

Probability Assessment of the Fuel Tank Structural Feature Failures

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Zdzislaw H. Klim
Bombardier Aerospace

Adam W. Skorek
Université du Québec à Trois-Rivières

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ABSTRACT

The paper provides an approach to establish compliance with current regulatory standards applicable to lightning protection of the fuel tank structure for Non-Fault Tolerant Feature Failures (NFTFF) through a numerical probability assessment. The proposed procedure is using the criteria defined in the FAA Policy Guidance for fuel tank structural lightning protection and is aligned with the regulatory path described as petitioning for an exemption. Failure modes of structural components for which fault tolerance has been shown to be impractical need to be addressed and the overall likelihood of fuel vapour ignition due to these failure modes must be shown to be extremely improbable. In order to accomplish this, the quantitative assessment of the overall probability of fuel vapour ignition is performed, along with all relevant data to support the probabilities determined for the purpose of this analysis. The relevant non-fault tolerant structural design areas that may contribute to ignition sources inside the fuel tank when a failure occurs must be identified. Each type of non-fault tolerant feature failure must be assessed and the result has to be summed. The set of the potential failure modes regardless of the probability of occurrence is established by performing a complete wing tank survey in pertinent areas related to fuel tank lightning protection. If the failure assessment results in demonstrating that the design is free from ignition sources after an assessment of relevant single failure conditions, then the design is considered to be fault tolerant. If not, then further analysis is required per numerical probability assessment for the Non-Fault Tolerant Feature Failures. The subset of NFTFFs must be defined and the numerical probability assessment has to be performed. The purpose of the

assessment is to substantiate that the probability of failures associated with non-fault tolerant features that might lead to a fuel tank explosion belongs to the extremely improbable category. This paper intends to provide a practical method for the fuel tank structure numerical assessment along with a real-life example illustrating a potential application.

INTRODUCTION

A lightning strike is likely to occur on any aircraft during its useful life. Although most reported strikes to present-day aircraft result in little or no damage, roughly ten percent result in major damage. On average, about one military aircraft is lost each year due to a lightning strike [1]. The effects of lightning strikes may vary, depending on the aircraft design and particular system or the component affected [2]. There are many aircraft systems that are susceptible to lightning. The most vulnerable aircraft systems that might be impacted by lightning strikes are the engines and the fuel system, flight controls and avionics systems as well as the internal environmental controls. The possible consequences of lightning and static electricity interactions may range from minor (little or no adverse consequence) to catastrophic (loss of aircraft and/or crew and passengers).

Based on accident mishap data, a fuel system consisting of integral fuselage or wing tanks, has been the most vulnerable system in the aircraft in terms of catastrophic consequences. The design of adequate lightning protection for the fuel system will continue to be one of the most important lightning-protection requirements to be accomplished due to the hazardous nature of the fuel and fuel vapours and the potential for catastrophe if ignition should occur.

Additionally, adequate lightning protection of fly-by-wire flight control systems is becoming a critical requirement [1].

There are a number of requirements, imposed by the regulatory agencies concerned with aircraft certification that apply specifically to aircraft lightning protection. The key considerations of the applicable regulations are [3]:

- 1). That the aircraft must be protected against catastrophic effects of lightning and,
- 2). That equipment, systems, and installations whose proper functioning is essential, must be designed to ensure that they perform their intended function under any foreseeable operating condition.

Because it is expected that an aircraft will be subjected to lightning during its operating life, the design criteria and standards needed are ones that can ensure the adequate protection of aircraft equipment and systems. Special design principles must be applied on the aircraft to mitigate the lightning effect and to protect the sensitive component against critical damage. The design principles necessary to ensure protection against lightning's indirect effect for a new generation of aircraft based on an intensive use of Composite Fiber Reinforced Plastic are discussed in [2]. In particular, the metal foil efficiency embedded into the structural panel is demonstrated and different harnesses protection means are compared. Moreover, modeling results are validated with measurements on a specific demonstrator.

