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Safety Design and Test Verification of Uncontained Fragment Event for Aeroengine

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Abstract

The aeroengine uncontained high-energy fragment is a failure event with hazardous effects that is unanimously recognized by national standards and airworthiness regulations. This paper starts from the perspective of aeroengine uncontained high-energy fragment incident, summarizes the relevant regulatory requirements for the incident, analyzes the safety design of the aeroengine in response to the incident, and summarizes the test method for the incident. The reference for safety design analysis and experimental verification research of other hazardous events is provided.

Keywords

Aeroengine, Uncontained high-energy fragment, Aeroengine safety design, Aeroengine test verification.

1. Introduction

Safety is the eternal theme of the aviation industry, an aeroengine is the heart of the aircraft, and it is of great significance to conduct research to ensure its safety [1-3]. As the most direct carrier and object of safety, the aviation engine industry should implement targeted design assignments, manufacture implementations and verification demonstrations for aeroengines [4-5]. Regardless of whether it is the design, manufacture, and verification work of the industrial side, the certification work of the bureau, or the maintenance work of the operator, the most initial and core problem lies in its safety design, the answer to this question is reflected in the verification of safety work .

The aeroengine uncontained high-energy fragment incident defined by national standards and airworthiness documents as having hazardous effects and consequences, has been widely concerned and studied by scholars at home and abroad. Huang et al, have conducted a safety analysis of top-level incidents transferred from uncontainment [6]. Xu once studied the safety assessment of aircraft structure after the rotor uncontained failure occurred [7]. Lu et al, have studied the failure time from the perspective of aircraft design [8]. Zhu did an analysis of airworthiness certification technology on this issue [9].

The above researches have studied in detail the causes and possible harmful consequences of the aeroengine uncontained high-energy fragment incident and have conducted a safety analysis based on the aircraft body. However, they did not start from the perspective of the safety design of the engine itself, and analyze and summarized the safety design of the aeroengine for this problem and the corresponding verification process.

This paper will first summarize current industry standards and airworthiness regulations based on uncontained high-energy fragment incidents, analyze existing safety designs based on standards, regulations, and common failure causes, and fanally give corresponding test verification methods and verification requirements.

2. Analysis of Airworthiness Requirements for Aeroengine Uncontained High-energy Fragment

In the current CCAR 33.75 clause, the failure level of the high-energy fragment intolerance event is defined as hazardous engine impact. The maximum allowable probability of this failure level is 10^{-7}~10^{-9} times/flight hour, which is the highest level. In addition to the CCAR 33.75 clause, some other clauses of CCAR Part 33 and the current national military standards have made certain requirements for the issue of high-energy fragment intolerance [10]. The summary of these clauses is shown in **Figure 1**.

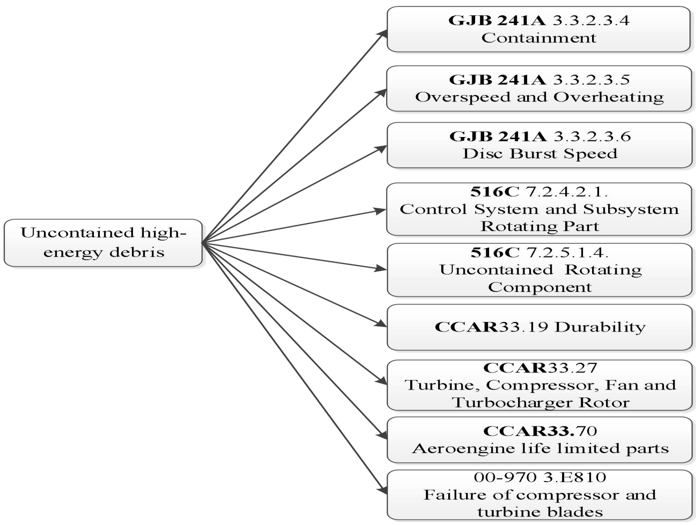

Figure 1: Standards and airworthiness requirements related to uncontained high-energy fragments.

These standards and regulations are summarized as follows:

(1)The engine has a structure that can contain a single non-energy-level width limiting fragment, and this structure can also contain other blades or delicate parts flying out. However, this part is not used to contain important rotating parts that have been broken. This also shows that important rotating parts always produce latent high-energy fragments.

(2)When multiple uncontained blades fly out, these types of events are considered to have a major impact on the engine because they are considered low-energy fragments. However, the high-energy fragment contained in the flying blades can have a hazardous effect on the engine.

