Preliminary Safety Assessment on System Design Level for Broadband Acoustic Liner Concepts for Aviation

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Abstract. Selected methods of the aviation safety assessment process according to ARP 4761 are introduced and conducted within the scope of a concept study for future broadband acoustic liners. While having similar primary functions and basic design, the acoustic liner concepts diverge concerning subfunctions and potential malfunctions. With the ARP 4761 safety assessment methods, significant differences in sub functions and possible malfunctions of the concepts can be identified. The results of the safety assessment are discussed, and the concepts are evaluated in terms of feasibility and safety.

1 Introduction

In recent decades, the noise reduction and efficiency enhancement of civil aircraft engines had been significantly influenced and advanced, by increasing the bypass ratio (**BPR**) [01], [02]. This trend will continue and play an important role in future years. The increase of the BPR is accompanied with a larger fan diameter. This is limited by the circumferential speed of the fan blade tips. In order to avoid aerodynamic losses due to compression shock waves, the maximum circumferential speed of the blade tips should not significantly exceed the speed of sound [01],[03]. Consequently, a lower rotational speed must be realised, which has a direct influence on the tonal frequency of the noise, emitted by the fan. On side of the engine, noise can be reduced by noise reducing linings, so-called acoustic liners. These consist usually of a rigid sandwich structure with honeycomb core, a perforated cover layer and a closed bottom layer. Due to acoustic effects, only one specific frequency can be attenuated for a liner with a fixed geometry (chapter 3). However, the noise emissions of aero engines have a low-frequency tonal and broadband character [01], [03]. By reducing the fan speed, the audible frequency spectrum is also shifted to a range with much lower frequencies. In order to adapt the currently used narrowband acoustic liners to this frequency shift, the height of the honeycomb core structures has to be increased [02], [04]. In case of lightweight design and an optimized aerodynamic resistance, the engine cowling structure is designed as short and as thin as possible [02]. Therefore, the available design space for acoustic liners is strictly limited. The operational and functional requirements predetermine the entire development process of the acoustic liner system from the very beginning. A large number of design criteria and engineering related disciplines has to be combined, for a corresponding implementation into a functional and safety compliant product.

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2 Safety Design Approach

2.1 Theory of System Function Analysis

A basic approach to identify all relevant system functions, which are necessary to fulfil a primary function under defined operating and boundary conditions of a mechanical system is introduced in the **VDI 2803** [05] and especially for aeronautical technical system in the **ARP 4754** [06]. Processes and methods are established, to provide a framework for the conception of new structures, functions, subsystems and algorithms. Previously unknown requirements and regulations are identified and described. Often this requires trade-offs between two mutually exclusive requirements. Such trade-offs are often a safety risk, which must be tracked and mitigated during the development cycle.

2.2 Theory of System Safety Approach

The **ARP 4761** [07] describes in detail the methods of a (Preliminary) System Safety Assessment (P)SSA and introduces various methods for the identification and evaluation of potential malfunctions and safety risks. Depending on the Technology Readiness Level (TRL) of the considered system, the actual system safety assessment (SSA) or a reduced preliminary system safety assessment (PSSA) can be carried out. The Functional Hazard Analysis **(FHA)** provides the foundation of every PSSA and uses the system function structure, which is set up with the input of the ARP 4754 [06]. It is a systematic, comprehensive investigation of failure cases to identify and classify failure conditions of these malfunctions with regard to their influence and severity for an aviation application. By negating a function, a corresponding malfunction will be implied. The most important steps of an FHA are briefly explained below.

- Identification of all relevant functions at a considered system level
- Identification of possible malfunctions (single failures and combined malfunctions)
- Detect possible failure effects on system level
- Classification of failure cases and effects [07], [08]

The result of the FHA is a summary of possible malfunctions, effects and failure combinations, which can occur during operation under defined operating or failure conditions. For the classification of the failure cases, all effects of a malfunction on surrounding structures and adjacent systems, as well as the influence on other system functions have to be identified. Following on the FHA, several methods can be carried out as part of the PSSA. The most common methods are the Fault Tree Analysis (**FTA**), Dependency Diagram (**DD**) and the Markov Analysis (**MA**). Defined during the FHA, a system of linked causes and effects is set up using the FTA, in order to record the number and combination possibilities of different main failure events (Top Level Event; **TLE**). The aim of the FTA is to combine different failure causes/ events by logical AND/ OR connections and display them on different levels. The respective higher-level failure event can then occur through at least one (OR gate) or only through a combination of several lower-level events (AND gate). This structure allows a specific failure event defined in the FHA to be broken down into its causes using a corresponding deductive TOP-DOWN approach [07], [09]. This process is continued until only basic causes exist, which are defined as external influences, unchangeable operating conditions or influences of surrounding systems and structures. Depending on the TRL of the development process, a qualitative or quantitative FTA can be carried out [07], [10].

