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Machining of the Fan Abradable Seal and its Impact on Thrust, Performance and Reliability of Aero Engines

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Aviation embodies a dynamic sector marked by a continual pursuit of progress, where the integration of innovative technologies and the refinement of more efficient techniques directly contribute to advancing the aeronautical industry. Companies operating within this realm are unwavering in their dedication to delivering increasingly reliable engines, emphasizing critical factors such as safety, quality, and mechanical efficiency. Strict adherence to performance parameters in the test cell to the engine approval process is imperative, aligning with the standards set by discerning customers and regulatory bodies. Maintenance, Repair, and Overhaul (MRO) companies sometimes face problems related to engine performance during tests in the overhaul process. This highlighted the need for a study on improvements in the process related to thrust parameters. This study analyzes the match grinding process between the abradable seal and the fan blades and shows how to ensure the engines meet the required thrust limits for approval. The dimensional relationship between these components serves as a machining reference, intending to achieve minimal clearance. This strategic approach optimizes the utilization of airflow responsible for thrust, thereby enhancing engine performance, efficiency, and reliability. The methodological approach involves a case study of the match grinding process, including an analysis of a sample of engines with results collected before and after applying the process. The study indicates that the reduction in surface roughness and control of minimum clearance result in a more efficient utilization of airflow. This leads to reduced turbulence and parasitic airflow, culminating in a significant 71% improvement in thrust for the evaluated engines compared to pre-process results. The proposed process allows repair stations to produce engines of high quality, reducing rejection risks in testing and rework. The results obtained in this study validate the efficacy of the match grinding process as a strategic initiative for improving the thrust performance of aeronautical engines.

Keywords: Abradable Seal, Match Grinding, Thrust, Turbofan Performance and Reliability

1. Introduction

The aeronautical engine industry has witnessed exponential safety, quality, and mechanical efficiency advancements. While airplanes stand as one of the safest and fastest modes of transportation globally, the challenge persists in developing economically sustainable engines that fully harness their generating capacity. Safety remains paramount, driving innovations in control systems, monitoring, and using resilient materials. Simultaneously, optimizing engine performance is crucial for cost-effectiveness in the aviation industry, impacting airline expenses and consumer costs, especially during critical phases such as take-off and landing. It is observed that aero-engine Maintenance, Repair, and Overhaul (MRO) companies sometimes encounter setbacks on the test bench, specifically related to the Thrust margin certification. This leads to rework, increasing labor, time investment, and subsequent delays, posing challenges to the company's overall processes. The proposed work analyzes the match grinding process between the fan's absorbable seal and the fan blades. The focus is on assessing the impact of this process on the Thrust parameters of the engines. Aeronautical engines must meet rigorous requirements for approval and certification, with the test bench serving as the final stage to ensure compliance with regulatory standards. The rejection at the test bench, particularly for the thrust margin certification, presents significant disruptions, including failure to meet contractual deadlines, spatial limitations in the workshop, and elevated logistical and re-testing costs. The primary challenge addressed in this study is to consider minimizing the risk of engine rejection by implementing match grinding on fan components responsible for Thrust generation. Ensuring aero engine performance demands intricate technical knowledge and skilled labor due to the numerous variables influencing engine parameters throughout the process. The study's scope is limited to the match-grinding process between the fan's absorbable seal and the fan blades, focusing on its influence on the engine's thrust margin. Stringent safety, quality, and mechanical efficiency demands are essential in aviation. MRO companies must deliver overhauled engines that meet contractual deadlines and operational certifications to remain competitive globally.

This study's research question is whether match grinding between the fan's absorbable seal and the fan blades can fully utilize airflow, enhancing thrust and engine performance. The assumption to be analyzed is that inserting a match-grinding process will contribute to optimal airflow utilization, thereby increasing the results of the thrust margin. The study unfolds in five chapters, encompassing an introduction, literature review, methodology, results, discussion of results, and conclusion.