A lightning protection system is often provided based on rules derived from practical experience and sound reasoning. However, for high-risk objects or equipment with large economic value, it is advisable to test the protection by current injection. Ideally, the current should have sufficient amplitude and a sufficiently short rise time when compared with real lightning. Such an approach is followed for instance for airplanes during certification activities [4]. A study was conducted on paintings which should behave as insulating materials in or as conductors depending on their state [5]. An ionization process at the coating surface in a lightning environment must ensure a high conductivity in order for the flashover of the sensible area to be facilitated in respect to the breakdown. It is shown in the study that a painting selection can be drawn in order to facilitate electrical flashover.

The paint thickness might also be a root cause of the potential hazard to the aircraft. An analysis was conducted on aircraft equipped with a tail fuel tank which is potentially subjected to lightning strike [6]. This hazard may be significantly increased due to an incorrect paint thickness. To meet customer color scheme requirements, the tail tank is usually painted. However, to meet aircraft lightning protection requirements and aircraft type specification, it is critical that the total primer/topcoat paint applied to the tail-tank exposed metal surfaces be as thin as possible. The tail cone is

designed as a specific zone which prevents lightning from remaining attached to the tail fuel tank. The recommended paint thickness on the tail fuel tank is a certification criterion and should be limited to 0.005 inch maximum. Measurement of paint thickness of as much as 0.015 inch compared to the required maximum of 0.005 inch has been reported. Lightning dwell time, which could increase the risk of melt-through or hot spot ignition, is a function of type and of thickness paint. Excessive paint thickness on the tail fuel tank can compromise the ability of the tail cone to act as a lightning discharge point. The deficient painting may affect the aft tail cone fairing capacity for lightning discharge and preclude its intended function as an entry/exit location for lightning strike [6].

Because of the variation in assessment factors and their uncertainty, a probabilistic or statistical approach is used to express a relationship for the probability of failure (or survival) of a critical aircraft equipment per flight hour. For single equipment, that is a subject of potential lightning strike, this relationship can be expressed as [1]:

$$P_F = P_S \cdot P_A \cdot P_E \quad (1)$$

where p_F is the probability of a critical aircraft equipment failure due to lightning per flight hour, p_S is the probability of a lightning strike to the aircraft per flight hour, p_A is the probability of attachment to a particular aircraft location (e.g., a wing), and p_E is the probability of the equipment failure for a strike to a particular attachment location. Both p_S and p_A can be predicted from historical lightning strike and attachment-point data [7]. The principal challenge is in developing a statistical approach for predicting p_E as a function of lightning-strike intensity, induced transient levels, and equipment sensitivity. In addition, the p_E values for several equipment must be considered when a system failure probability is determined.

The probabilistic approach was also adopted in the hazard assessment related to the incorrect paint thickness on the aircraft tail fuel tank [6]. The hazard probability assessment $P(q)$ to get $[q]$ lightning strikes on the aircraft tail fuel tank with a catastrophic effect on aircraft operation was defined as a probability of simultaneous occurrence of a number of events as follows [6]:

$$P_{(q)} = p_1(q) \cdot p_2 \cdot p_3 \cdot p_4 \quad (2)$$

where:

- $p_1(q)$ – probability that an aircraft will experience $[q]$ strikes in $[n]$ hours of operation,
- p_2 – probability of a direct strike on the tail fuel tank, regarding the ratio between the tail fuel tank surface and total aircraft surface exposed to the lightning strike,
- p_3 – probability related to the suspected “batch” of aircraft and assessed as a ratio between the numbers of suspected aircraft and total fleet equipped with the tail tanks,
- p_4 – probability that the lightning strike intensity is sufficient to cause a catastrophic damage to the aircraft.