- **Qualitative FTA** – Identification of all possible causes of the TLE. Applicable even with low TRL at the beginning of the development process.
- **Quantitative FTA** – Determination of the probability of occurrence of unwanted TLEs. Only available for higher TRL with sufficient knowledge of the system.

Based on the qualitative and quantitative FTA, a Common Cause Analysis (**CCA**) should be carried out. With the methods of the CCA, the ARP 4761 [07] provides further methods for a more detailed analysis of the external influences, as well as the effects and influences on different engine zones and the behaviour of redundant systems with corresponding malfunctions.

3 Functional Concept Design

All investigated liner concepts have identical material compositions. The geometrical changes and the resulting physical effects for noise reduction due to these changes are explained below. In the beginning of each safety assessment, a suitable functional structure of the considered system is established. For the development process of new broadband acoustic liner concepts, the functional analysis according to ARP 4754 [06] is used.

3.1 System Function and System Architecture

The development process according to ARP 4754 [06] begins with the function definition of the top level system. In the case of airworthy systems, the main system is always the aircraft itself. From this point, various main functions (aircraft top-level functions), are defined and gradually refined. Each identified function has to be fulfilled by a system component or item. With increasing level of detail, different basic functions can access identical subfunctions and executing subsystems. An example of this are the main functions "Passenger Comfort" and "Environmental Control", as both have a subfunction “Noise Reduction”. The implementation of this function for engine sided noise can be supported in both cases by appropriate acoustic liners in the nacelle. However, the area of influence of the function is fundamentally different. The function or requirement for "Passengers Comfort" refers to an internal event, which influences the passengers themselves. The branch "Environmental Control" references everything external to the aircraft. Functions, which switch over to the next function level as a diamond symbol are not further considered because they have no or a minor influence on the TLE in case of noise emission and noise reduction. In addition to a direct reference to the system functions of the acoustic liner, intermediate systems can be defined. These refer to the respective superordinate aircraft function and give the subordinate functions a new specified direction. In the case of the function "Passengers Safety", no direct reference to the acoustic liners can be made. However, the subordinated system "Nacelle" is partly responsible for the basic containment of the core engine structure. In addition, the entire engine-sided, noise-reducing lining is installed in the nacelle. Structural integrity and resistance to external and internal strains corresponding to the requirement profiles are necessary, even if these do not have any safety-relevant functions for the nacelle or the aircraft. Due to the integration of the acoustic liners in the nacelle structure, the function of noise reduction is also required. In addition, further nacelle functionalities like “Aerodynamic inner Contour” can be described and directly connected to the liners. Other features such as "Provide Air" or "Prevent Negative Effect of Icing" refers to other systems, which are integrated in the nacelle [11]. The entirety of all functional areas, which can be derived in a Top-Down approach from the aircraft level, provides a specified functional profile of the acoustic liner. This will be adapted specifically to the liner in a further step of integration. In addition to ARP 4754 [06], a method for functional analysis according to VDI 2803 [05] was chosen for the detailed elaboration of the liner-related functions. All liner main functions are further subdivided and described in detail. The methodology according to VDI 2803 [05] shows implementation possibilities, trade-offs and functions with negative influences. Output of VDI 2803 [05] is a detailed functional structure, which indirectly provides a possible recommendation to the system architecture. The main functions and the derived basic components are identical for all concept types of acoustic liners. The path, which is used from a main function to the system component, significantly determines the detailed functional behaviour and the system architecture. As each type of liner pursues a different physical concept for reducing noise, the geometrical design is very different despite of identical boundary conditions. The functional analysis according to ARP 4754 [06] does not provide a direct transfer of the function into a system architecture. This deductive method of the ARP 4754 [06] has been enhanced by Mischke et al. [12], where a system architecture is defined

