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Survey on Thermal Stress and Fatigue Analysis Techniques in Jet Engine Components

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Abstract: *In essence, jet engines are propulsion engines that compress incoming air to high pressure before allowing it to combine with fuel. This allows combustion to occur in the combustion chamber because of the high temperature. This review gives an in-depth overview of the jet engines' performance and reliability problems, namely their structural behaviour, thermal loading, and fatigue mechanisms. The key components and working systems of the engine are shown together with their monitoring devices and controls for power setting. The study is centred on high-temperature gas thermal stresses, pressure and inertia forces as mechanical loads, as well as their joint effects of temperature and mechanics on the distribution of deformation and stress. Finite-element method applied to the pistons exposed to thermal, mechanical, and coupled loads points out the areas that are most vulnerable to failure. The review also covers the fatigue phenomena, namely, stress-life and strain-life characteristics, vibration-induced stress cycles, and creep-fatigue at high temperatures. To summarize, the author points out as the major advantage of the article the necessity of accurate load forecasting and the advancement in diagnosis methods concerning motor lifespan and safety.*

Keywords: Jet Engines, Thermal Stress, Mechanical Load, Fatigue Analysis, Structural Integrity

I. INTRODUCTION

Every time, new technologies are developed that are inventive enough to fundamentally alter the character of military operations[1]. As the world becomes more focused on sustainable aviation, turbojet engines fueled by hydrogen are also entering the market as relevant in the field of aviation because they are low-carbon, efficient, and ecologically friendly [2]. Component-level models, state-space models, and artificial intelligence networks are examples of common models for aviation engines. Artificial intelligence networks and state-space models are quicker, but their range of flight envelope computations and real-time performance are limited[3]. Nonetheless, component-level models play a crucial role in aviation engine modelling as they may be constructed in accordance with various engine topologies and run within a wide range of flight envelopes. The creation of new aircraft engine parts frequently depends on enhancing and perfecting an already-existing "legacy design." Contemporary aviation engineering is also confronted with more and more challenges in the optimisation of combustion processes and the minimisation of harmful emissions from aircraft engines.

One approach to improve aviation safety is through advancements in material science; another is through the development of new and suitable aircraft or jet engine components. The history of aviation demonstrates that one of the most important factors in ensuring safe aircraft operation is the precise and appropriate design of the aircraft and jet engine components. Failure or malfunction of a jet engine can be disastrous. When examining a high-pressure turbine (HPT) in an aviation engine[4], according to the authors, over half of failures in first-stage blades are caused by damage to turbine blades and discs. Certain sections of the aeroplane must be adequately monitored as they operate. Jet engines now employ cutting-edge technologies for health monitoring. As such [5], one of the reasons real-time defect detection techniques must be used is to ensure the structural soundness and operational efficiency of turbine and compressor blades in jet engines.

In civil aviation, composite materials with good mechanical qualities—that is, high specific strength, stiffness, fatigue, and temperature—are frequently utilised. The most typical new generation of large civil aircraft, such as the Boeing 787 and Airbus A350, have body structures made of composite materials that account for 50% and 52% of their weight, respectively [6]. Composite panel + metal beam, composite panel + composite beam + metal rib, and other hybrid constructions have become commonplace in civil aircraft architecture[7]. Thermal fatigue or thermal shock (where the rate of heating or cooling is rapid) is a common term used to describe the phenomenon of metal fractures caused by cyclic thermal stresses created by heating or cooling. Engine heads are among the parts that are susceptible to heat fatigue[8], brake discs and exhaust manifolds in the automobile sector, dies and die stamping in the metal forming sector, and ingot moulds in the steel sector. Typical examples of castings that experience thermal fatigue while in use include ingots and the cast iron moulds used to cast steel ingots[9].

The process of regulating the heat and energy of each combined propulsion subcomponent as well as the entire system is known as thermal and energy management of combined propulsion[10]. The integrated propulsion system of hypersonic aircraft makes the research of thermal and energy management extremely important. First off, because hypersonic aircraft often fly at high Mach numbers for extended periods of time, the propulsion system must endure extremely high aerodynamic heating and thermal loads while operating properly under severe temperature conditions[11]. To guarantee the safety of aviation vehicles, fatigue testing and fatigue strength evaluation of common joint details of aircraft structures are also essential[12]. Researchers have focused on evaluating the fatigue strength of titanium alloys and on the design of common aviation joints.

