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Inclusion of structure and loads objectives in the definition of probability for Flight Control System failures in the frame of FTB#2 Clean Sky 2

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Abstract

The problem of Static Loads issuing probability requirements for system failure cases, from the point of view of interaction of Systems and Structure, has become more relevant in recent years, since the complexity of aircraft systems has increased. In this paper, we analyze flight control system failure cases for the Clean Sky 2 FTB#2 aircraft, by performing simulations with the latest loads calculation software at Airbus Defence and Space. The results indicate that Static Loads is complementary to System Safety Assessments in terms of failure probability targets in failure cases related to aileron runaway.

1. Introduction

For a number of years the impact of Flight Control System failures on loads and structure has been evaluated once the scenarios and probability of failures were defined in the System Safety Assessment (SSA). In general, the hypothesis behind this approach was that failure cases do not size the structure. As later-generation airplanes developed, the complexity of the systems has evolved in a way that could challenge this hypothesis.

The goal of this paper is to describe how Static Loads can contribute to include structural objectives for Flight Control Systems Safety Assessments.

Static Loads is a department within the Flight Physics Center of Competence at Airbus Defence and Space. The activities performed by Static Loads are, among others, the development of Static Loads models for flight loads and ground loads, usage of simulation codes for maneuver conditions and gusts, loads analysis, nodal loads generation for finite element models (FEM), obtaining clearances for flight and ground loads, specifications, support and analysis of flight tests in the loads environment, development of methods and tools for loads calculations, certification documents, and preliminary aircraft design support.

Structural objectives are given in terms of probability objectives for failure conditions, which can be included as additional input to those defined under CS 25[5] Subpart F. Specific examples will be given in the frame of the Regional FTB#2 (Flight Test Bed 2) as part of the Clean Sky 2 program.

To define structural objectives, Static Loads first performs a preliminary analysis of failure cases for the Flight Control System Functional Hazard Assessment (FHA). The FHA provides a list of safety and reliability objectives for failure conditions associated to the aircraft flight control system, according to the methodology established in CS 25.1309 and related Acceptable Means of Compliance. Static Loads selects the failure cases that could be potentially sizing for design loads. Afterwards, a maximum probability in order for failure loads not to exceed static design loads is calculated, following CS 25.302 requirements (Interaction of Systems and Structure) and Appendix K, for cases impacting either at Time of Occurrence (ToO) or at Continuation of Flight (CoF). Probabilities are selected based on the fact that a safety factor multiplied by the failure case loads should not exceed ultimate design loads. This safety factor is a function of the probability objective, and has different dependencies based on whether the failure case has an impact on ToO or CoF.

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Examples of failure cases for which Static Loads has defined probability objectives are the following: aileron jamming, control wheel gearing error, and uncountered runaway of one aileron. Additional contributions are maximum deflections for maneuver loads alleviation (MLA) systems, which are established based on a benefit-cost assessment taking into account the expected failure probability.

The probability requirements issued in the FHA and in the previously described Static Loads analysis are preliminary and shall be completed in a further step, the System Safety Assessment, according to the system definition and evolution, under CS 25 Subpart F. This document shows examples of the need of taking into account structural requirements due to Static Loads in parallel to those issued under CS 25 Subpart F.

2. State of the art review

The relation of loads calculations with System Safety probability objectives and CS 25.302 has not been found to be extensively documented in research papers. In spite of this, it is a procedure that is used in the industry. We believe that it is important to document this procedure since non-compliance with Subpart C, CS 25.302 could lead to serious consequences in aircraft development and certification. It is also important since loads calculations and the FHA or SSA are usually performed in parallel in the same period of time.

This section provides a review of the state of the art of interaction of Systems and Structure, mostly in research publications. The following topics related to CS 25.302 have been covered in research papers, and are briefly described in the following paragraphs:

- More integrated flight simulation techniques.
- Flight control system design as part of multidisciplinary optimization (MDO).
- Relationship between failure detection, isolation and recovery (FDIR) and structural design for weight reduction.
- Maximum useful gust loads alleviation (GLA) when complying with regulations.

In a meeting within the Air Transport Network - Next Generation project[12] in the frame of EASA, about the current status and future challenges of aircraft certification and simulation, it was stated that one of the future challenges is to begin taking more and more into account the interaction of Systems and Structure in the simulation field, since simulation is becoming more and more integrated.

The interaction of Systems and Structure was also given key importance in the frame of MDO,[8] specially in flight control system design as part of the loads process in MDO.

An article[13] about FDIR in aerospace speaks about the current industrial practice for runaway detection, among other things, and how there is a need for improvement of failure detection of this kind. Failure detection improvement, when looked at from the point of view of CS 25.302, could lead to lower final deflection in the runaway, and this could potentially have favorable consequences on design loads, aircraft weight or fuel consumption. The article[13] also reflects the need to take into account these kinds of regulations in order to have a realistic vision of modern design concepts. Our paper calculates loads for aileron runaways of different runaway times, and analyzes them from the interaction of Systems and Structure perspective.

Another source[6] also underlines the importance of EASA regulations CS 25.302 when related to failure detection in electrical flight control systems (EFCS). There are two important facts: regulations should be complied with, and there are constantly more strict goals for weight saving to improve aircraft performance. As a consequence, failure detection methods in EFCS should improve. The book[6] provides specific examples on an A380 oscillatory failure case. No oscillatory failure cases are analyzed in this paper, since the analysis of those kinds of failure cases corresponds to Dynamic Loads.