3.2 Broadband Liner Concepts

A first topological and geometric concept for the flexible broadband liner concepts can be derived through the functional structure according to ARP 4754 [06] that has been extended by sub-system components [07], [12], [13]. Figure 1a presents a state of the art narrow-band acoustic liner utilizing a sandwich design with a rigid honeycomb core (**SHR-Liner**; Standard Helmholtz Resonator Liner). Figure 1b shows the structure of the **FHR-Liner** (Foil Helmholtz-Resonator Liner), which is quite similar to the SHR-Liner. Flexible foil structures that are integrated into the walls of the honeycomb core are the only difference. Knobloch et al. [04] show that the flexible foil elements of the FHR-Liner cause a significant increase of the integral damping factor compared to the basic structure of the SHR-Liner. Additionally, a shift of the damping curve into the low-frequency range has been demonstrated [04]. Figure 1c introduces the **PR-Liner** (Plate Resonator Liner) concept from Kisler et al. [14] for increasing broadband damping in aircraft engines. This concept can be derived from the sub-function "Reduce Noise". The perforated face sheet of the SHR-Liner has been completely replaced by a flexible foil layer. The acoustic functionality of this liner concept has also been demonstrated by Knobloch through acoustic wind tunnel tests [04]. Based on the system functions and the system architecture, a PSSA according ARP 4761 [07] is carried out in order to define possible malfunctions and the resulting low-level requirements, which are specially tailored to the liner functions. This development stage is an iterative optimization process between ARP 4754 [06] (providing structure and functions) and the ARP 4761 [07] (providing malfunctions of structure and functions). The interplay is continued until the failures of system architecture and system functions are within an acceptable range and meet the requirements from [15], [16], [17].

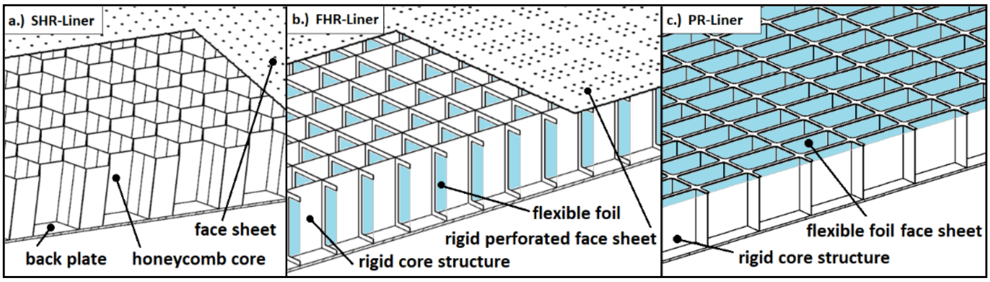

Fig. 1: Current acoustic liner and new liner concepts with flexible structure

4 Safety Concept Analysis

4.1 FHA

The first step of the safety assessment process is the FHA, to identify potential malfunctions. The definition of a malfunction can be made by the negation of a system function identified through ARP 4754 [06] and VDI 2803 [05]. This implies that a required function, which is not executed, could be defined in the broader sense as a failure or malfunction of the system.

Due to a lightweight sandwich design using fibre composite layers and honeycomb core, structural failures can be described as "Loss of Structural Integrity" due to fibre or matrix breakage. Depending on the considered component, different TLEs can be identified. The different physical implementation of the noise reduction significantly influences the position of the flexible structures (foils) in the sandwich structure. Thus, the system architecture of FHR-Liner and PR-Liner deviates from each other, which has a direct influence on the possible malfunction in the individual system components. The loss of structural integrity due to delamination (matrix breakage) between the fibre composite layer and cell-support core, can be defined in the components "Top/ Bottom Layer" (fibre composite) and "Sandwich Core" for FHR- and PR-Liner. Damage or detachment of the flexible foil must be coupled to the honeycomb core for the FHR-Liner and to the upper cover layer for the PR-liner. The potential basic failure or even TLEs for the individual reference geometries (liner components) are shown in Table 1 (a-d). Subsequently, possible consecutive faults or failure effects are identified for each TLE. These are further subdivided until a classification process of CS-25, AMC 25-1309 [15] of the TLE based on their effects and the severity of the impact on the operating behaviour of the aircraft in certain flight conditions, the intensity of labour for the flight crew and the comfort of the passengers. The TLEs of the liner structures detected in Table 1 can be converted into four basic failure effects (**FE**).