1. PROBLEM STATEMENT

The requirements related to the fuel tank ignition prevention are outlined in paragraph 25.981(a)(3) [8] and state that no ignition source may be present at each point in the fuel tank or fuel tank system where a catastrophic failure could occur due to the ignition of fuel or vapours. To show compliance, it is necessary to demonstrate that an ignition source could not result from each single failure, from each single failure in combination with each latent failure condition not shown to be extremely remote, and from all combinations of failures not shown to be extremely improbable. The effects of manufacturing variability, aging, wear, corrosion, and likely damage shall be considered. Direct compliance with § 25.981(a)(3) typically implies that three independent, effective, and reliable protection features (or sets of features) be provided to prevent ignition sources for design areas of the fuel tank. The fuel tank areas of concern with regards to potential lightning related ignition sources are joints that include fasteners penetrating to the exterior of the tank to lightning strike zones surfaces and other mechanical joints in tank structures in zone which must conduct lightning currents between potential attachment points.

The ANM-112-08-002 policy requires that direct compliance be demonstrated where it is practical [9]. If direct compliance cannot be demonstrated, then either the Special Condition or Exemption routes to compliance may be considered in all or parts of the fuel tank structure [10]. Determining the practicality of direct compliance requires an assessment of each area of design along with an initial review of the fault tolerance capability of the design. In general, where the design shows dual fault tolerance [i.e. two of three (or more) features have failed but the design remains effective against ignition sources] direct compliance may be achieved. Where the design can only tolerate a single failure (or no failure) before there is an ignition source risk, additional design options should be considered to determine if dual fault tolerance can be achieved. If so, then this design feature should be added as long as it is practical to do so. If not, then the design cannot achieve direct compliance and the policy may be applied as long as the design area in question is within the policy definition of the fuel tank structure. If the

applicant demonstrates that direct compliance is impractical, an alternative approach for lightning protection compliance of the fuel tank structure may be used. Per the policy, the fuel system architecture and average flammability exposure must be taken into account to determine an appropriate compliance path. The partial exemption is an option, if the fuel system relies upon conventional unheated aluminum wing or an equivalent design and the fleet average flammability exposure is lower or equal to 3%. If the average flammability exposure of a fuel tank within the wing of the airplane model being evaluated is higher than 3%, the estimated flammability exposure for the fuel tank has to be taken into account during the assessment.

2. COMPLIANCE BY APPLYING THE EXEMPTION PATH

The direct compliance with § 25.981(a)(3) typically implies that three independent, effective, and reliable protection features (or sets of features) be provided to prevent ignition sources for the fuel tank design architecture. This approach is feasible in the case of a new aircraft program, when different design options are available from the beginning and might be implemented without excessive difficulties. For an aircraft model that is derived from an existing one, the implementation of the three protection features is usually technically impossible or impracticable. Therefore, the Special Condition or Exemption Path can be adopted as a recommended method to demonstrate compliance according to the policy guideline [10]. An exemption path is only possible if the flammability cannot be shown to meet the enhanced criteria required by the special conditions. This approach is a combination of the design assessment for the fault tolerance behavior and of a numerical probability assessment in cases where the design fault tolerance is impractical. The exemption path approach will be discussed in detail in this paper.

2.1. FAULT TOLERANT DESIGN

The presence of two independent, effective and reliable features of protection against each of the sparking modes potentially identified for the fuel tank design must normally be demonstrated to meet the fault tolerant requirement. Alternately, it may be possible to demonstrate that a particular design is “intrinsically safe”, in which case the two features do not need to be demonstrated. The term “intrinsically safe” describes the design being incapable of releasing sufficient electrical or thermal energy under normal operating conditions, anticipated failure conditions, and environmental conditions which could cause an ignition source within the fuel tank. For structural lightning protection, this concept can essentially be applied to designs that are demonstrated to tolerate all failure modes free of ignition sources due to lightning, i.e., there is no failure mode

or combination of failure modes that can result in an ignition source.