In an article about about GLA system design,[7] CS 25.302 regulations are mentioned. The report speaks about the efficient design of GLA systems by implementing predictive control on aeroservoelastic aircraft models. CS 25.302 comes into play since failed GLA systems can have an influence on static sizing, so there is a maximum GLA that the aircraft can benefit from if complying with Appendix K regulations. In this paper, a similar result for maximum MLA that the aircraft can benefit from is provided, instead of GLA.

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At Airbus Defence and Space, and for the C295MW aircraft with new control system integration, there are several occasions in which reviewing failure cases from the point of view of CS 25.302 has been done. In particular, within the steps linked to the Flight Test Bed (FTB) for the European Framework program Clean Sky 2, failure cases revision has been done for FTB#2 Step 0 (also referred to as C295 P1 RTF) and FTB#2 Clean Sky 2 Step 1 and Step 2. For the C295 P1 RTF, a technical report was released that analyzed flight control system failure cases given in its SSA, using expected probabilities when possible. The expected probability is the probability that the system is intended to provide (at least) in the end; sometimes, an expected probability is not required to be calculated as such for CS 25 Subpart F, which is the case in failure cases that have either minor (MIN) or major (MAJ) categorization. The failure cases that were analyzed were the following:

- Loss of control of one elevator.
- Jamming of one elevator.
- Partially damped flotation of one elevator.
- Undetected erroneous gearing of control wheels (low speed gearing at high speed).

The final result was that the selected failure cases were below the limit loads, i.e. do not size the structure. Note that in this case, the standard approach was followed, where no requirements were previously made in parallel to the SSA by performing a previous FHA analysis. It was simply checked afterwards that System Safety requirements had no impact on Static Loads.

However, in this paper, a new approach will be described, where for the analysis of FTB#2 Step 1 and Step 2 failure cases, full simulations are performed in each case, and some probability target requirements are made in parallel to FTB#2's SSA.

3. Clean Sky 2 project general description

Clean Sky is a European joint technology undertaking aimed at research for reducing CO_2, gas emissions and noise levels produced by aircraft.[4]

Figure 1: Clean Sky 2 program logo[4]

Clean Sky 2 is the continuation of Clean Sky and it was founded in 2014. It is basically a re-thinking of the whole Clean Sky program in order to bring the current achievements in Clean Sky to a further level of complexity and maturity. The top level objectives for this program are developing technologies capable of:[1]

- Increasing aircraft fuel efficiency by reducing $\mathrm{CO_2}$ emissions by 20-30% compared to 2014 state-of-the-art aircraft.
- Reducing NO_x emissions by 20-30% compared to 2014 state-of-the-art aircraft.
- Reducing noise by 20-30% in dB.

The transition from Clean Sky to Clean Sky 2 top level goals are represented graphically in figure 2.

The Clean Sky 2 project is relevant since the environmental impact of aviation is significant. Greener aircraft technologies are required in order to reach the objectives that IATA has set in their $\mathrm{CO_2}$ emissions roadmap (figure 3).

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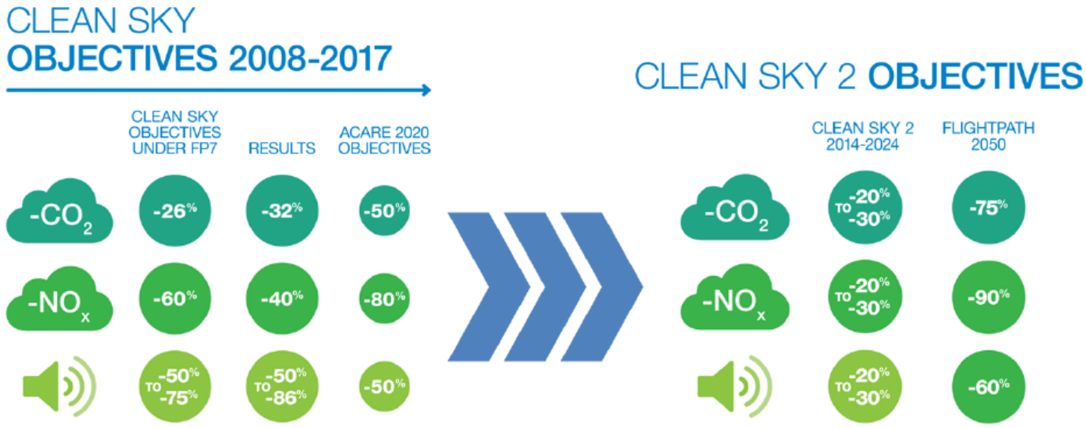

Figure 2: Clean Sky transition to Clean Sky 2[2]

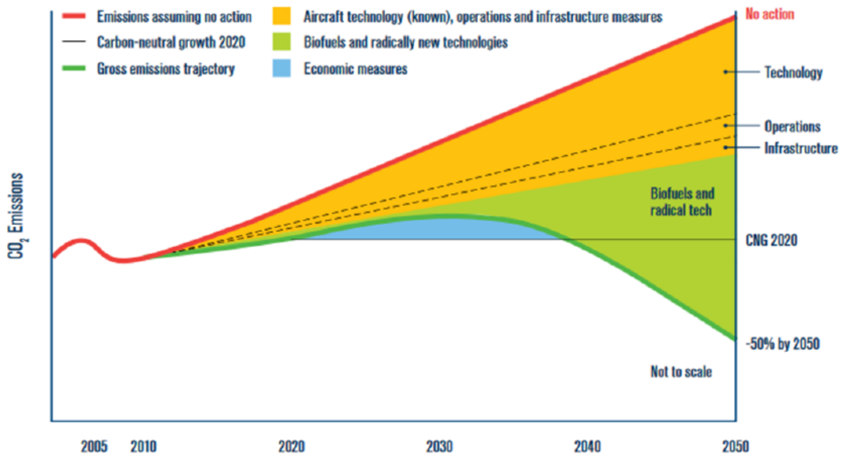

Figure 3: IATA carbon dioxide emissions roadmap 2[2]

