

Integrated Safety Risks Assessment of A Low-Pressure Turbine Section of An Aeroengine

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Abstract

Safety engineers aim to ensure that systems are designed, developed, and operated safely and reliably, in compliance with applicable regulations and standards. Safety is defined as the backbone of the aviation industry. To achieve and maintain the desired level of safety, risk analysis is a critical analytical tool. This scientific approach is employed to identify, evaluate, and manage hazards effectively. The primary objective of risk assessment techniques, in addition to ensuring compliance with legal requirements, is to mitigate operational risks and enhance overall safety. Engine failure constitutes a hazardous, emergent situation in aviation and aeronautical engineering, with the potential for severe consequences. While the low-pressure turbine section significantly influences the aviation safety of modern aircraft, this particular section has not received proportionate consideration. This paper addresses risk identification and management in the third and fourth stages of the low-pressure turbine in a JT8D engine. A framework is proposed for this purpose, utilizing historical failures' data, failure mode and effect analysis, and event tree analysis techniques. Both economic and technical effects are considered during the thorough investigation of hazards. Investigations have shown that blade shroud wear can cause vibration and fatigue, leading to blade fracture and engine cover rupture. Based on the safety risk assessment, some recommendations for inspection and maintenance procedures are suggested. Regularly inspecting, monitoring vibration, accurately measuring torque, and visiting shops are the recommended actions. Some airlines have conducted this procedure, and the experience shows that it effectively reduces the risk rate in the field.

Keywords: Safety Risk; Maintenance; JT8D engine; LPT; Blade Fracture.

Nomenclature

DSA	Deterministic Safety Analysis
EVT	Event Tree Analysis
FHA	Functional Hazard Assessment
FMEA	Fault Mode and Effects Analysis
FTA	Fault Tree Analysis
ICAO	International Civil Aviation Organization
LPT	low-pressure turbine
PSA	Probabilistic safety analysis
RCA	Root Cause Analysis

1. Introduction

Since the introduction of jet engines into the aviation industry in the 1960s, various types of engines have been designed, built, and used, enabling billions of flights. Although numerous kinds of accidents have been reported, safety has consistently been a primary concern,

as emphasized by international aviation associations and organizations [1].

The engine's critical role in ensuring safe flight has made it a top priority for both manufacturers and operators. The JT8D engine family, developed by Pratt & Whitney, exemplifies such an engine, having provided reliable service for an exceptionally long period. Initially introduced in the 1960s, this engine family remains in operation today [2]. Over its lifespan, the JT8D has logged more than 600 million flight hours and transported billions of passengers.

Each engine presents its own unique advantages and disadvantages. One of the significant challenges facing aero engines is blade breakage, particularly within the low-pressure turbine (LPT) section. Failures of this nature most frequently occur in the third and fourth stages of the turbine [3]. Blade failure can lead to engine shutdowns and emergencies. In some instances, it can precipitate an uncontained engine failure [4], wherein

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blade fragments are radially ejected from the engine housing. A notable example of such an incident occurred at Taipei Airport in 2018 [5]. Figure 1 illustrates the repercussions of this event.

Aircraft engine safety analysis is a critical area of study, and this article aims to contribute to this discourse. The subsequent sections will introduce the safety analysis, review previous research, identify critical cases using risk analysis methods, and propose necessary actions to mitigate these risks for the LPT section of a JT8D engine.



Figure 1. LPT incident for a JT8d engine [5]

2. Safety Analysis

Safety engineering is dedicated to ensuring that systems and processes operate safely, reliably, and in compliance with regulatory standards. This objective necessitates comprehensive system analysis, wherein risk and safety management involve the identification, evaluation, and mitigation of risks to prevent accidents [1]. This process is commonly achieved by determining the severity and probability of potential events and implementing measures to reduce or eliminate their critical effects [6]. Such analyses can be conducted at various stages of a system's life cycle.