2. Literature Review

This section thoroughly examines the existing literature concerning the primary theoretical foundations that form the basis of this study. The objective is to enhance the comprehension of the relationship and Properties of the Abradable Seal with the Blades, Thrust of Tubo-Fan Aero Engines, and performance of Turbofan Aero Engines. A review was conducted with informative sources and pertinent previous studies addressing relevant issues, which have, in various ways, contributed to the progression of knowledge in this field.

2.1 Relationship and Properties of the Abradable Seal with the Blades.

Jiaguangyi Xiao et al. (2021) highlight that modern aero engine blades are designed for better airflow utilization, impacting interactions with abradable coatings. While reducing gaps enhances efficiency, it also increases the risk of blade tip rubs, which are managed by abradable coatings. Piollet (2019) stresses the need for accurate prediction tools to understand non-linear vibrations resulting from reduced clearances, presenting a 3D finite element model. Yun Qi Tong et al. (2021) focus on the effectiveness of abradable seal coatings in improving compressor efficiency, emphasizing the importance of abrasiveness and resistance. Bin Lu et al. (2017) investigate high-speed abrasion between abradable coatings and fan blades, acknowledging the compromise in designing materials with conflicting requirements. FZ Mohammad et al. (2021) discuss the application of abradable coatings in gas turbine engines, highlighting their role in reducing parasitic air flow, improving dimensional tolerance, and decreasing specific fuel consumption. They note location-specific material selection and performance gains of 0.3-1% in power and a 2.5% improvement in thrust and specific fuel consumption. Junhong Zhang et al. (2020) developed a dynamic model to analyze the effects of friction faults between blades and abradable coatings on rotor vibration. They find a strong influence of friction on rotor vibration, with natural frequencies affected by rotation speed and initial clearance. Overall, these studies contribute valuable insights into the complex relationship between blades and abradable coatings, which are crucial for optimizing aero engine performance, reducing fuel consumption, and ensuring safety in operation.

2.2 Thrust of Tubo-Fan Aero Engines

F, Barbosa (2022*)* conducted a comprehensive review of studies on aero engines, where several authors delve into the evolution and advancements in turbofan engine technology. The research focused on developing High Bypass Ratio (HPBR) and Ultra-high Bypass Ratio (UHBPR) turbofan engines. The study underscores the historical progression of the Bypass Ratio (BPR), highlighting its correlation with improvements in propulsive efficiency. Over the years, BPR has increased from a Low BPR of 2:1 to an Ultra-high BPR of 13:1 and beyond in UHBPR engines, marking a significant stride in the aviation industry's quest for energy efficiency and environmental sustainability. Barbosa emphasizes that the heightened BPR, particularly in UHBPR engines, enhances propulsive efficiency by directing more air to the secondary flow, optimizing thrust generation. However, challenges arise, such as larger engine components impacting logistical aspects and aircraft design. Hakan Caliskan et al.'(2021) further explore the relationship between turbofan engine performance and environmental concerns, stressing the industry's commitment to lower fuel consumption, reduced emissions, and enhanced efficiency. Ahmed F. El-sayed (2017) delves into the historical context of turbofan engines, highlighting their efficiency in achieving high thrust capacity and low fuel consumption. The addition of fans has played a crucial role in this efficiency, enabling increased airflow and contributing to the widespread use of turbofan engines in both civil and military aviation. Hua-Dong Yao et al. (2020) discuss the adoption of UHBPR engines as a realistic alternative for achieving environmental targets, reducing specific fuel consumption noise emissions, and increasing thrust capacity. The authors suggest that UHBPR engines offer a pragmatic solution compared to futuristic aircraft designs with electric propulsion, aligning with the industry's need for efficiency and reduced environmental impact. Barbosa's (2022) revisit in the review emphasizes that while UHBPR engines contribute significantly to environmental parameters and overall propulsive efficiency, their implementation requires careful consideration of factors like engine positioning, nacelle sizing, and aerodynamics to minimize drag forces. Denis Buosi et al. (2022) address the aerodynamic challenges associated with UHBPR engine implementation, highlighting the need for compact design solutions to counter increased frontal area, drag forces, and weight, ensuring compatibility with the wing structure. Yong-Ping Zhao et al. 's study (2020) adds a dimension to the discussion by emphasizing the crucial role of thrust regulation in engine control and its importance for safe and efficient aircraft engine operation. The study underscores the challenges in measuring engine thrust during flight, necessitating the use of performance parameters as indirect indicators for control systems. These studies underscore the dynamic landscape of aero engine development, from historical advancements in turbofan engines to the emergence of UHBPR engines as a promising solution for achieving enhanced efficiency and meeting stringent environmental standards. The review emphasizes the constant need for innovation in aeronautical engineering to address the evolving challenges in pursuing sustainability in aviation.