(3)The connotation of uncontained of fan blades should be considered for high-energy fragments (corresponding to hazardous effects) and low-energy fragments (corresponding to major effects).

(4)According to experience, if the casing with the highest pressure (compressor delivery pressure) ruptures, inclusive high-energy fragments will be produced. This situation should be treated as a hazardous effect.

According to the airworthiness clause, the probability of hazardous effects is “extremely remote”, and the quantitative index is 10^{-7} times/flight hour. The probability of major effects is “remote”, and the quantitative index is 10^{-5} times/flight hour.

3. Analysis of Airworthiness Requirements for Aeroengine Uncontained High-energy Fragment

The failure causes of uncontained high-energy fragments can be mainly divided into: failure of main rotating parts, failure of main bearing, rotor overspeed, turbine disk overheating, foreign-body aspiration, the rear oil sump caught fire and blade falling off [11].

Because the above failure causes may occur in various parts of the engine, the fault tree analysis(FTA) for the failure of the uncontained rotor can be drawn as shown in **Figure 2**.

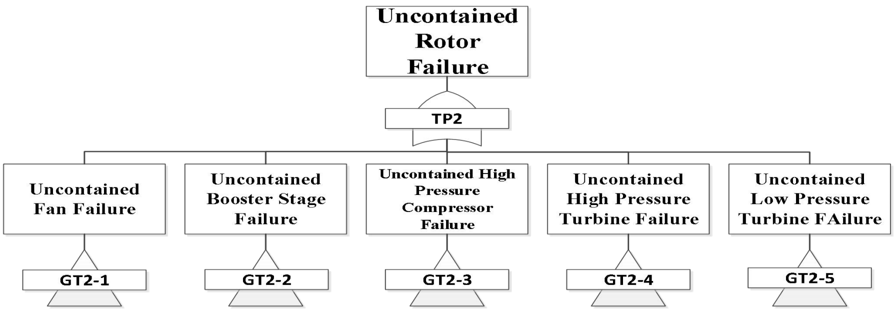

Figure 2: Fault Tree Analysis of Uncontained Rotor Failure

3.1. Safety Design of Uncontained Fan Failure

The size of modern fan fragments will be increased to a certain extent to support greater blade mass, and the axial width will also be increased to reduce tongue and groove stress.In addition, modern fan blades are made of titanium, which is a lightweight, corrosion-resistant, high-strength alloy. The design of the blade is based on experience, with a single shank tongue and groove and a partial span shield. The tip diameter and longer tongue and groove in the blade design can make the disc load in line with experience. The airfoil is forged to achieve close tolerance dimensions and polished to the final shape. The interlocking surface of the shield of the part span is machined and formed, and the tungsten carbide coating can play a protective role.

In order to improve the fatigue strength of the tongue and groove and reduce the possibility of fretting, the machined pressure surface of the blade is generally coated. The stress concentration in the blade tongue and groove is reduced by the compound fillet radius. By providing sufficient allowable vibration intensity to maintain operation in the case of stalled engine command excitation and crosswind, the blade can avoid fatigue damage.

Titanium fan blades are fitted into the axial grooves of the blades, and the fan disc is held in place by a spring-loaded fixed pin assembly. At the same time, the integrated locking mid-span cover during installation can improve the rigidity of the blade assembly. The rear position of the mid-span shield also provides the blade's resistance to bird strike damage and other foreign objects.

3.2. Safety Design of Uncontained Booster Stage Failure

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Uncontained booster stage failure mainly divides into two parts: hub failure and blade failure.

For the hub, in the design process, the design of the turbocharger hub tends to be conservative to prevent overspeed.

For turbocharger blades, they are mainly made of titanium alloy, and forged with a complete platform form and single-handle tongue and groove. The blade airfoil and root are shot peened with glass beads to improve fatigue strength. A sufficiently large axial gap between the blades and the guide blades can reduce the risk of debris stuck in the pressurization stage when the main blade fails, and avoid the failure of multiple blades.

In addition, the combined booster stage stator guide vane casing and fan casing can contain any booster stage blades. Compared with the airfoil tongue and groove, the blades/discs with higher standards will have higher strength, which will cause the blade failure to produce the least fragments, so as to ensure that the rotor incomplete event does not occur.