The Clean Sky 2 overall program structure[2] consists of aircraft configurations, often referred to as IADP (Innovative Aircraft Demonstrator Platforms), integrated technologies demonstrators (ITD) and transverse activities (TA). The following three IADPs are defined in the Clean Sky 2 program:

- Large passenger aircraft (LPA), which covers large commercial aircraft application for short, medium and long range in air transport.
- Regional aircraft (REG), which refers to Regional turboprop aircraft for regional connections.
- Fast rotorcraft (FRC) whose goals is new configurations for helicopers and commuter fixed wing aircraft.

The integrated technologies demonstrators, which comprise the relevant technology streams for all vehicle applications, consist of:

- Airframe ITD (AIR), which treats topics that affect the global vehicle level design.
- Engines ITD (ENG), which refers to propulsion and power plant solutions.
- Systems ITD (SYS), which refers to on-board systems, equipment and flight management.

TAs consist of transverse activities across IADPs and ITDs:

- ECO-Design TA (ECO), addressing materials, processes and recources for the life cycle optimization of technologies, components and vehicles.
- Small Air Transport TA (SAT), comprising airframe, engines and systems for small aircraft.

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FTB#2 belongs to the Regional IADP initiative. The Regional FTB#2 is the major in-flight demonstrator for integrated technologies that Airbus Defence and Space is leading as part of the Clean Sky 2 program. The strategy of the FTB#2 demonstrator is based on the semi-morphing wing concept, consisting in wing geometry adaptation to flight conditions by means of the deflection of a high number of complementary and redundant wing control surfaces.

A model of the flight test bed platform is shown in figure 4.

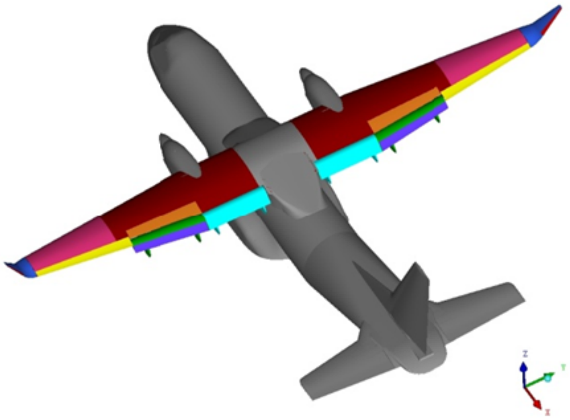

Figure 4: FTB#2 aircraft model[3]

From the structure and materials point of view, which is one the most relevant parts of this paper, the technology lines set for technology readiness level (TRL) review in 2022 for the REG IADP at Airbus are the following:

1. Morphing winglet, with micro electromechanical actuator integration.
2. Composite wing box.
3. Multifunctional flap, with a tab with independent actuation.
4. Advanced spoiler and aileron.
5. Advanced integrated cockpit including composite materials.

Lastly, note that FTB#2 is divided into two steps, Step 1 and Step 2, with different technologies to be demonstrated in each of them.

4. Interaction of Systems and Structure

System Safety delivers probability objectives under CS 25.1309 (in Subpart F), which apply to systems like flight control systems, electrical power systems and hydraulic systems among others. System Safety probability requirements are delivered in two steps:

- The FHA is a systematic examination, evaluation and assessment of all the system functions, with the aim of identifying and classifying all the potential hazards to the aircraft. A safety level is defined via safety objectives.
- The SSA is the step following the FHA. It is a systematic examination of the proposed system architecture to demonstrate compliance with the FHA requirements.

For a long time, the standard hypothesis has been that failure cases described in the FHA do not size the structure. However, as aircraft systems have developed over time, this assumption has been found not to be true in some cases. Sometimes, it has been found that the FHA does not provide enough details or provides a probability objective that would be sizing for the structure. In this case, Static Loads should be able to issue requirements in parallel to Subpart F, and these requirements should be reflected in the SSA.

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In order to issue these requirements, Static Loads looks at the Interaction of Systems and Structure section in CS 25 Subpart C. This section states that for aircraft equipped with systems that affect structural performance either directly or as a result of their failure, this performance should be evaluated following CS 25 Appendix K. Sometimes, probability requirements are issued, and sometimes the equations in Appendix K simply confirm that the failure case is not sizing for the structure.

Static Loads focuses on flight control system failure cases. An analysis is performed of all flight control system failure cases presented in the FHA and SSA that have a potential impact on Static Loads, except of the extremely improbable failure cases, with a probability objective of $P_j \leq 10^{-9}$, which Appendix K says should not be evaluated. Static Loads will therefore analyze failure cases with $P_j > 10^{-9}$.