2.3 Performance of Turbofan Aero Engines

Several studies have been conducted to enhance the performance of turbofan engines, which are crucial for the operational efficiency of commercial aircraft. Chanpeng Cai, Yong Wang, et al. (2023) proposed a method optimizing variable geometry regulation in turbofan engines to reduce fuel consumption while maintaining constant thrust. Their simulations indicated a 30% reduction in acceleration time on the ground, enhancing flight safety and substantially lowering fuel consumption, surpassing environmental expectations. Hakan Aygun et al. (2022) compared gas turbine and turbofan engines, emphasizing the latter's superior thrust production and lower Specific Fuel Consumption (SFC), making them ideal for commercial aircraft. Their study highlighted the significance of component efficiency, mainly the compressor, in influencing turbofan engine performance. Improved polytropic efficiency increased net thrust during take-off and cruise, showcasing the potential for overall performance enhancement. Lorenzo Fedele et al. (2020) focused on the maintenance assessment of high bypass ratio turbofan engines. They underscored the importance of constantly monitoring performance parameters for economic and safety reasons. Maintenance activities play a critical role in ensuring safe, reliable, and economical operation, focusing on increasing the durability of engine performance and air transport reliability. Xuesen Yang et al. (2022) conducted computer simulations on turbofan engines with ultra-high bypass ratios, explicitly studying the secondary air system (SAS). Their co-simulation methodology highlighted the mutual interactions between engine parameters and SAS, improving the accuracy of engine performance simulations in various operating conditions. Gangoli et al. (2020) aimed to develop a multidisciplinary turbofan engine design tool for conceptual designs and robust analyses. They conducted a parametric analysis, exploring the impact of key design features on engine performance. Higher values of design parameters were found to enhance performance at the expense of engine size and efficiency. Daniel A Trowbridge et al. (2022) analyzed the impact of extreme altitudes on turbofan engine performance; the model simulated engine operation at varying altitudes, power settings, angles of attack, and levels of component deterioration. The results emphasized the significant influence of the aircraft wing on overall engine operation, surpassing other sources of variation. In conclusion, these studies collectively contribute to understanding factors influencing aero-engine performance. As the aviation industry strives to meet environmental challenges, these research efforts are vital in implementing new technologies, innovating processes, and ensuring consumer safety.

3. Methodology

The study examined the match-grinding process applied to the fan abradable seal. It analyzed its correlation with engine thrust margin results, a critical parameter for engine certification at aircraft maintenance test benches. This research focuses on reviewing the match-grinding process of the fan abradable seal across a sample of engines. It integrates experts' practical experience, theoretical knowledge, historical data, and cutting-edge literature. The match-grinding study involved contributions from professionals, including power plant engineers, quality specialists, and assembly operators, with experience ranging from 5 to 32 years in their respective fields. Various resources were utilized to structure the study effectively, including a historical thrust margin performance data review and a current literature review. The data collection process comprised several steps: 1) conducting a state-of-the-art literature review, 2) gaining insights into the match-grinding process through practical observation and knowledge sharing with the technical team, 3) assessing the potential impact of the match-grinding process on engine performance, particularly regarding thrust margin, and 4) obtaining historical thrust margin results from a sample of engines and performing a quantitative analysis of test results before and after the match-grinding process to determine its significant influence on thrust margin. Once the necessary data were evaluated, a thorough literature review was performed to establish a solid theoretical foundation and better understand the relationship between the match-grinding process, the fan abradable seal, and the fan blades concerning turbofan engine thrust performance.