3.3. Safety Design of Uncontained High Pressure Compressor Failure

Due to the conservative design of the compressor, rotor failure is almost impossible. As for the blades, the HPC(high pressure compressor) stator guide vane casing is a solid structure made of stainless steel. The HPC stator guide vane casing is locally thickened to seal and improve the vane. The purpose of this design is to withstand the energy within the arc length of the blade. Therefore, the compressor casing is a solid shell that can accommodate the failure of a single compressor blade.

The design requires that the crushing stress of all blade dovetails is less than 75% of the 0.2% yield point, and other engines have successfully operated under this crushing stress level. The blade with the axial tongue and groove will improve the wear resistance of the tongue and groove and prolong the service life after using the copper-nickel-indium coating.

The compressor blade design should also incorporate reinforcement functions to improve impact resistance. After using the guide blades with axial spacing, it can also be well adapted to the impact load formed by improving the blades.

In the case of overload, the standard for the strength of the parts is to design the disc-shaped dovetail to have the highest strength and gradually reduce the radial strength toward the tip of the blade. Therefore, blade failure will generate minimal debris and is unlikely to cause

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non-contained rotor failure events.

3.4. Safety Design of Uncontained High Pressure Turbine Failure

The overheating problem of the high pressure turbine is very important. In the safety design, the forward and backward rotating air seals are assembled on the HPT(high pressure turbine) rotor shaft, and an air cooling cavity is provided around the rotor system. The integral coupling nut and pressure tube are used to seal and form the inner cavity. The rotor disc and blades of the inner cavity are cooled by the continuous flow of CDP air. The CDP air is guided to the cavity through diffuser blades that are part of the forward sealing system, so overheating of the disc is considered extremely unlikely.

A variety of protection measures during design can prevent the core rotor from overspeed, excessive fuel flow required by FADEC will cause multiple failures of the ECU. In this case, the hydro-mechanical governor will limit the fuel flow to the engine, thereby preventing the HPT from overspeed.

The bearings are designed to meet all life requirements while using the smallest roller/ball element diameter to minimize heat generation. The core rotor 4 bearing design can achieve very stable rotation and has improved dynamic characteristics. The shock absorber bearing in the third position can accommodate the tip friction of the turbine blade. No.4B bearing is installed in a soft shell, and the bearing does not bear any radial load. The BPT air seal will act as a temporary false bearing in the event of a bearing failure to control radial movement.

For the lubricating oil system, almost no lubricating oil will flow to this area of the rotor for combustion, and the rotor will not malfunction due to this reason. The leaked oil is more likely to flow centrifugal to the front stage of the compressor, so there is no problem.

The amount of cooling air provided is 1.5 times the amount required to compensate for the air seal gap that may occur under the worst-case "g" load condition. The extra volume provides considerable margin for these abnormal operations.

In addition, the HPT stator guide blade is a solid structure that surrounds each stage of the blade in the radial direction. It consists of shield segments mounted on a shield bracket, which is in turn connected to the HPT receiver. The stator guide blade is designed to contain the energy equivalent to the loss of a complete blade. In the case of overload, the standard of component strength is to make the disc-shaped tongue and groove have the highest strength, while the radial strength towards the tip of the blade gradually decreases. In this way, blade failure will generate minimal fragments and is unlikely to cause an incomplete rotor event.

3.5. Safety Design of Uncontained Low Pressure Turbine Failure

Low pressure turbine discs are processed by forgings. The forgings should have thicker holes/webs and integral flanges, and be milled through scallops to reduce the billet concentration and prolong the life of the LCF. The scallop design was optimized using finite element method and photoelasticity test correlation. The cooling circuit should be able to provide positive environmental control even when the sealing performance is reduced, by providing cooling air to the BPT and LPT disk cavities, so as to avoid any contact with the hot exhaust flow and prevent over-temperature. Even if FADEC closes the hole for cooling, it will provide the least amount of cooling air flow to control the disk temperature.

In the event of a rupture of the low-pressure shaft, extra care must be taken in the engine design to avoid the risk of severe over-rotation of the LPT. The definition of LPT's axial clearance is based on the fact that if the low pressure shaft ruptures and subsequently moves the rotor backwards, the severe friction/contact between the blade and the guide blade will cause torque and power loss, thereby avoiding severe over-rotation.Under normal circumstances, the energy consumption is low and there is no harm to the aircraft.

The excessively high temperature in the LPT cavity may be the result of overheating of the disc rim due to the inhalation of hot air from the intake duct. The amount of cooling air provided is 1.5 times the amount required to compensate for the air gap that may occur under the worst-case maneuvering load conditions. This excessive capacity provides considerable margin for these abnormal operating conditions.