Two fundamental paradigms underpin safety analysis: probabilistic and deterministic approaches [7]. PSA focuses on quantifying the risk associated with various initiating events to verify compliance with safety targets. It employs best-estimate data and assumptions, leveraging operational experience from analogous systems to generate realistic risk predictions. In contrast, DSA evaluates the consequences of postulated design-basis events to ensure they meet predefined acceptance criteria and safety goals, thereby demonstrating the efficacy of defense-in-depth strategies and the structural integrity of protective barriers.

An effective safety analysis is inherently systematic, grounded in validated information, and requires the participation of relevant stakeholders. This multidisciplinary approach enables decision-makers to formulate accurate, well-supported conclusions. Beyond purely technical factors, a comprehensive risk assessment must also consider interrelated aspects of security, environmental impact, and economic feasibility.

Numerous studies have developed and demonstrated the application of diverse safety methodologies. Established techniques, such as FMEA, FTA, and ETA, remain widely used across the automotive, energy, medical, and aerospace sectors due to their structured nature, despite frequent reliance on expert judgment.

Concurrently, modern data-driven approaches and machine learning techniques are increasingly utilized for risk, reliability, and safety assessment [8–10]. These methods offer powerful predictive capabilities but require large, high-fidelity datasets. Furthermore, computational simulation techniques, such as Monte Carlo and Markov modeling, are effectively employed to understand and predict complex system behaviors under uncertainty.

This paper specifically addresses applications within aeronautical engineering and the aviation industry, where safety is an unequivocal priority, as reflected in stringent international regulations and a substantial body of research. The increasing complexity of modern aircraft and their subsystems presents significant engineering challenges. Consequently, engineers continually work to mitigate risks and reduce accidents by addressing persistent threats, including fire, human error, maintenance deficiencies, fatigue, fractures, and wear.

Substantial research has been dedicated to these areas. For instance, Jiang Wang et al. [11] investigated fire-related risks in aviation, while Lee et al. [13] developed a physics-informed, data-driven model integrated with Weibayes and fatigue crack growth models for risk-based maintenance planning. Gan et al. [14] applied a model-based approach to aero-engine safety evaluation, and Lalis et al. [15] utilized FMEA to analyze the reliability of aircraft engine lubrication systems. Aust and Pons [16] employed attribute agreement and Kappa statistics to assess the performance of aircraft engine blade inspection quantitatively. Salvador et al. [17] incorporated big data and machine learning to enhance system reliability. Recognizing that external factors also influence safety, Boyd [18] utilized flight-tracking data to identify and address safety shortcomings in general aviation cross-country operations. Bills et al. [19] analyzed methodologies used in aviation accident investigations, noting that agencies often employ a combination of frameworks—such as Reason-based, Rasmussen-based, Bow Tie, and SHELL models—simultaneously.

This relentless focus on safety has yielded measurable results. The International Civil Aviation Organization (ICAO) reported a significant decrease in the global accident rate per million departures, declining from 4.7 in 2008 to 2.79 in 2019 [20]. This improvement is largely attributable to enhanced operational procedures, technological advancements, and stricter safety regulations. While pilot-related factors remain the leading cause of accidents, mechanical failures—particularly those involving engine components—constitute a critical secondary contributor. Turbine blade failures, for instance, can precipitate sudden power loss, engine

shutdown, and necessitate complex emergency procedures.

Catastrophic engine failures can result from fractured disks, liberated blades, or fuel system malfunctions. Notable cases include the uncontained failure of the right engine of a McDonnell Douglas MD-88 (N996DL) during takeoff from Tucson International Airport in March 2001, as well as the uncontained failure of the fourth-stage blades in a JT8D-219 engine on an MD-88 at Atlanta Airport in November 2012 [21].

The specific risk of uncontained rotor failure has been a significant focus of research. Wang Fengchan et al. [22] developed verification methods for airworthiness compliance, Li Mailiang et al. [23] identified and quantified associated hazards, proposing a methodology based on AC20-128A that employed FTA and FHA. Zhao Zhenqiang et al. [24] applied boundary discretization to assess the safety of full-scale rotor engines and to optimize aircraft system layouts. Dang Xiangjum et al. [25] used Bayesian Networks to incorporate uncertainty into safety optimization models and identified major risk events.

