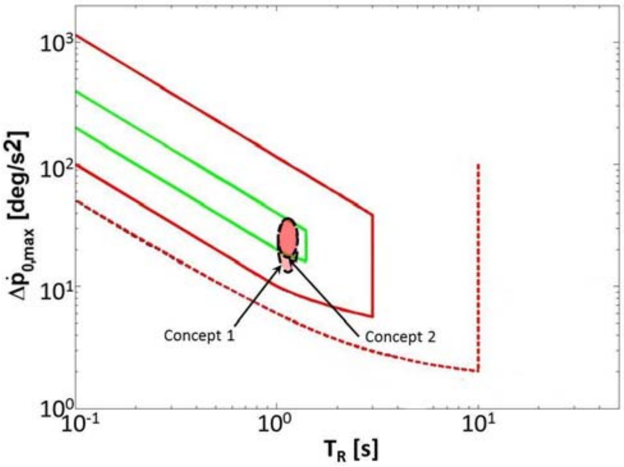

Fig. 10 Handling qualities for all flap settings within the whole flight envelope with 15°/s roll rate

One can clearly observe in Fig. 10 that the handling qualities of both concepts are very good. Concept 2 shows even slightly better results (possibly due to the larger flap and therefore smaller flap deflection angles), but generally both concepts are in an acceptable range in terms of maximum roll acceleration and roll time constant. As mentioned above the flap deflection rate mainly influences the roll acceleration, hence the handling qualities.

The lower roll rate in these simulations mainly results in lower flap deflection angles, thus lower flap hinge moments. Lowering the hinge moments inevitably lowers the necessary power supply for the flap actuation. Fig. 11 exemplarily shows the maximum hinge moments within the whole flight envelope for flaps in clean configuration.

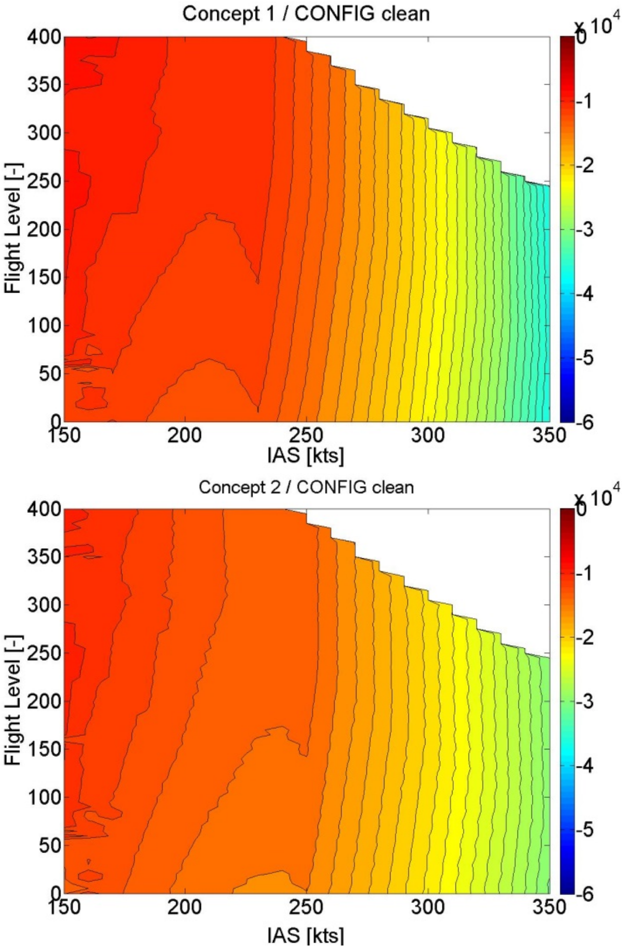

Fig. 11 Maximum hinge moments in Newtonmeter with concept 1 (top) and concept 2 (bottom) in clean configuration

The boundary in the upper right corner of the diagrams is the Mach number boundary of the flight envelope. The colourcoding in the figure reveales that the hinge moments of concept 2 are slightly lower that those of concept 1. This is caused by the larger flap at concept 2 which results in lower necessary flap deflections, hence lower hinge moments. For the approximation of the actuation effort these hinge moments needed to be upscaled to the A350 in order to evaluate the effect on the existing ADGB in terms of actuation power necessary to enable these flap dynamics.

4. System aspects

The three basic requirements for the ADGB subsystem were given in section 1, which require typical high lift actuation system characteristics: operating a panel under high loads with low actuation speed. The development of an actuation system for primary flight control application would need the opposite: operating a panel under low loads with high actuation speed.

Therefore, it was clear from the beginning of the project that for the transfer of the principal application, some modifications of the ADGB subsystem might be necessary. Usually, any flight control system is developed under the strict application of the V&V process (s. Fig. 12).