At ToC, in the flight conditions described in Appendix K (a reduced design loads envelope), failure loads multiplied by a reduced factor of safety (FS), which in turn is dependent on P_j, should be at most ultimate design loads, in order not to have the structure sized by failure cases. Equation 1 should be complied with, and $FS(P_j)$ is shown in figure 5. A reduced factor of safety is used, since failure case loads can be higher than limit loads in some conditions.

$$FS(P_j) \times Loads_{ToC} \leq 1.5 \times Loads_{limit} \tag{1}$$

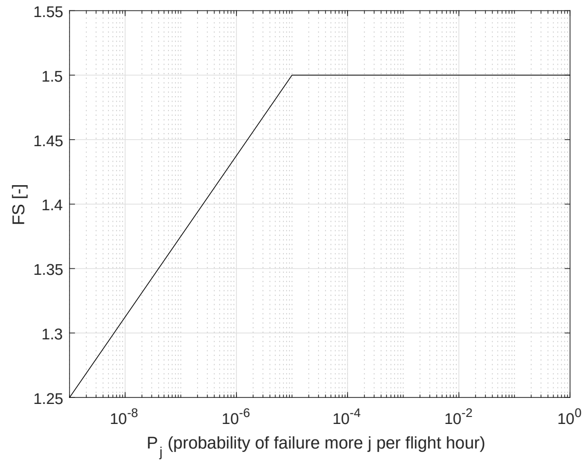

Figure 5: Reduced factor of safety as a function of P_j as shown in CS 25 Appendix K

In CoF, for static strength substantiation, the loads conditions in the failed state, described in Appendix K, multiplied by a reduced factor of safety dependent on the probability of being in failure condition (Q_j), should be withstood by the structure, complying with equation 2, in order for the structure not to be sized by the failure case. $FS(Q_j)$ is shown in figure 6. Q_j is actually a function of P_j. The two are related by the average time spent in failure condition in hours (T_j), for failure cases which have an impact in CoF ($Q_j = T_j P_j$). Sometimes this time is calculated as the risk time of the failure case provided in the FHA or SSA, and sometimes it is taken as half the typical patrol time, as has been done in FTB#2's failure cases analysis.

$$FS(Q_j) \times Loads_{CoF} \leq 1.5 \times Loads_{limit} \tag{2}$$

Given equations 1 and 2, Static Loads is able to, in summary, provide P_j objectives with the goal in mind that failure cases should not be sizing for the structure.

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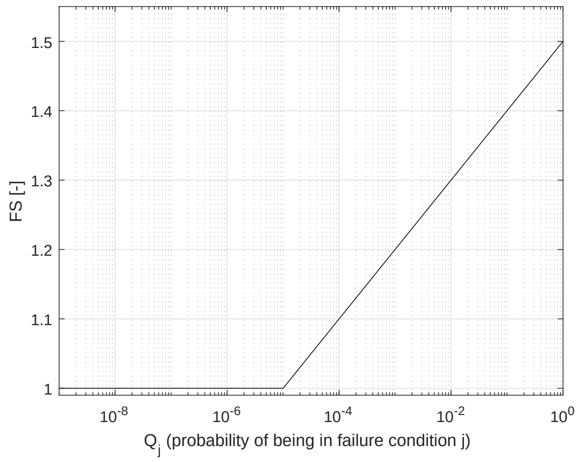

Figure 6: Reduced factor of safety as a function of Q_j as shown in CS 25 Appendix K

5. FTB#2 probability requirements by Static Loads

In this section, failure cases for Step 1 and Step 2, given by the System Safety department in FTB#2's FHA, have been assessed to determine their impact on Static Loads. Failure cases that have been analyzed, among all the failures listed in the FHA, are a reduced subset composed of:

- Failures with $P_j > 10^{-9}$, which means that the failure case is not extremely improbable.
- Only failure cases leading to uncommanded control surface responses, independently of their origin (electronic-related, hydraulic...). In relation to uncommanded control surface responses, only aileron failure cases have been studied, since the target rolling rate is obtained using only aileron in the design loads loop. Also, maximum flap and flap tab deflections are covered in FTB#2's design loads loop.
- From the subset of failure cases that could have an impact on Static Loads, failure cases that are covered by others have not been analyzed either. For example, there are some failure cases that, in the FHA, are divided into two scenarios: the in-flight scenario, and the take-off, approach or landing scenario. The latter scenarios would be covered by the in-flight failure case, since it is calculated at a higher speed.

Detailed information for these failure cases and any acronyms and references used in this section are given in the original failure cases publications for FTB#2[9].[10]

5.1 Analysis for Step 1 configuration

The selected failure cases for analysis are summarized in table 1.

Table 1: System Safety objectives for FTB#2 Step 1 based on FHA tentative numbers

Functional failure	**P_j objective**
Loss of control of one aileron	$< 10^{-5}$ in flight
Jamming of one aileron at normally encountered position	$< 10^{-5}$
Countered and corrected runaway of both ailerons	$< 10^{-4}$ in flight, $< 10^{-5}$ close to ground
Countered and corrected runaway of one aileron	$< 10^{-4}$ in flight, $< 10^{-5}$ close to ground
Undetected erroneous automatic gearing for control wheels (low speed gearing at high speed)	$< 10^{-7}$ in flight

Note that, as we specified previously, a reduced safety factor will be needed, accompanied by a probability objective, only if failure loads exceed limit loads.