The study validated its findings through a comprehensive methodology that combined theoretical research, expert insights, and quantitative data analysis. The validation process involved experienced professionals, including power plant engineers, quality specialists, and assembly operators, who contributed their practical knowledge to assess the effectiveness of the match-grinding process. Historical thrust margin data was analyzed before and after implementing match grinding, directly comparing performance outcomes. Additionally, a literature review established a strong theoretical foundation, ensuring that the observed improvements aligned with existing research on airflow dynamics and engine efficiency. By integrating expert evaluations, empirical data, and historical performance trends, the study effectively confirmed the positive impact of match grinding on thrust margin, reinforcing the reliability and applicability of its findings.

4. Results

This section delineates initiatives to improve the thrust margin outcomes of an aero-engine assembly. It elucidates the fan abradable seal machining and the match grinding processes with the fan blades, ensuring minimal clearance between the components. Furthermore, it incorporates a comparative analysis of the thrust margin results obtained before and after these processes. The study's outcomes are presented by leveraging the information and data acquired and aligning them with the hypotheses in the introduction.

4.1 Fan Abradable Seal

In the pursuit of enhancing thrust margin outcomes, damaged sections of the fan abradable seal, as depicted in Appendix A are typically repaired. In these specific regions, a targeted application of abrasive coating is applied solely to rectify the damage. However, this approach fails to ensure a minimum clearance between the rotor and stator components, resulting in diminished airflow utilization due to unregulated clearance. A rehensive reconstruction process of the abradable seal is employed, irrespective of the damaged area, to address this issue. This methodology enables precise control over the clearance between the rotor and stator components, ensuring the attainment of minimum acceptable values for a more efficient utilization of airflow. Initially, to show the method's effectiveness, a two-dimensional assessment of the surface is conducted to evaluate the extent of flatness oscillation in the abradable seal. Appendix A illustrates an example of such an assessment, wherein color variation indicates fluctuations in the surface roughness of the abradable seal. The displayed image highlights a markedly uneven surface with elevated roughness, directly impacting the adequate flow of air responsible for engine thrust. A three-dimensional model of the sample surface is generated to achieve a more precise representation, as depicted in Appendix A.

4.2 Match Grinding Process

In this scenario, match grinding is employed to eradicate excessive roughness from the abradable seal's surface, ensuring a minimum clearance between the rotor and stator components. This, in turn, optimizes the utilization of the airflow that is responsible for generating the engine's thrust. The match grinding process involves determining the machining value of the abradable seal by using the size of the largest fan blade as a reference. This approach facilitates the machining process to achieve a minimum permissible clearance between the parts. Figure 2 illustrates the assembly along with the controlled clearance.

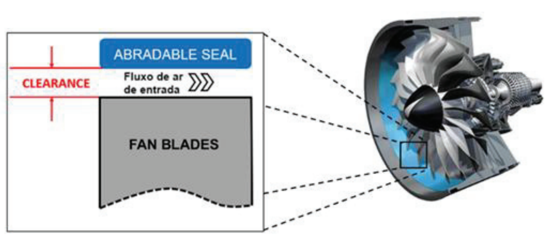


Fig. 2. Illustration of the assembly along with the controlled clearance

The match grinding process involves the utilization of a tool affixed to the fan, featuring a rotating blade and support for a touch probe. This tool is employed to measure the abradable seal of the fan using a feeler gauge. The goal is to identify areas around the circumference exhibiting tighter roundness based on a desired pattern indicative of abrasive material deposits. Additionally, areas with a tighter roundness may require evaluation against specified limits. Once these areas are pinpointed, the machining process begins, initially targeting removing sections with the highest material concentration. Machining to reach final reference dimensions begins following the standardization of the abradable seal's surface to achieve a more uniform roundness. Post-match grinding, the surface undergoes another scan using 4D inspection software. The use of the same region selected previously ensures a robust comparative analysis. Initial two-dimensional readings of the surface exhibit significantly positive results compared to the pre-machining reading, as illustrated in Appendix A.