A. Structure of the Paper

The structure of the paper is as follows: The main parts of a jet engine with their operating characteristics are described in Section II. Thermal stress analysis is given in Section III which comprises the effects of thermal, mechanical, and coupled loads. Methods of fatigue analysis are shared in Section IV. Section V is for the literature review, while Section VI wraps up the paper by presenting the main findings and future work.

II. Structural Components Within Jet Engine Assemblies

Jet engines are a kind of reaction engine that produces thrust through jet propulsion by releasing a fast-moving jet. It works on the third law of motion that was introduced by Newton, which states that the acceleration of gas out of the engine has a reaction of the same magnitude and opposite direction, which propels the aircraft forward. Modern aviation would not be the same without jet engines because of their efficiency and power, such that high-speed travelling through long distances is possible. The invention of jet engines has transformed the world of aircraft as it has brought faster, efficient, and reliable air travel. Jet engines prove to be essential in commercial aviation, as well as in military usage and space travel. High speed and altitude have created new frontiers and missions that had never been thought of can now be made.

A. System Structure of a Jet Engine

An aero engine is a sophisticated and complex system consisting of more than 30,000 components. It is divided into five main components, according to the direction of air flow, namely: intake, compressor, combustion chamber, turbine and tail nozzle [13]. Fig 1 shows the structure of an aero engine. In the first half of this section, this paper summarizes the reliability techniques for proper operation of turbine and bearings.

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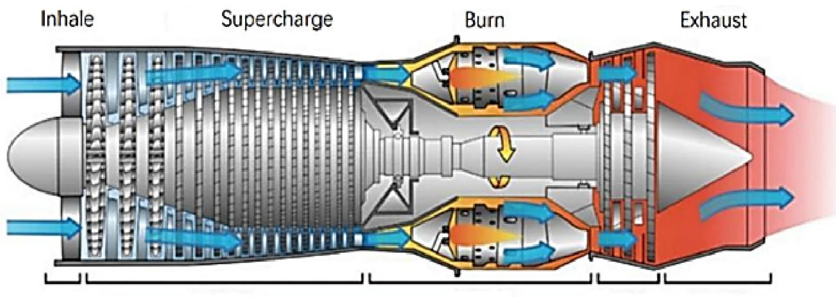

Fig. 1 Structure of an Aero-Engine

- *Turbine Blades*

Given the large number of rotating components in aero-engines, the study of fatigue failure mechanisms and blade life prediction has been a focus in the structural strength and dependability of aero-engines. The blades have been subjected to coupled effects of high circumferential fatigue, low circumferential fatigue, thermomechanical fatigue, creep, etc., and the resulting tiny cracks are difficult to monitor and diagnose, which seriously threaten the normal operation of aero-engines.

- *Main Bearing*

The main control unit of an aero-engine is the fuel control device, which endures for a long time under extreme conditions of high temperature, high pressure, and intense vibration, with a high failure rate in aero-engine field use. The life and reliability of the product are the short boards currently restricting the enhancement of China's equipment capability.

- *Aero Engine*

Aero-engine system is complex, researchers mostly the data after feature extraction, and then fault diagnosis. Aero-engine reliability engineering runs through all aspects of design, manufacturing, testing, storage, use, maintenance and management, etc. China's aero-engine reliability work has made some progress in the development process from understanding, improving to establishing specifications based on continuous summarization and learning from abroad, a set of standard technical specifications have been formulated and relevant management regulations have been promulgated. The level of aero-engine reliability (mean time between failures flight hours) has increased from tens of hours in the early days to 120 h.