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Loss of control of one aileron. In this case, the aileron's position cannot be commanded by the crew and it is continuously driven by aerodynamic loads to a zero hinge-moment position. This failure case has an impact in CoF. The hinge moment estimation is given by equation 3.

$$M_{hinge} = q_\infty S_{ref} c_{ref} \cdot (C_{i,ref} + C_{i,\delta_\alpha}\delta_\alpha + C_{i,\alpha\delta_\alpha}\alpha\delta_\alpha) \tag{3}$$

The aileron floating position is calculated by setting M_{hinge} to zero in equation 3, for different angles of attack. It has been checked that the most critical aileron position is produced at the highest angle of attack, and, when adding the angle of attack and aileron contributions in the Static Loads model, the most critical load on the aileron monitor station is produced. No inertial alleviation has been introduced for this initial estimation. Afterwards, simulations are performed by jamming the aileron at its most critical position given by the M_{hinge} equation, in the right wing and in the left wing separately. Calculations are performed on a reduced loads envelope for pull-down and pull-ups at V_C. The result is that none of the calculated failure loads exceed the design limit loads.

Jamming of one aileron at normally encountered position. In this case one aileron is fixed at its normally encountered position and the crew cannot correct the failure. This failure case is always detected, and it has an impact in CoF. The position of the jammed aileron is determined by the result of equation 4, at a roll rate of $\Delta p = \pm 1/3 p_{max}$, which has been considered an acceptable roll rate. In 4, V is the true airspeed.

$$\Delta\delta_a = -\frac{b}{2V}\frac{C_{M_x\hat{p}}}{C_{M_x\delta_a}}\Delta p \tag{4}$$

The most critical aileron deflection is obtained from equation 4. Since equation 4 consists of an aileron deflection increment, loads are calculated for conventional maneuvers, and the contribution of $\Delta\delta_a$ is added later with the aerodynamic loads model. A reduced loads envelope is considered at V_C and V_F for balanced maneuvers in cruise and landing configuration. Additionally, a vertical and frontal gust of 40% nominal intensity as stated in CS 25.345(a)(2) is added, in 1g and landing conditions.

The result is that for torque at the outer wing monitor station that integrates the whole aileron, the ratio between failure and limit loads is 1.114. Therefore, a reduced safety factor is needed, of FS =1.5/1.114=1.346, and this consists of maximum allowable probability of $Q_j \leq 2.88 \times 10^{-1} \rightarrow P_j \leq 6 \times 10^{-2}$, if considering $T_j = 5$ hours. 5 hours is assumed to be half the typical patrol time for the flight test bed platform. The critical point is shown in figure 7.

However, a note in Appendix K states that if the probability objective P_j is greater than 10^{-3}, a factor of safety of 1.5 should be applied to all limit load conditions. Therefore, the probability requirement in order to apply a reduced safety factor of 1.27 is actually $P_j \leq 10^{-3}$.

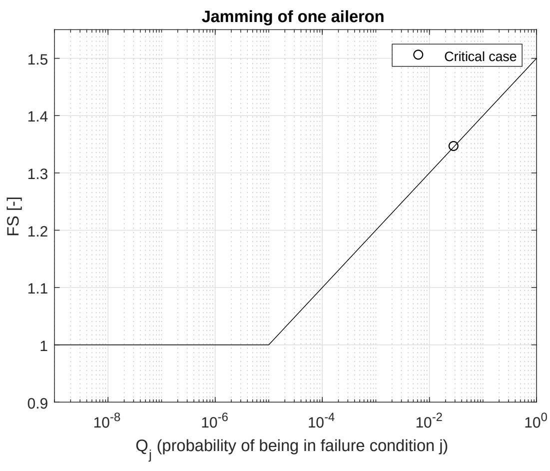

Figure 7: Reduced factor of safety for jamming of one aileron at normally encountered position failure case

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Countered and corrected runaway of both ailerons. In this case, both ailerons move in one direction without being commanded, and the system is able to identify and correct the failure. This failure case has an impact in ToC. The failure case has been calculated for different runaway times, simulating from trim points in a reduced flight envelope (1g conditions at V_C and V_F). The FHA for Step 1 does not provide a runaway time, so different runaway times, 0.15 s, 0.3 s and 0.6 s, have been simulated in order to obtain the one for which the failure case would be sizing for Static Loads, depending on the probability objective given by System Safety. The aileron movement in this failure case is simulated as shown in figure 8.

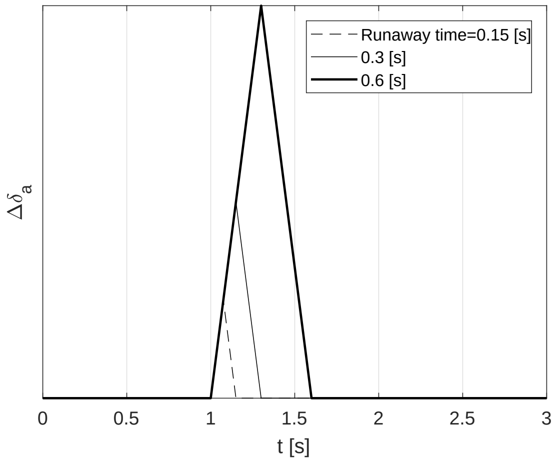

Figure 8: Aileron runaway deflection with respect to trim position

The failure load-limit load ratio for this failure case is calculated for shear force and pitching moment at the aileron monitor station in the right and left wing. The highest ratio at each runaway time is picked, since it is the one for the highest failure loads. The mentioned ratio is shown in figure 9, as well as its corresponding reduced safety factor, with a maximum value of 1.5. We want to calculate the value of the runaway time that gives a reduced safety factor of 1.5. In order to obtain this, interpolation is performed in figure 9. For $P_j \leq 10^{-9}$, the runaway time should be kept under 530 ms, a value that has been slightly rounded up from the exact result, since a higher runaway time is worse in terms of Static Loads. An additional result, the runaway time for $P_j \leq 10^{-5}$, 420 ms, has also been obtained by linear interpolation. The final reduced safety factor versus runaway time curve is shown in figure 10.