. The color scale indicates that surface variation demonstrates regularity after the match grinding process, signifying a noteworthy reduction in surface roughness. This reduction enhances airflow efficiency, positively impacting the effective utilization of incoming air to generate engine thrust. In summary, 3D modeling of the sample surface, as depicted in Appendix A, was conducted for comparative and illustrative purposes. While surface variations are still observable, primarily due to the high resolution of the equipment used, the post-machining sample modeling reveals a less attenuated and more uniform surface. This is evident from the low color gradation throughout the sample. The analyses and implementation of the described process substantiate the engines' final thrust margin results.

4.3 Thrust Margin

Thrust constitutes a fundamental and primary characteristic inherent to turbofan engines, serving as a pivotal performance parameter assessed during the conclusive engine testing phase for ultimate approval. The engine must meet prescribed minimum criteria by discerning customers and regulatory bodies. The net thrust, a variable contingent upon distinct aero engine models, spans a spectrum ranging from 20,000 lbf (88.96 KN) for diminutive engines to approximately 115,000 lbf (511.5 KN) for their larger counterparts. The thrust margin, a crucial metric, is elucidated as a percentage denoting the ratio of resultant thrust to the stipulated minimum permissible thrust value necessary for test bench clearance. A meticulous match grinding process follows the comprehensive reconstruction of the fan abradable seal. A quantitative analysis of the thrust margin of some engines that did not undergo the process proposed in this study, compared to the same number of engines subjected to the process, demonstrated an improvement of approximately 71 percent, representing a 0.74 increase in the average thrust margin results.

5.0 Discussion of Results

It can be asserted that the initial hypothesis has been validated based on the research results. The investigation revealed that the match grinding process between the abradable seal and the fan blades significantly contributed to maximizing airflow utilization. Consequently, this enhancement led to improved engine thrust and performance. Notably, when an engine functions optimally, it places less demand on its components, extending its lifespan. The reduction of surface roughness in the abradable seal facilitated the creation of a more uniform air passage. This decrease in surface irregularities reduced turbulence and minimized parasitic airflow caused by air escaping due to excessive clearance. Consequently, the utilization of incoming airflow becomes more efficient, culminating in an enhancement of engine thrust. The data presented in the results section, indicated a substantial improvement in average thrust margin values, approximately 71%, compared to previous averages. This outcome effectively validates the efficacy of the grinding process. These findings show that incorporating the proposed process outlined in this study can ensure that companies deliver higher-quality engines to customers. This, in turn, mitigates the risks associated with engine failure during testing, avoids the need for extensive rework hours, and prevents adverse impacts on production.

Moreover, adopting the match grinding process can be deemed an efficient practice for maintaining and enhancing the performance of aero engines—an imperative consideration for the aeronautical industry. It is essential to note that the results obtained in this study do not delve into the influence of different types of abradable seal materials. This aspect, which could be relevant in refining the process and final performance results, remains unexplored. Therefore, it represents a potential avenue for future research and inquiry to further enhance the subject's understanding.