*B. **Operation of a Jet Engine***

The amount of fuel fed into the combustion chamber is the only factor influencing the thrust produced in a jet engine. Since the engine's other control mechanisms are automated, the turbojet or turbofan engine's power is managed by a single thrust lever. The fuel flow into the combustion chamber is monitored and measured by an electronic engine control unit, which is coupled to thrust levers, according to the engine's internal temperature and other associated parameters[14]. When it comes to jet engines, a gauge that monitors the rotational speed keeps an eye on each revolving segment. Gauges are named according to their location as follows:

- **Exhaust Gas Temperature (EGT):**The temperature of the exhaust that is released after going through the turbine.
- **Turbine Inlet Temperature (TIT):** The temperature of the gas at the turbine's input point in order for it to expand. Since it is difficult to quantify and comes straight from the combustion chamber after mixing with the fuel, this is thought to have the greatest temperature.
- **Interstage Turbine Temperature (ITT):** The temperature of the gases between the low-pressure turbine at the end of the turbine and the high-pressure turbine at the beginning of the turbine. Jet engines include many turbines.
- **Turbine Outlet Temperature (TOT):** The temperature of the gas when it is channelized to the nozzle and leaves the turbine after the expansion is complete.

Fig. 2 RPM Gauges of Jet Engines

The control and monitoring panel of a jet engine, shown in Fig. 2, consists of various analogue gauges and indicator lamps that monitor key engine parameters, such as temperature, pressure, fuel flow, and rotational speed. The arrangement gives instant access to the operational data that are necessary for the assessment of engine performance and safety monitoring, both for pilots and technicians.

C. Power Setting Operations

The operations of power settings in jet engines mean changing the throttle levels to determine the amount of engine thrust the aircraft needs in accordance with the flight conditions [15]. The pilots control the flow of fuel and the pressure of the compressor so as to get the required power settings for take-off, climbing, cruising, and landing [16]. The power settings made in this way not only provide the best engine performance but also the least fuel consumption and the highest safety [17], by keeping combustion stable and avoiding situations such as stalling or overheating.

- ***Engine Pressure Ratio (EPR)***

An instrument known as an Engine Pressure Ratio (EPR) gauge is typically used to measure thrust in jet engines. To put it another way, the pressure that is measured with an EPR gauge is the difference between the engine's input pressure and the turbine's exit pressure. It shows how the air entered through the intake has been treated by the engine. EPR gauges are essential for enabling a jet-powered aircraft's power settings[17]. When considering turbofan jet engines, the engine's thrust is mostly dependent on the turbofan's fan speed. A gas generator turbine tachometer, which is used for engine starting and other system operations, is also included with them. By activating the thrust levers at, a sufficient pressure, either as determined by the turbofan's speed or with the aid of an EPR gauge, the first power setting is accomplished. The EPR gauge serves as a tool for compensating and the EPR is visualised in Fig. 3:

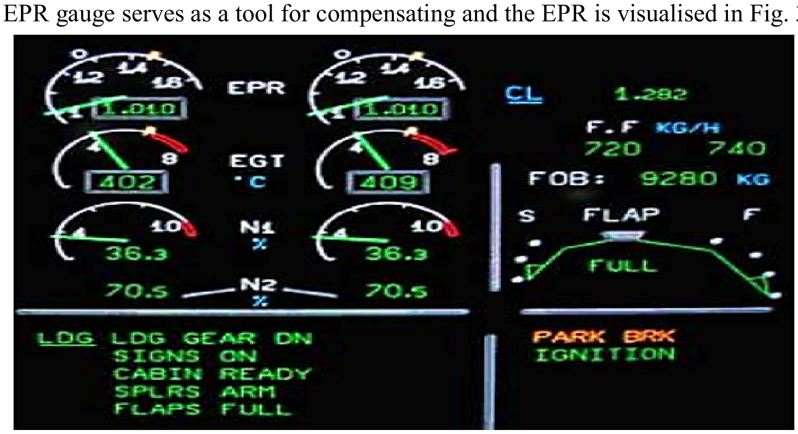

Fig. 3 Engine Pressure Ratio (EPR)

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- ***Thrust Levellers in Jet Engines***

The proportionality that exists between thrust and temperature and speed (rpm) determines the relationship between thrust and the thrust levers in jet engines. This enables the efficiency to be raised at a comparatively greater temperature and rpm. Consequently, increasing the throttle action generates greater thrust. The thrust leveller diagram is displayed in Fig. 4.