Uncontained failures are often initiated by fan blade fractures, disk ruptures, or casing containment failures. These events can generate high-energy debris, posing a severe threat to aircraft integrity. For the JT8D engine family, blade failures in the LPT section—particularly in the third and fourth stages—have been identified as a predominant and hazardous failure mode [20].

While prior research provides valuable insights into uncontained failures and general rotor dynamics, a significant gap remains: the absence of a dedicated, quantitative risk analysis specifically for blade failures in the third and fourth stages of the low-pressure turbine in JT8D engines. The continued widespread use of this engine family makes a stage-specific risk assessment both critical and timely to inform proactive maintenance and safety protocols. Existing studies often address broader engine-level events or different components (e.g., fan blades) and frequently rely on qualitative assessments or aggregated data that is not specific to these critical LPT blades.

This study directly addresses this gap by performing a targeted probabilistic risk assessment of blade failure in the specified LPT stages. By integrating FTA with operational data, this research aims to: (1) determine the likelihood and severity of this specific failure event, (2) identify the leading root causes and contributing factors, and (3) propose mitigation strategies to enhance the safety and reliability of the JT8D engine platform.

3. The proposed approach to risk analysis and management

Turbojet engines, as complex systems with thousands of interdependent components, pose significant challenges to comprehensive modeling. This issue is particularly evident in older engines, such as the JT8D, which lack

sensors and have limited data availability. Maintenance and repair data are often recorded in a binary format (serviceable or failed), driven by operational constraints and the need to reduce costs.

To assess risks under data-scarce conditions, qualitative and quantitative methods such as FTA, FMEA, and ETA are employed. This paper proposes a hybrid approach that integrates FMEA and EVA for risk assessment in legacy engines. The primary advantage of this method is its simplicity and practicality, making it particularly well-suited for legacy systems with limited data. Fig. 2 shows the proposed approach.

In the first step, the engine structure and principles should be reviewed to identify failures and hazards. Then, the causes of the main failure are evaluated. Airworthiness Directives (ADs), Service Bulletins (SBs), the engine manual, textbooks, and historical failure reports are good technical and scientific references for understanding actual conditions and identifying problems. Conducting ETA is recommended to evaluate the final effects and create a reliable basis for management decisions.

To enhance the identification of the main problem and its causes, an RCA is carried out. In this process, significant factors are investigated, and control and/or corrective actions can be proposed to mitigate or eliminate the consequences of failures. The completion of the FMEA and risk analysis follows these steps. To finalize the FMEA table, data collected or determined in previous steps are used in the FMEA process. ICAO regulations and guidelines can be used to perform the risk analysis. The risk level should be reduced to tolerable or acceptable levels; often, we suggest inspection or maintenance tasks for this purpose. An example of the LPT stages of a JT8D engine is used to explain the proposed approach in the remainder of the paper.

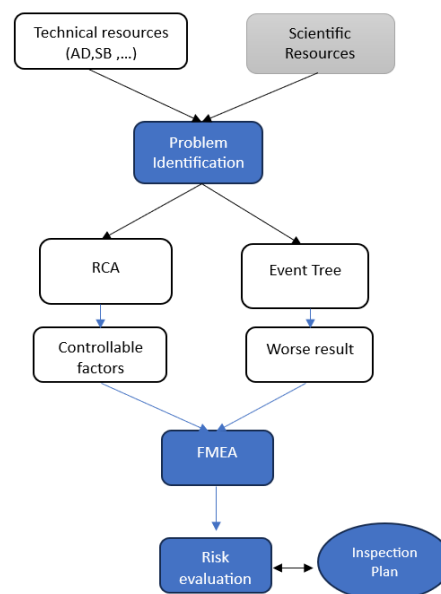


Figure 2. The proposed approach for risk assessment

4. Case study

4.1 Problem Identification

The LPT is a section of a jet engine that harnesses exhaust Stream Energy to drive the engine shaft and rotate the low-pressure compressor. Located at the back of the engine, a failure in the LPT leads to immediate performance degradation, requiring the pilot to follow emergency landing procedures. LPT failures are often caused by blade or disc ruptures, primarily due to two failure types: fatigue loads during normal operation and shroud wear. While corrosion can initiate fatigue cracks, its impact is relatively minor.