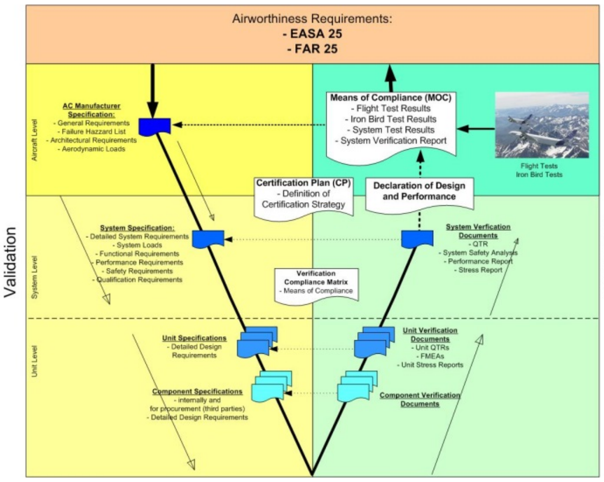

Fig. 12 V&V Process for System Development

This process starts for the system manufacturer with the requirements from the aircraft manufacturer. This role has been taken over by DLR. The required transmission and ADGB motor speeds have been derived by Liebherr from the simulation results under consideration of requirement given in section 2.

However, it turned out very quickly, that with the current ADGB performance characteristic no roll control can be achieved to fulfil the roll control requirements as defined in CS-25 [7]. Therefore, the V&V process on the validation side has been applied for the next step the other way round. Based on two modification steps with different changes on the ADGB subsystem, the achievable performance of the system was used for analyses regarding the achievable roll performance of the aircraft.

4.1 Performance

The following data characterises the current ADGB subsystem:

Max. output power:	3kW
Max. motor speed:	2187 rpm
Max. flap transmission speed:	238 rpm
Operation limited to:	< 10 sec

These characteristics would lead to a flap deflection rate of 0.28°/s, which is far away from a necessary deflection rate of 16°/s in order to fulfil the CS-25 aircraft roll control requirements and Level I handling qualities. The ADGB subsystem and the interface to the flap system was analysed in detail in order to determine two modification steps.

Step A modification:

- Changes restricted to the ADGB subsystem only – no change for flap system.
- No architecture change of the ADGB subsystem.
- Design margins of the e-motor used
- Better cooling of the e-motor and the motor control electronics (MCE) in order to increase limited operation time.

Step B modifications:

- Changes not restricted to ADGB subsystem – flap system transmission speed increased.
- No architectural change of the flap system (gear ratios, limit loads, failure speeds and monitoring not affected)
- Requires change of ADGB e-motor (windings)
- Requires change of MCE (higher power capability)

With the above modifications, the following flap transmission and flap panel deflection rate have been achieved (s. Table 2)

	Step A	**Step B**
Flap transmission speed [rpm]	336	1188
Flap panel deflection speed [°/s]	0.43	1.4

Table 2 System dynamics with modifications

One can see that the maximum transmission speeds remain in the typical range which is known from conventional high lift systems. It is implied that with these speeds no change of the high lift monitoring would be needed (i.e. overspeed monitoring).

4.2 System Safety

Besides the discussed performance issues, system safety considerations were the second subject area to be investigated. A quantitative requirement for “loss of flaperon function (with respect to roll control)” can be derived by the consideration that a total loss of roll function on aircraft level is usually required to be:

$$P_{roll} < 1.0 \cdot 10^{-9} / FH$$

If the flaperons would have to ensure roll control alone, the above requirement would be applicable. However, modern commercial aircraft usually comprise more than just one roll control device – usually there are two pairs of ailerons and several pairs of spoilers available to ensure roll control.

The following scenario serves as an example: The current system layout of the Airbus A350 shows that after total loss of the hydraulic systems, one pair of ailerons and and one pair of spoilers will be actuated electrically in order to ensure roll control. If, due to the initial consideration that the ADGB subsystem should reduce system effort, the pair of spoilers is replaced by the ADGB subsystem, the following requirement becomes applicable:

$$P_{required} < 1.0 \cdot 10^{-4} / FH \ .$$

This number is very pessimistic and implies that the probability for loss of the remaining pair of ailerons is in the order of:

$$P_{ail} < 1.0 \cdot 10^{-5} / FH \ .$$

In the following the analysis of what can be reached for the ADGB subsystem is described in detail. A fault tree analysis (FTA) has been performed in order to determine the contribution of all subsystem failures including mechanical failures of the affected flap system. Fig. 13 shows the system scheme which has been used for this FTA. All mechanical units within the drive path from the ADGB subsystem to the outer flap panel have been considered as well as the failure rates of the ADGB subsystem (including MCE) as well (grey zone in Fig. 13).