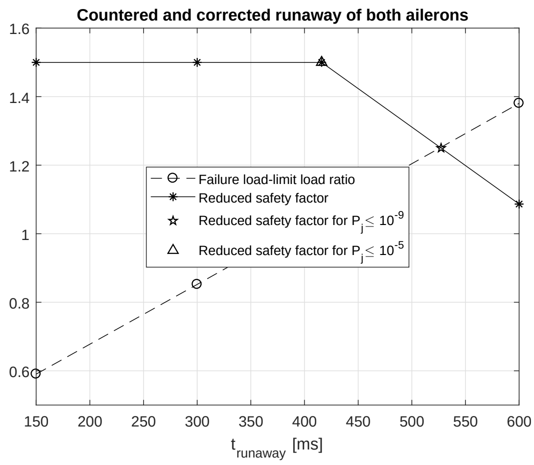

Figure 9: Failure-limit load ratio and reduced safety factor for different runaway times in countered and corrected runaway of both ailerons failure case

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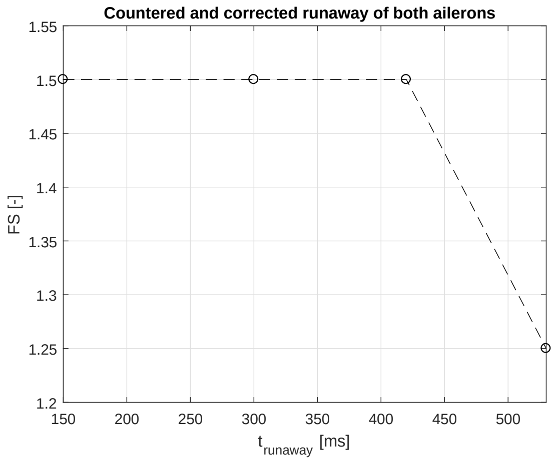

Figure 10: Maximum allowable reduced factor of safety for different runaway times in countered and corrected runaway of both ailerons failure case

Countered and corrected runaway of one aileron. The same procedure is followed as in the countered and corrected runaway of both ailerons. For $P_j \leq 10^{-9}$, the runaway time can be 560 ms at most. For $P_j \leq 10^{-5}$, the runaway time should be lower than 450 ms.

Low speed gearing of control wheels at high speed (undetected). This failure case has an impact in CoF. The aileron deflection is calculated at the maximum roll rate, at V_A and at $2/3N_{zmax}$, and this aileron deflection is then applied in the same maneuver at V_C. The final result is that for the shear force at the aileron monitor station, the failure loads exceed the limit loads with a factor of 1.320. Therefore, a reduced safety factor is needed, of FS =1.5/1.320=1.136. This corresponds to a probability objective of $Q_j \leq 2.3 \times 10^{-4} \rightarrow P_j \leq 4.6 \times 10^{-5}$.

A summary of the previous Static Loads probability requirements is shown in table 2. Table 2 shows that Static Loads can issue two important requirements in parallel to the SSA in this case: limiting the maximum runaway time in two failure cases. The rest of the probability objectives are coherent between System Safety and Static Loads, since a lower probability objective given by System Safety means that the failure case is already covered in terms of Static Loads.

Table 2: Probabilities for FTB#2 Step 1: objectives from FHA tentative numbers, and objectives calculated by Static Loads

Functional failure	P_j **System Safety objective**	P_j **Static Loads objective for failure case not to be sizing**
Loss of control of one aileron	$< 10^{-5}$ in flight	No requirement
Jamming of one aileron at normally encountered position	$< 10^{-5}$	$\leq 10^{-3}$
Countered and corrected runaway of both ailerons	$< 10^{-4}$ in flight, $< 10^{-5}$ close to ground	If $t \geq 530$ ms $\rightarrow < 10^{-9}$, $420 \leq t < 530 \rightarrow P_j$ varies between $\leq 10^{-5}$ and $\leq 10^{-9}$, $t < 420$ms $\rightarrow$ No requirement
Countered and corrected runaway of one aileron	$< 10^{-4}$ in flight, $< 10^{-5}$ close to ground	If $t \geq 560$ ms $\rightarrow < 10^{-9}$, $450 \leq t < 560 \rightarrow P_j$ varies between $\leq 10^{-5}$ and $\leq 10^{-9}$, $t < 450$ms $\rightarrow$ No requirement
Undetected erroneous automatic gearing for control wheels (low speed gearing at high speed)	$< 10^{-7}$ in flight	$\leq 4.6 \times 10^{-5}$

Lastly, the previous requirements by Static Loads have been compared to those made in the SSA for the Step 1 configuration in table 3. Note that some probability objectives have changed according to the system definition and evolution, among other activities. However, the probability objectives are coherent with those defined in the FHA, and only in case of the aileron runaway failure cases would Static Loads have to be taken into account, since the runaway time has still not been defined in Step 1's FHA.

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Table 3: System Safety objectives for FTB#2 Step 1 based on SSA tentative numbers

Functional failure	**P_j objective**	**Expected probability**
Loss of control of one aileron	$< 10^{-5}$ in flight and close to ground	Not required
Jamming of one aileron at normally encountered position	$< 10^{-5}$	Not required
Countered and corrected runaway of both ailerons	$< 10^{-4}$ in flight and close to ground	Not required
Countered and corrected runaway of one aileron	$< 10^{-4}$ in flight and close to ground	Not required
Undetected erroneous automatic gearing for control wheels (low speed gearing at high speed)	$< 10^{-5}$ in flight	Not required

5.2 Analysis for Step 2 configuration

The selected failure cases for analysis are summarized in table 4. Note that for Step 2, only a preliminary failure cases description has been provided by System Safety at this point, and no official FHA or SSA has been released yet, so the objectives obtained by Static Loads will not be contrasted with the FHA or SSA, as was done in Step 1.