To assess fatigue life, mechanics-based models, physics-of-failure methods, and finite element analysis are employed, with a focus on stress or strain behavior. Cracks are monitored by size and location, and failure occurs when a crack exceeds a defined threshold. In this context, damage tolerance and reliability-centered maintenance techniques are essential for risk management, making inspection procedures and intervals crucial for risk reduction.

Fatigue life has been extensively studied, while shroud wear, which also contributes to blade fractures, has received comparatively less attention. This complex wear process can result from the contact between blades in the engine assembly, specifically using a Z-notch design that applies normal load on the shroud while allowing minimal freedom for vibration damping. Increased wear leads to greater blade clearance, subjecting them to high-cycle loads that can cause sudden fractures. This failure mechanism, characterized as typical fretting damage in the turbine region, has been reported five times globally in JT8D engines. The principles of shroud wear are illustrated in Fig. 3, with notch wear on the contact surfaces shown in Fig. 4.

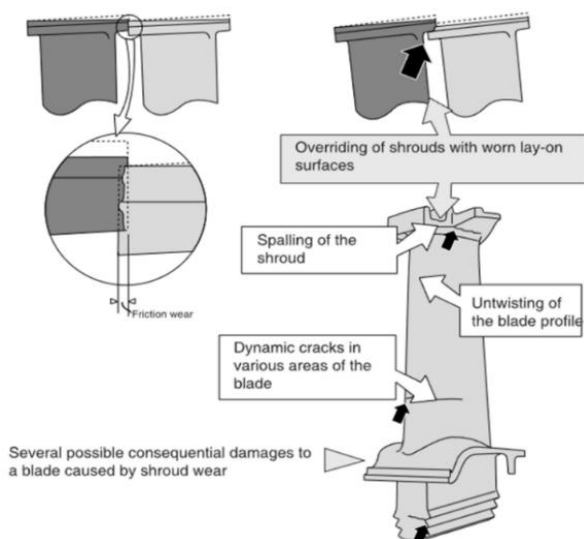


Figure 3. Shroud wear [27]

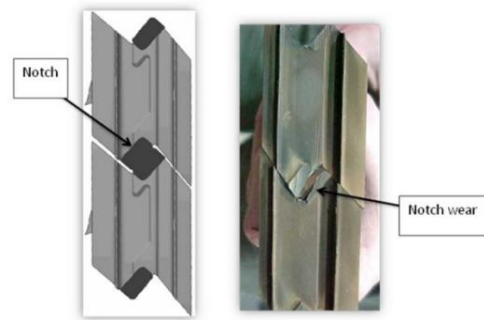


Figure 4. Notch wear

The contact and normal load between blades are utilized for vibration damping, as vibration levels in this area are high and can be influenced by other engine stages. This failure mode represents a specific wear process occurring at the contact interface between two components under load, subject to micromovement caused by forces such as vibration. The amplitude of relative sliding motion is typically less than one millimeter, sometimes as low as 3–4 nanometers.

To investigate this failure mode, it is essential to identify the key factors and parameters influencing the wear mechanism. The Archard wear equation is a fundamental and applicable model for studying the wear process.

$$V = \frac{kPD}{H} \quad (1)$$

The total volume of wear debris produced is denoted by V , with k a dimensionless constant, P the total normal load, D the sliding distance, and H the hardness of the softest contacting surfaces. According to Equation 1, key factors influencing the wear process include the friction coefficient, the normal load between the blades, material properties, and the displacement value.