In order to demonstrate fault tolerance, testing needs to be carried out first with one feature of protection artificially disabled (to reflect the failure mode), and then with the other protection feature disabled. Non-sparking performance must be demonstrated in both cases to substantiate fault tolerance. If it is not possible to design a test with one feature of protection artificially disabled, then detailed analysis will be needed to demonstrate the effectiveness and independence of this feature. If two independent, effective and reliable features (or sets of features) cannot be identified in the design and if there is a failure mode identified that demonstrates that the design is not intrinsically safe, in that case a numerical analysis must be conducted to demonstrate that the risk of ignition of fuel vapours resulting from this non-fault tolerant design is extremely improbable.

The set of the potential failure modes regardless of the probability of occurrence needs to be established by performing a complete wing tank survey in pertinent areas related to fuel tank lightning protection as defined by FAA "Policy Guidance for Fuel Tank Structural Lightning Protection" [10]. If the failure assessment results in demonstrating that the design is free from ignition sources after an assessment of relevant single failure conditions, then the design is considered to be fault tolerant. If not, then further analysis is required per numerical probability assessment for the Non-Fault Tolerant Feature Failures (NFTFF). The subset of NFTFF must be clearly identified and the numerical probability assessment shall be performed according to the guideline provided in the Policy.

2.2. CHARACTERISTICS OF THE PROTECTION FEATURES

The compliance through the exemption path has to rely on the double protection features that must be independent, effective and reliable. Those features' characteristics are described below.

The Independent Features are those that are not subject to common cause failures that could also compromise the other protection feature relied upon to provide the fault tolerance. The sealant covering a potential ignition source such as an external fastener, might be considered an independent feature if it will preclude that failure of the fastener with sufficient robustness and if it does not allow voltage or thermal spark products to reach the flammable vapour space. An example of a protection feature that is not independent is a layer of sealant, that if the fastener fails, will, through that failure, remove or damage the sealant in a manner which eliminates its ability to prevent arc products resulting from a failure of the fastener.

The Effective Features are those that are shown to adequately prevent ignition sources when exposed to the expected lightning current threat at that location. The effectiveness is typically determined as a result of testing. In some cases, single features alone can be demonstrated to be effective. In other cases, multiple features may be required to be combined to be effective so they would be considered effective as a set. An example of a protection feature that is not effective is a layer of sealant that is insufficiently robust to contain the arc products resulting from the failure of another protection feature such as an interference fastener.

The Reliable Features are those features whose failure modes and failure rates are such that they are not normally expected to fail during the life of an airplane or the life limit of the feature, when installed correctly per design. Some failures may be expected over a fleet life of airplanes but are not expected on the typical airplane. Most structural features can be found to be reliable as long as they are designed with adequate margin, to ensure durability and robustness, and are installed with sufficient controls.

2.3. NON-FAULT TOLERANT FEATURE FAILURES (NFTFF)

The potential failure modes which may lead to the loss of one of the protection features or sets of features must be clearly identified. Failure modes for structure and structural joints may be determined based upon a structured design review process. The sources of information to support the identification of failure modes should include the manufacturing process data assessment, service history records, and developmental test data. The failure modes that should be considered are those that may occur during the life of an airplane or a fleet of airplanes of a particular model.

Typical failure modes that need to be considered are the failure modes which may lead to the loss of one of the protection features during the life of the aircraft so that these failures can be included in tests and/or analyses to establish whether the failures may cause ignition sources in the event of an aircraft encounter with lightning. Failure conditions to be considered may include the manufacturing quality escape conditions. Typically these consist of the misaligned fasteners, incorrect fastener size, drilling issues (e.g., hole quality, failure to remove burrs, etc.), incorrect fastener type or coating, and many others. As an example, two typical failure modes, a double hole and a gap between the mating parts are presented in [Figure 1](#).

The detailed study was performed in the rib installation in terms of what the potential failure modes are regardless of the probability of occurrence. The same analyses were also performed for other main components of the wing tank area, as spars, splices and wing skin. The dedicated group of electromagnetic compatibility (EMC) specialists completed