Loss of control of one aileron. This failure case is different from Step 1 since a runaway time is indicated (150 ms), and there is a new type of aileron actuator and aileron brake. The transient response of the loss of control needs to be modeled as a damped movement upwards. For 150 ms, the worst position of the aileron is -4.8°. This deflection is already covered by the design loads loop, and by the equivalent failure case in Step 1.

Countered and corrected runaway of both ailerons. In this case, the runaway time is specified in the description of the failure case provided by System Safety, 150 ms. Given the previous calculations in Step 1, none of the calculated failure loads exceed the design loads.

Countered and corrected runaway of one aileron. The same rationale is followed as in the previous case (Countered and corrected runaway of both ailerons in Step 2). The result is that since the calculated loads do not exceed limit loads, Static Loads has to make no requirement.

Uncountered runaway of one aileron. The aileron moves its trailing edge downwards without being commanded, up to the mechanical limit. It is displaced at the maximum actuator rate. The aileron movement with respect to trim position is modeled as shown in figure 11. Loads are calculated by starting a simulation from a trim state of 1g at V_C and V_F in landing conditions. The result is that for shear force at the right aileron monitor station, the failure loads over the limit loads is 1.508. Thus, the probability requirement would have to be $P_j \leq 10^{-9}$.

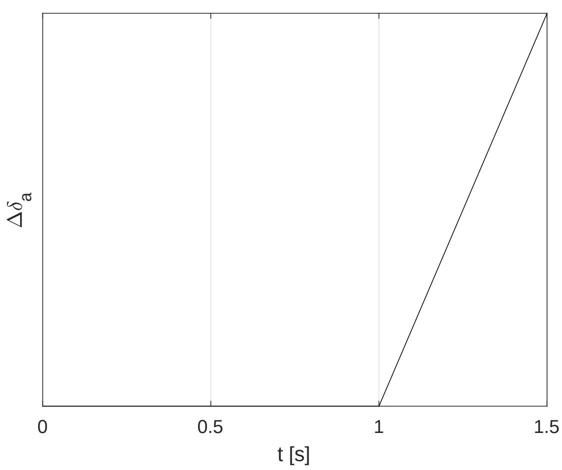

Figure 11: Aileron runaway deflection with respect to trim position

Table 4 provides a summary of the probability requirements from the Static Loads standpoint.

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Table 4: Probability for FTB#2 Step 2: objectives calculated by Static Loads

Functional failure	P_j **Static Loads objective for failure case not to be sizing**
Loss of control of one aileron	No requirement
Countered and corrected runaway of both ailerons	No requirement
Countered and corrected runaway of one aileron	No requirement
Undetected erroneous automatic gearing for control wheels (low speed gearing at high speed)	$\leq 10^{-9}$

6. Maneuver loads alleviation maximum deflections

The goal of MLA is to reduce wing bending moment in maneuvers. The MLA in FTB#2 works by symmetrically deflecting aileron (δ_a) or winglet tab (δ_{wt}) upwards. To summarize what happens in these conditions, lift is reduced at wing tip and the angle of attack needs to be increased in order to maintain the same lift. To minimize the effect of angle of attack increment, the inner flap tab (δ_{ift}) can be deflected downwards.

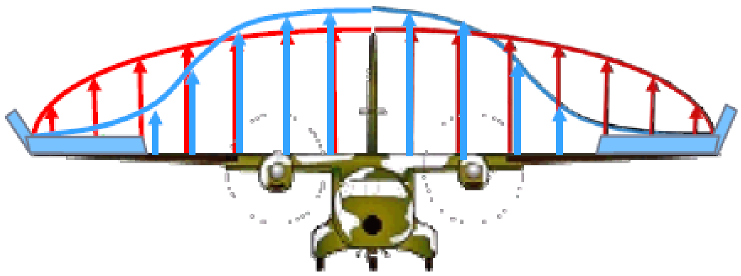

Figure 12: Schematic lift distribution on wing with δ_a and δ_{wt} symmetrically deflected[11]

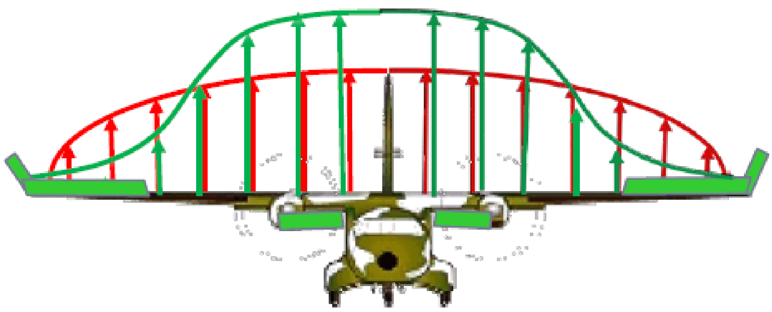

Figure 13: Schematic lift distribution on wing with δ_a, δ_{wt} and δ_{ift} symmetrically deflected[11]

Referring to the MLA activation logic, symmetric control surfaces deflections increase in absolute value between the activation load factor and reach a stop value reserved for functions that are not direct control laws. Figure 14 shows a scheme of the MLA logic in FTB#2 for the three mentioned control surfaces. Even though these three surfaces can be used for MLA goals with different function priorities, in this section's calculations, only the aileron deflection is used.