In an LPT, wear is affected by material composition, vibration, assembly loads (contact loads), temperature, shroud dimensions, and the number of flight cycles. Some of these factors can be monitored in the field; for example, vibration can be tracked with an installed pickup sensor, though the original JT8D engine design lacked vibration-monitoring sensors. Contact loads can be measured with a torque meter, while visual inspections and wear monitoring can occur during maintenance visits.

Vibration affects blade displacement, and as this displacement increases, so does the wear volume, leading to greater blade clearance. This cycle continues until final failure occurs. The production of the JT8D engine has ceased, and many of these engines have accumulated high flight cycles, potentially resulting in increased vibration. Although the sources of vibration are often unclear, their effects are significant, making vibration monitoring crucial for preventing hazardous situations.

The assembly or contact load between blades also influences the wear process. Excessively high loads can reduce blade-to-blade movement, thereby decreasing wear volume. However, increased loads can create

intolerable issues: high-pressure loads may lead to localized stress and diminished vibration damping, both of which are vital to turbofan engine performance. Therefore, contact loads should not exceed predefined limits. Conversely, reducing the load decreases control over clearance and the wear process, potentially leading to more displacement and blade fracture.

Wear volume increases with the frequency of movement, often defined by flight cycles. More flight cycles create conditions that facilitate increased movement between blades. Previous research has addressed this issue; for instance, Lakshminarayana et al. and Bertrando studied the effects of wear on shrouded blades in LPTs. Bertrando demonstrated a linear relationship between the logarithm of wear volume and the logarithm of the number of operating cycles (Fig. 5). Notably, doubling the operating time does not yield a proportional increase in metal wear. Additionally, he proposed a new design to mitigate wear on the blades.

4.2 Event Tree Analysis

The ETA method is a valuable tool for safety analysis, particularly in systems that require actions to mitigate hazardous or catastrophic events. It defines the success and failure states of a system and assesses the effectiveness of existing barriers. ETA is particularly useful for analyzing sequential processes in risk and safety contexts and can be employed quantitatively, as the probabilities of various events are known, allowing for

the determination of overall system success or failure probabilities.

For instance, if debris exits from the end of an engine, it indicates engine damage and necessitates emergency procedures. Such incidents have occurred in several engines, resulting in flight cancellations without hazardous outcomes. However, if debris breaches the engine cover and impacts the aircraft fuselage, it could cause significant damage and lead to an uncontrollable situation (Figure 6). To date, this specific event has not been reported globally, suggesting an extremely low likelihood of occurrence.

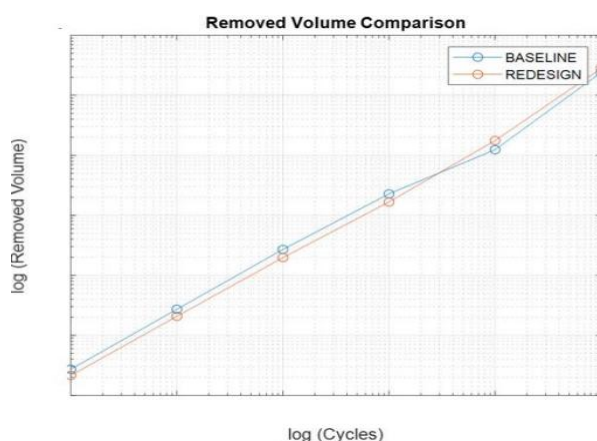


Figure 5. The relation between removed volume and cycles (movement) [30]