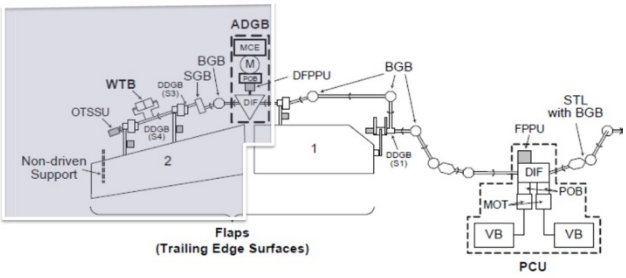

Fig. 13 System scheme for FTA

Since Liebherr has no information regarding failures of the flight control computers, no failure rates of the command path have been included. Fig. 14 shows the (top level) fault tree analysis.

The achieved probability is:

$$P_{achieved} = 6.6 \cdot 10^{-6} \big/ FH \ .$$

By comparing this result to the derived requirement above, it turns out, that the general safety requirements for emergency operation (only electrical power available) can be fulfilled.

Also, the achieved probability could be improved by removing dormant failures by introducing pre-flight checks, hence, limiting dormant failures just to the length of the flight duration. Such pre-flight checks would not increase the work load of the pilots, since they could be initiated automatically.

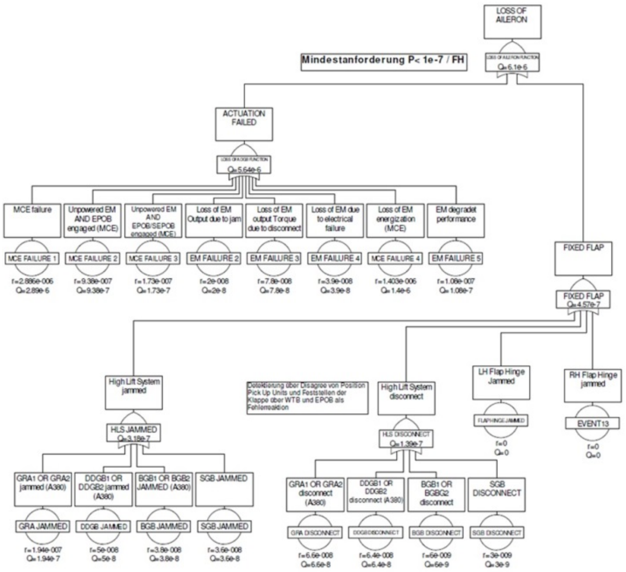

Fig. 14 Fault Tree Analysis

As a summary of the system considerations one can say that the lack of performance is currently the only show stopper.

5. Flight dynamics evaluation with available system performance

As described in section 4.1 the ADGB cannot provide the necessary dynamics of 16°/s flap deflection rate outlined in section 3 without major changes in the ADGB design. Hence, the outer flap could not be used for regular primary flight control. However, the achievable flap dynamics might be sufficient for emergency operations, for example if the aircraft loses the hydraulic supplies and is controlled by the electrical back-up systems only. For such an application, the electrical back-up system for roll control would be enhanced by “outer flap roll control”. Hence, normal back up roll control could be simplified, possibly by using less aileron or spoiler actuators (electric hydraulic actuators EHA or electric back-up hydraulic actuators EBHA).

In order to investigate the possibility of a flap system with dynamics of 0.43°/s without any change of the ADGB and 1.4°/s with minor changes of the ADGB (s. section 4.1) to act as additional emergency flight controls, the flight dynamics analysis was performed again with these flap dynamics. The analysis was not performed within the whole flight envelope, but only for worst case scenarios. Also, only concept 2 (extended outer flap length) was analysed, as it already showed in the previous flight dynamics evaluation (s. section 3) to be the most promising concept.

For both system dynamics two scenarios were analysed, namely in clean configuration and with full flaps, both at low speed and low altitude. As the inner flaps cannot be deployed in the analysed case with dual hydraulic failure, the stall speed of the full flap configuration is significantly increased in this case. Therefore, the simulations were performed with a much higher airspeed of 150 kts. The scenario should cover the case with dual hydraulic failure and additional malfunction of the EBHAs. For this reason solely the outer flaps were used for roll control. Thus, altogether four cases were simulated and analysed regarding the time to accomplish the manoeuvre described in AMC 25.147 and handling qualities. As described in section 3.1 with all engines operating the time to accomplish the required manoeuvre must not exceed 7 seconds. Table 3 depicts the times to accomplish the manoeuvre as evaluated in the simulation.