- FE 1: Loss of structural Integrity
- FE 2.2: Airflow disruption
- FE 2.1: Aerodynamic airflow impairment
- FE 3: Influence on noise-reducing properties

Table 1: Possible TLEs of FHR- & PR-Liner at first iteration

Reference Geometry	Failure Case (TLE)
Basic Design	
Sandwich Core [a]	a.1: Delamination (core and composite layer) → (FE: 1+3) a.2: Overstress of the core → (FE: 1+3) a.3: Clogging of drainage holes → (FE: 3)
Back Plate [b] (Lower Composite Layer)	b.1: Delamination of composite layer → (FE: 1) b.3: Overstress of composite layer → (FE: 1)
Specific for FHR-Liner	
Face Sheet [c] (Upper Composite Layer)	c.1: Delamination of composite layer → (FE: 1) c.2: Overstress of composite layer → (FE: 1) c.3: Clogging of cover layer holes → (FE: 3)
Flexible Foil [d] (Part of Sandwich Core)	d.1: Damage to foils (thermal + mechanical) → (FE: 3) d.2: Replacement of foils → (FE: 3)
Specific for PR-Liner	
Face Sheet [c] (Upper Composite Layer)	c.1: Delamination of composite layer → (FE: 1) c.2: Overstress of fibre composite layer → (FE: 1)
Flexible Foil [d] (Part of Top Layer)	d.1: Damage to foils (thermal + mechanical) → (FE: 2.1+3) d.2: Replacement of foils → (FE: 2.1+2.2+3)

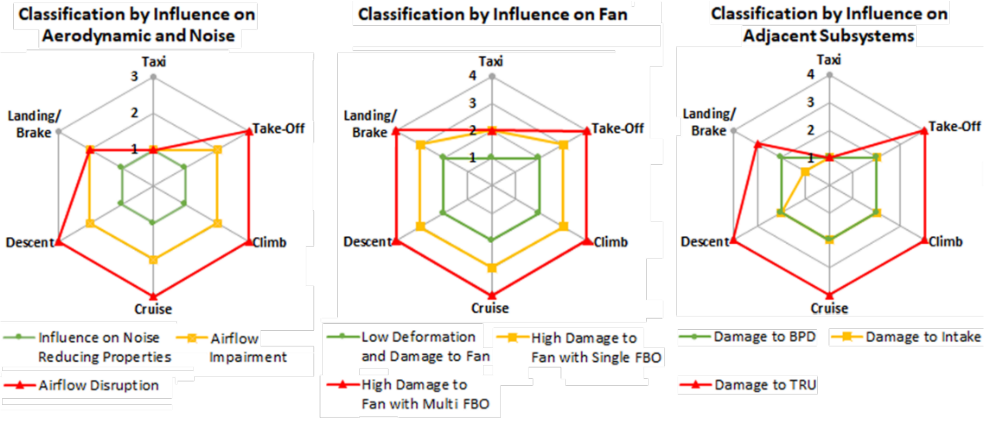

Fig. 2: Classification of different failure effects, due to the subsystems affected by the TLEs (Table 1) for different flight phases [15], [16]

4.2 CCA

A basic knowledge of internal and external effects and influences is required, in order to investigate the failure effects of the TLEs detected by the FHA. The CCA methods described in chapter 2.2 can be used to detect and classify influences on and by adjacent subsystems (ZSA) and influences by external events and operating conditions (PRA). As the liner system is not an actively operated technical system and has no actuators, sensors or locking mechanisms, a CMA can be omitted within the context of a preliminary safety analysis. By positioning the acoustic liners in the cold gas flow of the aero engine, the basic adjacent subsystems Intake, Fan, Bypass-Duct (BPD) and Thrust Reverser Unit (TRU) can be detected. As potential liner failures can damage the detected subsystems to different degrees during differing flight phases, the liner must be classified for varying flight phases and different types of failures. This is shown in Figure 2 for six basic flight phases of a flight cycle. The severity of the faults is classified via the guidelines referenced in the EASA CS-25.1309 [15] into the following areas.