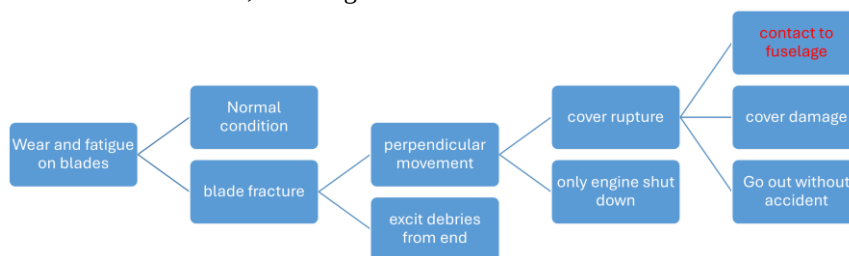


Figure 6. Event Tree for the LPT section's blade

Historically, five confirmed instances of cover rupture in JT8D engines have been acknowledged by the FAA, but Iranian airlines have not reported such events. Given that these engines have accumulated over 700 million flight hours, there is concern that a future incident could result in blade rupture and cover failure. The probability of fuselage damage following a cover rupture is estimated at 0.5. This conservative estimate is based on factors such as the engine's installation location, its dimensions, and the aircraft fuselage design. The value used in this study is a strict (conservative) estimate, representing a worst-case scenario, and is endorsed by experts who have overhauled and maintained more than 400 engines. Therefore, the probability of fuselage damage is:

$$Pr = 1/2 \times 1/(7 \times 10^8) = 7.14 \times 10^{(-10)}$$

Although this value is extremely remote, the cover rupture (local damage) is selected as the worst consequence, and its risk is evaluated in the next section.

4.3 Root Cause Analysis

RCA involves identifying the root causes of problems to implement effective solutions and systematically prevent hazardous events. This process utilizes a combination of data collection, principles, techniques, tools, and methodologies to uncover the underlying causes of an event. In this context, the primary cause of blade failure has been identified as wear between blades, which increases clearance and leads to high-cycle fatigue. To validate this finding, relevant scientific and technical reports were reviewed, and multiple meetings were conducted with engineers, as discussed in previous sections.

4.4 Failure Mode and Effect Analysis

FMEA is a systematic approach to identifying and preventing potential problems. FMEA focuses on identifying weaknesses and defects to enhance safety and reduce risk. Various standards, including MIL-STD-1629A, ICAO, and SAE J1739, provide guidelines for conducting this analysis and determining risk value (RPN). Given the inherent hazards in aviation, the authors followed the procedure detailed in the ICAO "Safety Management Manual" (Doc 9859, 2018). This guideline covers hazard and failure identification, understanding consequences, assessing hazard rates and severity, and

determining risk indices, ultimately informing decision-making regarding tolerability.

For the LPT section of a JT8D engine, FMEA is conducted in a tabular format. This table outlines various components and functions, with a specific focus on the desired failure modes, as illustrated in Table 1. Severity ratings are based on the ICAO manual and take into account the engine's location on the aircraft, LPT position, engine configuration, and operational experience within Iranian airlines. The FMEA was carried out through collaborative efforts involving a team of experts from ten Iranian airlines and MRO organizations, involving three meetings with the participation of 20 experts.

Table 1. FMEA for blades of stages 3 & 4 of a JT8D

Function/Item	Potential Failure Mode	Effect	Severity	Cause	Occurrence	Prevention	Detection	RPN
Blade Stages 3 & 4	Crack	ENG failure	D	Impact, Pre-existing defects, Operational, Poor manufacturing	C	-	Shop visit	DC
		Cover damage	C	Impact, Pre-existing defects, Operational, Poor manufacturing	D	-	Inspection, change over time.	CD
	Creep/fatigue	ENG failure	D	Operational, Poor maintenance	D	Check 01 every shop visit	Shop visit	DD
	Oxidation	performance reduction	E	Environmental, Pre-existing damages	C	-	Shop visit	EC
	Corrosion	performance reduction	E	Environmental, Operational	C	-	Shop visit	EC
	Erosion	performance reduction	E	Impact, Environment, Operational	C	-	Shop visit	EC
	Dent/nick	performance reduction	E	Impact	C	-	Shop visit	EC
	Wear/Fretting	Fatigue crack only	D	Operational, Poor maintenance	D	Check 01 every shop visit	Shop visit	DD
		Fatigue crack and Cover damage	C	Operational, Poor maintenance	E	Standard blade	Vib and torque check and surface control	CE
	Degradation of the coating on the LPT blade	Performance reduction	E	Operational, Environmental	C	-	Shop visit	EC
	Vibration	ENG failure	D	Unbalancing and Misalignment	E	Personnel Training, calibration	Test	DE
	Inner Object Damage	ENG failure	C	Impact	D	-	Operator/shop	CD