The overheating in the LPT cavity may also be caused by the decrease of cooling air caused by the rupture of the seventh-stage cooling system tube, the engine is designed with sufficient flow margin to operate safely under the condition of loss of cooling air due to broken tubes. However, the expected safe operating time of the seventh-level cooling system pipes that are completely cut off and maximum severity repairs cannot provide enough margin to keep the engine running until the cut pipes are detected through regular maintenance. Therefore, a differential pressure switch has been added to the seventh-stage cooling system to ensure that a broken tube is detected.

For the blades of low-pressure turbines, the stator and guide blades are solid components, consisting of a shell and a part with a cover installed inside. The shield is an open honeycomb, brazed on the sheet metal backing. Low pressure turbine blades should have an integrated top shroud and platform. Double sinusoidal tongue and groove are designed to make the root of the blade and the column and groove of the disc obtain a lower stress concentration level.

In the case of overload, the standard of component strength is to design the disc-shaped tongue and groove to have the highest strength, and gradually reduce the radial strength toward the tip of the blade. Therefore, blade failure will generate minimal debris and is unlikely to cause an incomplete rotor event. Blade malfunctions and irregularities are unlikely to result in the release of debris, thereby causing damage to the fuselage

4. Test verification of Uncontained High-energy Fragment

The relevant standards and airworthiness requirements for typical engine hazardous events (GJB241A and CCAR Part 33) have been given in Figure 1. After the industry has carried out the corresponding safety design, it needs to verify the airworthiness of the product through a certain conformity verification method. Among the various compliance methods, the test is a commonly used method in verifying the content because it can directly demonstrate the compliance of the product [10].

This paper sorts out and summarizes the compliance test items of non-contained high-energy debris events as shown in **Table 1**.

Table 1: Compliance test items for uncontained high-energy Fragment events

Dangerous event	Airworthiness requirements	Compliance test items	Test equipment
Uncontained High-energy Fragment (The engine itself causes)	33.19 Durability	Containment test on fan/supercharged casing tester; Engine inclusive test	Rotating Tester; Ground Test Bed
	33.27 Turbine, Compressor, Fan and Turbocharger Rotor	Fan rotor overspeed test; High pressure compressor rotor overspeed test; High pressure turbine rotor overspeed test; Low pressure turbine rotor overspeed test; Uncontained Roulette Integrity Test	Rotating Tester
	33.70 Key piece	Low-cycle fatigue test of life-limiting parts	Rotating Tester
	33.94 Blade containment and rotor unbalance test	Containment test on fan/supercharged casing tester; Fan shaft strength test caused by blade fracture; Strength test of installation joint caused by blade fracture; Engine blade containment and rotor unbalance test	Rotating Tester; Ground Test Bed
Uncontained High-energy Fragment (External risks)	33.76 Ingestion of foreign objects: birds ingestion	Bird ingestion test of fan blades on tester; Bird impact test of engine fan blades; Strength test of engine mounting system caused by bird strike of fan blades	Tester; Bird launcher; Rotating Tester; Ground Test Bed
	33.77 Ingestion of foreign objects: ice ingestion	Ice ingestion test	Ground Test Bed
	33.78 Ingestion of foreign objects: rain ingestion and hail ingestion	Rain ingestion test; Hail ingestion test;	Ground Test Bed

The test requirements used to verify the conformance of aeroengine high uncontained

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fragment are summarized in **Table 2**.