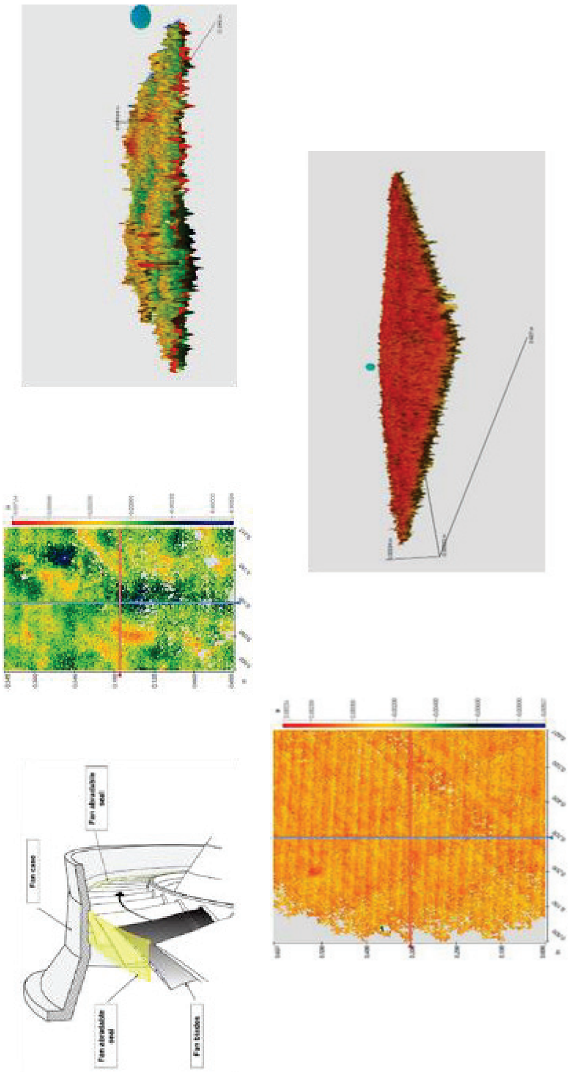
This study presents a novel approach to optimizing aero-engine performance by investigating the impact of match grinding between the abradable seal and fan blades, an area with limited prior research. Unlike traditional maintenance techniques that focus on standard component replacements, this research explores precision machining to enhance airflow dynamics and engine thrust. The study demonstrates that reducing surface roughness in the abradable seal minimizes turbulence and prevents parasitic airflow, leading to a significant 71% improvement in average thrust margin values. This innovative application of match grinding enhances engine efficiency and, reduces failure risks during testing, minimizes rework, and improves production outcomes. By integrating advanced machining techniques into Maintenance, Repair, and Overhaul (MRO) processes, this research provides a new, practical method for improving aero-engine reliability and longevity. Additionally, it highlights a critical area for future exploration—the influence of different abradable seal materials—offering further opportunities for innovation in engine performance optimization

6.0 Conclusion

Based on the combined findings presented in the section results, an examination of relevant literature, and the application of methodological guidelines, the assumption that subjecting the fan abradable seal to the match grinding process, minimizing clearance between rotor and stator components, yields improved thrust performance in aero engines has been successfully validated. Addressing the central question guiding this research—namely, whether match grinding between the fan abradable seal and fan blades can optimize airflow utilization and consequently enhance thrust and engine performance—the application of the proposed process demonstrates that a comprehensive reconstruction of the abradable seal, coupled with meticulous match grinding to control clearance to its minimum, leads to more efficient air utilization. This is attributed to reduced surface roughness in the abradable seal, promoting a smoother air passage with diminished turbulence and decreased parasitic airflow resulting from air escape due to excessive clearance. Consequently, the engines' thrust exhibits notable improvement, affirming the efficacy of the applied approach. The initial hypothesis finds validation, as the incorporation of match grinding between the fan's absorbable seal and fan blade components to minimize clearance enhances airflow utilization and improves thrust margin results. The data presented in the results section shows a substantial enhancement in average thrust margin values—approximately a 71% improvement compared to previous averages. In summary, adopting the proposed process from this study can ensure companies deliver higher-quality engines to customers, thereby mitigating the risk of test bench failures, minimizing rework hours, and reducing overall production impact. Additionally, this approach offers practical contributions to powerplant professionals by shedding light on the relationship between fan buckets and the fan abradable seal in the match grinding process. Considering this study, there is an opportunity to integrate additional areas of knowledge that can contribute value to the process and results of engine thrust performance. This includes exploring the impact and benefits of utilizing different abradable seal materials and developing more effective processes and tools to ensure higher-quality delivery. Furthermore, an analysis of the roughness inside the fan case, where the airflow makes contact and could potentially impede its full passage, warrants consideration.

Appendix A. Fan Abradable Seal and Surfaces

Fan abradable seal; two-dimensional; assessment of the surface and three-dimensional model of the sample surface



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