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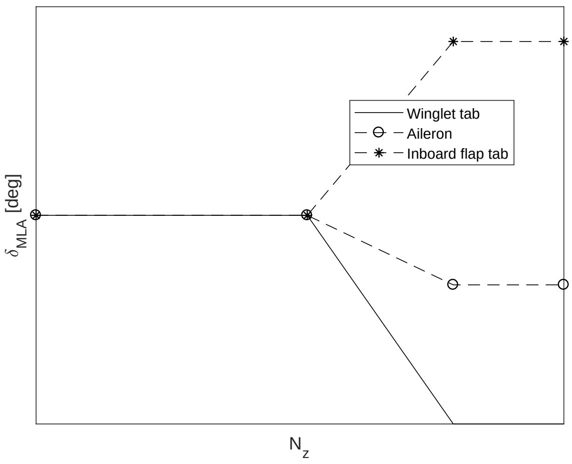

Figure 14: MLA scheme

A failure case of unavailable MLA with a probability objective of $P_j < 10^{-3}$ is hypothesized. With this information and FTB#2 design loads, we can calculate the maximum aileron deflection that can be used for balancing structural design benefit with aircraft controllability. It is assumed that MLA is always active for design loads, but note that this is an isolated assumption for this exercise, since this was not always true in the initial FTB#2 design loads loop. Therefore, equation 5 applies.

$$\frac{FS}{1.5} \leq \frac{Loads_{limit}}{Loads_{CoF}} \rightarrow \frac{FS}{1.5} \leq \frac{Loads_{MLA\ active}}{Loads_{MLA\ unavailable}} \tag{5}$$

This hypothetical failure case of unavailable MLA has an impact in CoF. The time spent in failure condition is 5 hours, so half the time is taken as T_j. Given these data, equation 2 can be expressed like equation 6.

$$FS(Q_j) \cdot Loads_{MLA\ unavailable} = FS(5 \times 10^{-3}) \cdot Loads_{MLA\ unavailable} \leq 1.5 \times Loads_{MLA\ active} \tag{6}$$

The reduced factor of safety corresponding to $Q_j = 5 \times 10^{-3}$ is 1.27, shown in figure 15. Therefore, the ratio of limit loads over loads at the failure condition would be at most $1.27/1.5 = 85\%$. This means a load alleviation of 15%. Note that it would not make sense for loads alleviation to be higher than 15%. A higher MLA would mean using extra aileron deflection that has no structural design benefits, but that diminishes the aircraft's controllability.

In order to check for the aileron deflection that corresponds to 15% loads alleviation, calculations are performed at the same critical pull-up flight condition with different symmetric aileron deflections. Results are presented in table 5. Given these results, a deflection of approximately $\Delta\delta_a = -8°$ is then considered the maximum MLA deflection that provides static strength substantiation and is not sizing for Static Loads.

Table 5: Bending moment at wing root loads and alleviation for different MLA deflections at selected pull-up condition

	Failure case $\Delta\delta_a = 0$	**MLA with** $\Delta\delta_a = -8°$	**MLA with** $\Delta\delta_a = -10°$
Load at CoF referred to failure case bending moment at wing root [-]	1	0.85	0.81
Loads alleviation (%)	0	15.4	19.6
Ultimate load referred to failure case bending moment at wing root [-]	1.27	1.27	1.21[a]

[a] Equation 2 is not true so the failure case is sizing for Static Loads

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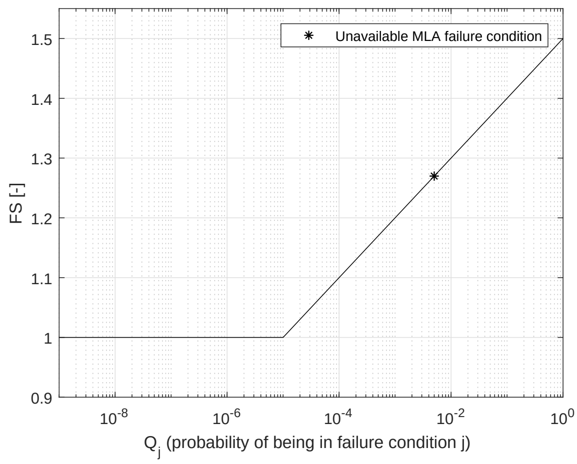

Figure 15: Reduced factor of safety for hypothetical unavailable MLA failure case

7. Conclusion

In this paper, it was brought to light that the procedure of analyzing flight control system failure cases from the point of view of CS 25.302 is not extensively documented in research papers, and the reasons why it is important to document this procedure have been described.

In addition, it was stated that it is important that Static Loads issues probability objectives in parallel to those issued under CS 25 Subpart F for flight control system failures, since sometimes those failures are sizing for Static Loads.

By analyzing different failure cases in the frame of FTB#2, a runaway time requirement for certain probability targets has been issued in parallel to the Step 1 FHA, for two failure cases: countered and corrected runaway of both ailerons, and countered and corrected runaway of one aileron. Static Loads was also able to issue probability targets only from Step 2 preliminary information, already making a requirement for the uncountered runaway of one aileron failure case to be extremely improbable, only from preliminary failure cases descriptions.

Lastly, a benefit-cost analysis for obtaining the maximum aileron deflection that shall be used for MLA purposes, in terms of maximum structural benefit, has been performed.

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