Table 2: Compliance test items for uncontained high-energy Fragment events

Compliance test items	Test requirements
Containment test on fan/supercharged casing tester; Engine inclusive test	The containment test must verify that the compressor and turbine rotor casing are designed to contain the damage caused by the failure of the rotor blades. The containment test must verify that the compressor and turbine rotor casing are designed to contain the damage caused by the failure of the rotor blades.
Fan rotor overspeed test; High pressure compressor rotor overspeed test; High pressure turbine rotor overspeed test; Low pressure turbine rotor overspeed test; Uncontained Roulette Integrity Test	The engine must work stably for at least 5 minutes at the maximum allowable gas measurement temperature and 115% of the maximum allowable speed. After the test, the rotor should be within the allowable limit and there should be no signs of impending failure; After the over-rotation test is satisfactorily completed, use the same engine to work for 5 minutes at a temperature exceeding the maximum allowable steady-state gas measurement temperature of 42°C and no lower than the maximum allowable steady-state speed. After the test, the rotor should be within the allowable limit, and there is no sign of impending failure; All key rotating disc components should be tested on a rotating tester. The test speed should reach at least 122% of the maximum allowable steady-state speed, and the inner hole or core material should reach the highest design temperature. It should not be damaged after the test.
Low-cycle fatigue test of life-limiting parts	Carry out component low-cycle fatigue test to verify that the component should meet the 2 times life requirement.
Containment test on fan/supercharged casing tester; Fan shaft strength test caused by blade fracture; Strength test of installation joint caused by blade fracture; Engine blade containment and rotor unbalance test	Under the maximum allowable transient speed, when the fan, compressor or turbine blade breaks at the transition part between the blade body and the tenon, the engine should be able to fully contain it. In addition, the engine should contain all parts destroyed by the destruction of a single blade.
Bird ingestion test of fan blades on tester; Bird impact test of engine fan blades;	The test aeroengine shall be subjected to the bird-absorption test required by the clause. The swallowing birds should be scattered irregularly on the intake section to simulate the situation of encountering

Compliance test items	Test requirements
Strength test of engine mounting system caused by bird ingestion of fan blades	a flock of birds.
Ice ingestion test	The engine should be able to swallow hail without stalling, the thrust recovery time should not exceed the specified value of the model specification, the continuous thrust loss should not exceed 10% of the thrust in this working state, or there should be no major structural damage that can cause engine failure.
Rain ingestion test; Hail ingestion test;	The engine shall not cause unacceptable mechanical damage or unacceptable power or thrust loss or require the engine to stop after inhaling the required hail.

5. Test verification of Uncontained High-energy Fragment

This paper starts with the hazardous impact of uncontained high-energy fragment incidents, summarizes the formulation of engine safety design guidelines from the airworthiness point of view, analyzes the existing safety design methods, and summarizes the design assignment process of this safety issue. This paper also recapitulates the relevant content and corresponding requirements of the test in the compliance verification method for this problem.

This paper only studies and summarizes uncontained high-energy fragment incidents, but other hazardous events such as engine shutdown, uncontrollable internal fires in the engine and other hazardous events can also be analyzed by the methods of this paper.

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References

[1]Z. M. Fan, C. L. Sun, J. Bai. Fault tolerant controller based on deviation index function,Science Press, Beijing, China, 2004.

[2]J. Bai, S. Liu, W. Wang. Identification method for parameter uncertain model of aero-engine, Journal of Aerospace Power, Vol.23, 178-184, 2020.

[3]S. Liu, J. Bai, Q. Wang,W. Wang. Tracking Controller Design for Aero-Engine Based on Improved Multi-Power Reaching Law of Sliding Mode Control, International Journal of Aeronautical and Space Sciences,2019,5(12).

[4]J. Bai, S. Liu, W. Wang. Progress in the airworthiness technology of civil aero-engine.CEAS Aeronaut Journal, 2019,20(1): 722-731.

[5]J. Bai, S. Liu, W. Wang. The Nonlinear Single Controller of DGEN380 aeroengine Design. International Journal of Aerospace Engineering, 2019.

[6]Q. N. Huang, L. X. Zhang, C. H. Liu, H. J. Liu. Safety Analysis and Thought of Uncontained Top Event for Aeroengine Rot.aeroengine, 2009,35(02):6-9+23.

[7]H. S. Xv. Study on structural safety assessment method of civil aircraft Engine rotor after non-containment failure.Science technology and Engineering,2012,12(12):3023-3026.

[8]R. C. Lu, X. Z. Li, Y. Li, W. G. Hu, C. T. Non-containment design of engine rotor fragments in aircraft design, Acta Aeronauticaet Astronautica Sinica,2016,37(01):351-363.

[9]R. X. Zhu, Analysis of blasting airworthiness of engine and APU uncontained Rotor, Dual-use technology and products,2021(07):44-48.

[10]FAR Part 33.75, Airworthiness Standards: Aircraft Engines,Safety analysis.US:FAA,2021.

[11]L. Q, Y. J. LI, Y. Y. Cao, S. Y. Zhao, Z. T. Xv, L. Wang. Fault Tress Analysis of Aeroengine High-energy Debris Intolerance, Aeronautical Computing Technique,2015,45(03):35-37.

GJB 241A — 2010. General specification for aviation turbojet and turbofan engines, The General Armament Department of the PLA,2021