- No Safety Effects on the Engine (1)
- Minor Effects on the Engine (2)
- Major Effects on the Engine (3)
- Hazardous Effects on the Engine (4)

The classified fault behaviour and damage effects on the subsystems can be traced back to the TLEs listed in Table 1. Delamination and core failure can lead to loss of integrity of the FHR-Liner and small to large parts of the sandwich structure can be sucked into the cold gas path. Depending on the position of the affected liner structure, the aerodynamic flow contour (Intake, BPD) or even direct subsystems (Fan, TRU) can be impaired and damaged [10]. In case of the PR-Liner, a top layer failure can be equated with damage to the flexible foil, which covered the entire upper liner surface. The structural damage caused by pieces of foil on surrounding subsystems can be classified as Minor (PSSA for adjacent subsystems should be done). However, the removal of the foil top layer exposes the underlying honeycomb core, which results in significant flow impairment. This can have a massive influence on the efficiency and operational safety of surrounding flow-conducting subsystems. Due to the topological and geometric characteristics of the FHR- and PR-Liner, different malfunctions and effects can occur at the main components (top/bottom cover layer, honeycomb core, foils). Figure 3 shows the classification of TLEs from Table 1 to CS-25.1309 [15] in combination with the new liner concepts FHR and PR. As the liner

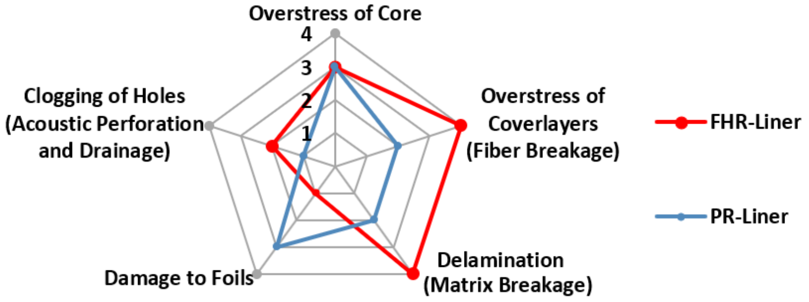

Fig. 3: Classification of different TLEs (Table 1) for FHR and PR Liner concepts

systems form the direct boundary to the flow duct (Intake, BPD), any loss of integrity of the liners can be supplemented by slight flow impairments or a critical flow disruption. These can be classified as “Minor Effect” or even “Major Effect”, depending on the position of the occurrence and the involved subsystem [15], [16]. Furthermore, any deformation of the liner structure will influence the noise absorbing properties. Due to the fact, that the noise emission is not classified as a safety relevant function, a classification of "No Safety Effect" can generally be set up. However, the classification shown Figure 3 is only a qualitative assessment for a first comparative study between the liner concepts. As a result of the qualitative assessment, the loss of integrity is more critical for the FHR-Liner than for the PR-Liner. Due to the rigid fibre composite structure, fragments of this layer can cause considerably more damage than the small top fillets and thin foil layer of the PR-Liner. However, since the FHR-Liner was designed based on the SHR-Liner (safety-optimized and in service for decades), the probability of such a failure occurring, can be classified as significantly lower than with the PR-Liner (quantitative classification of TLEs). Such a quantitative evaluation can only be reliably carried out with a higher TRL.

5 Conclusion and Outlook

Within the safety assessment process, basic failure scenarios of a new flexible acoustic liner technology were demonstrated. Because acoustic liners are technically simple systems, the majority of the addressed failure cases imply a structural failure of the fibre composite materials. Depending on the consequential failure and position of the damaged liner structure in the engine, this can lead to slight aerodynamic influences, as well as to thrust disturbances and critical damage to surrounding systems and components such as the intake, the fan or the bypass duct. The damage to the flexible foils is only of minor importance in terms of aviation safety. Due to their innovative geometric, functional and material adaptations and differences compared to conventional SHR-Liners, further basic and application-oriented investigations must be considered. Based on this, design adaptations for the liner concepts have to be performed to comply with the safety requirements of aviation authorities in order to benefit the full potential of the new broadband effective liner technology for future aircraft engines.

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