4.5 Risk Evaluation

According to the FMEA, the severity of blade fractures due to wear and fretting is classified as major (C index). This type of failure cannot be monitored or recorded during flight, and there is no option to install additional sensors. Therefore, we recommend implementing regular inspection intervals, which should be validated by

Airworthiness Directives from the engine manufacturer, expert opinions, and scientific principles.

Pratt & Whitney has issued various ADs aimed at risk reduction, with the most recent directive emphasizing the removal and replacement of blades after 5,000 flight hours. However, this directive does not account for the economic implications for operators outside the USA, potentially increasing operational costs and demand for new blades, which manufacturers and suppliers may

struggle to meet. Thus, we propose increasing the frequency of inspections and controls during the engine's service life, pending expert approval. Although this may raise operational costs, it is more reasonable compared to the expenses associated with replacing blades after 5,000 hours.

4.6 The recommended actions

To reduce risk in the aviation industry, a series of inspections and repairs is typically recommended. These procedures include visual inspection, vibration testing, and necessary repairs or replacements. The actions related to torque measurements are outlined below.

Wear and clearance between blades lead to decreased forces in the contact zone and increased vibration intensity. Monitoring and controlling these factors can significantly reduce the probability of failure. Torque measurements can be used to control the forces separating the blades, with a suggested control action every 225 flight hours, maintaining a torque of 14-16 pound-inches, based on ISO 6789:2017 (torque meter calibration standard). This process can be carried out on the wing at a low cost and with minimal time investment, similar to a pre-flight check but requiring slightly more time.

Vibration is a critical indicator for the health monitoring of aeronautic engines. However, because the engine lacks vibration sensors, measurements are time-consuming and expensive, necessitating periodic checks. Economic analysis and maintenance plans recommend conducting these measurements concurrently with engine checks every 450 to 500 flight hours. The complexity of engine vibrations, influenced by various internal and external factors, complicates interpretation and requires specialized knowledge. Fig. 7 shows vibrations recorded at different engine speeds as an example.

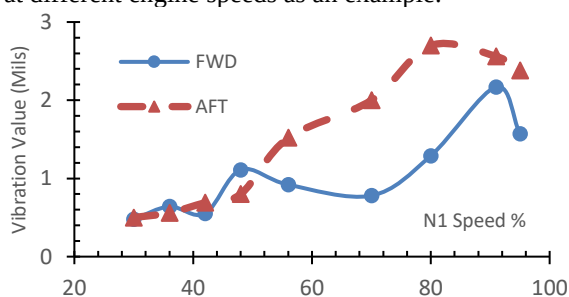


Figure 7. Vibration values of a JT8D engine during an engine test

In this study, twelve aero engines from different airlines were monitored over six months, with measurements taken from both the FWD and AFT. The highest recorded vibration value, representing the worst-case scenario, typically occurs near the maximum power point. Each engine exhibited unique vibration behavior, suggesting that monitoring should be tailored to each specific engine. Data indicated that increasing engine operating time correlates with higher vibration levels

(displacement). The manufacturer specifies a permissible vibration limit of 3 MILs.

The available data show that the maximum vibration values are in the range of 2 to 2.5 mm, and these values increase gradually with time and flight (Fig. 8).