	$\dot{\eta}_F = 0.43 \ {}^{\circ}\!/_{s}$	$\dot{\eta}_F = 1.4 \ {}^{\circ}\!/_{s}$
IAS = 180 kts Flaps clean	16.9 s	9.3 s
IAS = 150 kts Flaps full	9.4 s	6.3 s

Table 3 Time to accomplish roll manoeuvre

As can be seen in Table 3 the low flap system dynamics of 0.43°/s do not fulfill the requirement under any flap configuration. The flap system with the slightly higher dynamics of 1.4°/s is at least able to fulfill the requirement with full flaps. In clean configuration the requirement is violated as well with these flap dynamics. Another issue are the resulting handling qualities. The same handling quality criterion as described in section 3.2 was applied to the aforementioned four cases. The exact values for the maximum roll acceleration and the roll time constant are given in Table 4 and Table 5.

	$\dot{\eta}_F = 0.43\ {}^{\circ}/_{s}$	$\dot{\eta}_F = 1.4\ {}^{\circ}/_{s}$
IAS = 180 kts Flaps clean	0.43°/s^2	1.54°/s^2
IAS = 150 kts Flaps full	2.29°/s^2	4.45°/s^2

Table 4 Maximum absolute roll acceleration

	$\dot{\eta}_F = 0.43\ {}^{\circ}/_{s}$	$\dot{\eta}_F = 1.4\ {}^{\circ}/_{s}$
IAS = 180 kts Flaps clean	8.5 s	5.2 s
IAS = 150 kts Flaps full	5.5 s	3.2 s

Table 5 Roll time constant

Fig. 15 shows the results of the handling quality analysis in the boundaries of the different handling quality levels. The case with a flap deflection rate of 0.43°/s and clean configuration is not depicted in Fig. 15 as it lies outside the range of the plot. As can be seen in Fig. 15 for both flap dynamics only those cases with full flaps are barely controllable within the Level III boundaries. Both cases with clean configuration are beyond Level III handling qualities, hence not controllable, even with excessive pilot workload.

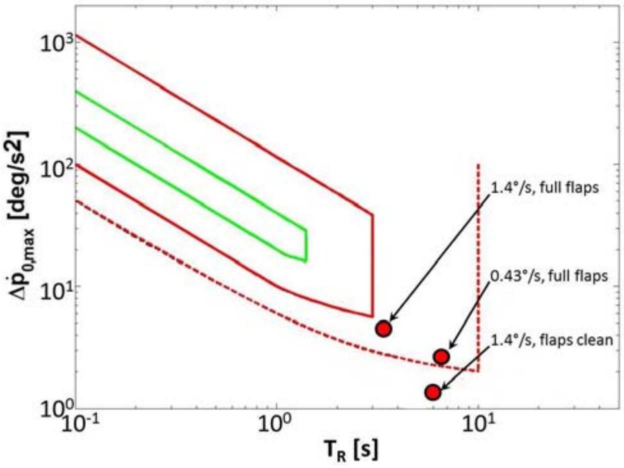

Fig. 15 Handling quality analysis with low system dynamics

The flight dynamics evaluation showed that the low flap dynamics with 0.43°/s flap deflection rate violate any of the requirements. Neither the time to accomplish the manoeuvre from the certification specification, nor the handling qualities can be achieved with such slow roll control. The flap system with a deflection rate of 1.4°/s appears a little more promising against these requirements.

Indeed, with clean configuration all requirements are violated, but at least with flaps in full configuration the requirement from CS-25 could be fulfilled and the handling qualities are inside the Level III area. Thus, the aircraft could possibly be controlled safely, but with excessive pilot workload. However, it is questionable whether such system dynamics could be sufficient to enable a proper backup roll control in case of full loss of hydraulic power and additional malfunctions of the EBHAs.

6. Conclusions

A flight dynamics and system performance analysis was conducted in order to evaluate possible function enhancements of modern transport aircraft high-lift systems. The outer flap of the A350 is driven by an active differential gear box (ADGB) and can be deployed independently from the inner flap. Thus, it could generally be used for roll control.

Simulations concerning requirements from the certification specification and handling qualities revealed a necessary flap deflection rate of about 16°/s for a regular use of the outer flap for roll control. However, system performance analyses revealed an achievable flap deflection rate with the existing A350 ADGB of 0.43°/s without any system modification and 1.4°/s with slight system modifications.

This feasible system dynamics would not be sufficient for roll control. Aircraft simulations revealed that the handling qualities would be in a way that the aircraft would be nearly uncontrollable for the pilot. However, the handling qualities are not so far away from Level III, which might be sufficient for emergency operations. Hence, it could be feasible to reach degraded but acceptable handling quality levels with slightly more design effort on system level. For future applications of a modified ADGB emergency roll control could be a reasonable back-up functionality of the outer high-lift flap.

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