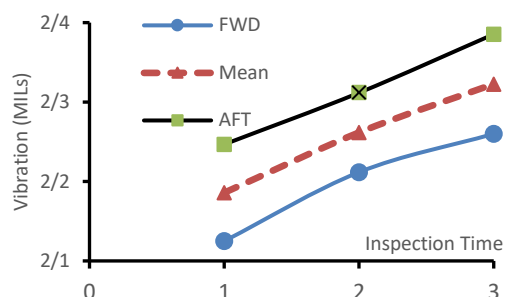


Figure 8. The average of vibration values during three inspection times for an engine

The average change between two inspections is about 0.08. Therefore, the slope and the rate of increase are small. As a result, we expect these engines to operate for about 4500–5000 hours from the initial state. In accordance with the Reliability-Centered Maintenance standards, the risk of having an engine visit the shop every 2000 flight hours is acceptable. Figure 9 illustrates the vibration values of an engine during four inspections. The values vary across different speeds, but they generally increase over time at each speed.

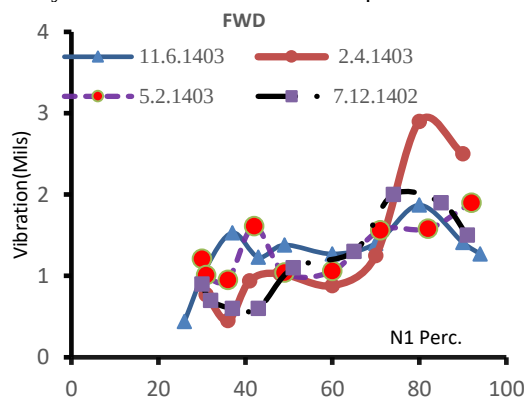


Figure 9. Vibration values of a JT8D engine (at different speeds and times)

Another essential task that complements torque control is visual inspection using a borescope. This widely employed non-destructive inspection method in aeronautical engineering ensures engine integrity. During shop visits, all blade surfaces are thoroughly examined, and any signs of wear are addressed through appropriate repairs. This procedure has enhanced the reliability and safety of Iranian operators, as reported by the Iranian Civil Aviation Organization.

The proposed maintenance procedures are summarized as follows:

- Torque Control and Visual Inspection: Every 225 flight hours.
- Vibration Monitoring: Every 450-500 flight hours.
- Shop Visit: Every 2,000 flight hours.

5. Conclusion

The JT8D engine is a widely used powerplant in the aviation industry, including among Iranian operators. A critical safety concern for this engine is the failure of its LPT blades, which could have severe consequences. This study investigates this failure mode through a comprehensive risk and root cause analysis utilizing established methodologies: FMEA, FTA, RCA, and EVA. Informed by expert opinion from the aviation industry, the study yielded a set of targeted corrective measures. These were incorporated into a structured maintenance schedule, which includes: Visual inspection (via borescope), Torque measurement on critical components, Vibration monitoring, and Scheduled overhaul.

The preliminary implementation of the proposed maintenance protocol has yielded encouraging results, demonstrating a measurable reduction in failure rates and adverse events associated with the LPT section. Initial data collected across various operational environments indicate that the protocol has effectively addressed critical maintenance issues that previously contributed to safety risks. For example, the number of engine failures has been reduced from six to two per year.

Specifically, the integration of rigorous inspection schedules, precise torque measurements, and vibration monitoring has allowed maintenance teams to identify potential issues before they escalate into significant failures. As a result, there has been a notable decrease in incidents of blade shroud wear and associated fatigue, which have historically posed a threat to engine integrity.

Furthermore, feedback from maintenance personnel underscores the value of implementing standardized procedures and best practices as outlined in the protocol. This has not only improved the overall reliability of the turbine section but has also fostered a culture of safety awareness among staff. Overall, these preliminary findings are promising and support the continued adoption of the maintenance protocol as a viable means to enhance the safety and reliability of the low-pressure turbine section in modern aircraft engines.

To further enhance the accuracy and predictive power of this analysis, future work is recommended. This should include numerical modeling and laboratory testing to deepen the understanding of underlying fretting wear mechanisms. Furthermore, integrating a methodology that explicitly accounts for the engine's operational history and life would significantly improve the precision of future risk assessments and maintenance planning.

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Conflict of interest

No conflict of interest has been expressed by the authors.

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