Fig. 4 Thrust Leveller in Jet Engine

III. THERMAL STRESS ANALYSIS IN JET ENGINES

Heat transfer plays an important role in the engine's operation as a type of thermal power machine, as it determines a number of technical parameters, including the engine's economic efficiency. Additionally, the thermal load grow as the temperature rises. The piston, the engine's primary heated component, must withstand a complex mechanical stress as well as a thermal load that is subject to periodic changes. An examination of the stress and deformation conditions under mechanical or thermal load alone is insufficient to accurately represent the piston's real operating condition.

Fundamentals of Thermal Analysis of the Piston in Jet Engines

This section, which is based on the fundamentals of thermal analysis, uses the finite-element software to analyse the piston's stress and deformation condition under the effects of the mechanical and thermal loads, respectively, and compares it to the stress and deformation condition under the coupling effect of the mechanical and thermal loads[18]. The research concludes that temperature is the primary element affecting piston intensity, which serves as the foundation for the piston's optimization design.

- *Thermal Load Analysis of the Piston*

The steady thermal load indicates that the piston's temperature field is constant while it operates and that the heat released from the ring zone, the piston's skirt, cooling chamber, etc., is equivalent to the heat flowing from the gas via the piston top. The thermal analysis of the piston is a stable thermal analysis of the problem without any internal heat source because the heat of the gas and the piston top is primarily produced by heat convection of the gas and the piston top, heat transfer within the piston follows Fourier Law, and no heat can occur within the piston itself.

- *Thermal Stress Analysis*

It is vital to ensure that the model does not experience any rigid-body motion during the thermal stress study. As a result, the piston must be constrained in all directions, and the additional mechanical stress cannot be introduced by the restriction.When the temperature field result automatically transforms into nodes, the applied temperature load during the thermal stress analysis is the temperature load.

- *Thermal Deformation Analysis of the Piston*

Fig 5 illustrates the piston's thermal deformation under the temperature load. The edge of the piston top, which is unconstrained, exhibits the greatest deformation, measuring 0.166 mm, as seen in Fig 6. As can be seen in the image, the distortion gradually decreases from the top surface of the piston to the skirt and from the piston's inside to its outside. The piston's temperature field is consistent with this, meaning that the same material undergoes distinct expansion deformation at various temperatures.

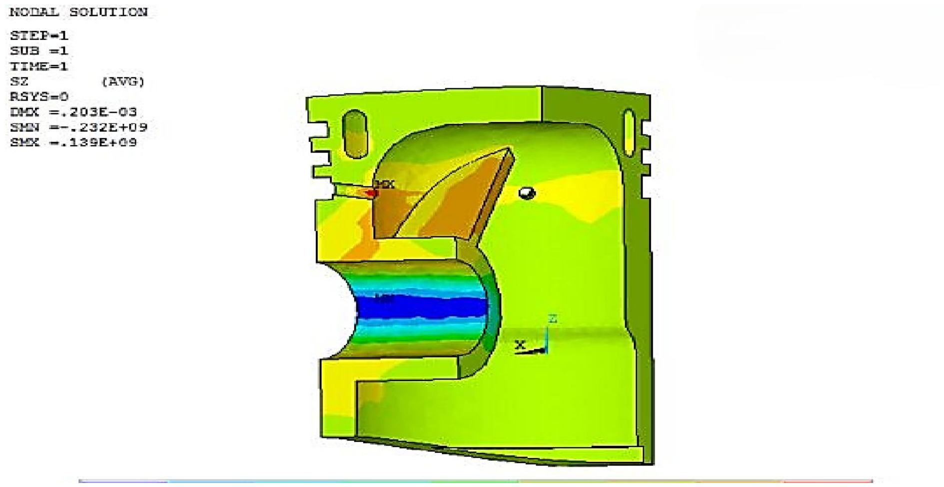

Fig. 5 Thermal Stress Nephogram Within the Piston

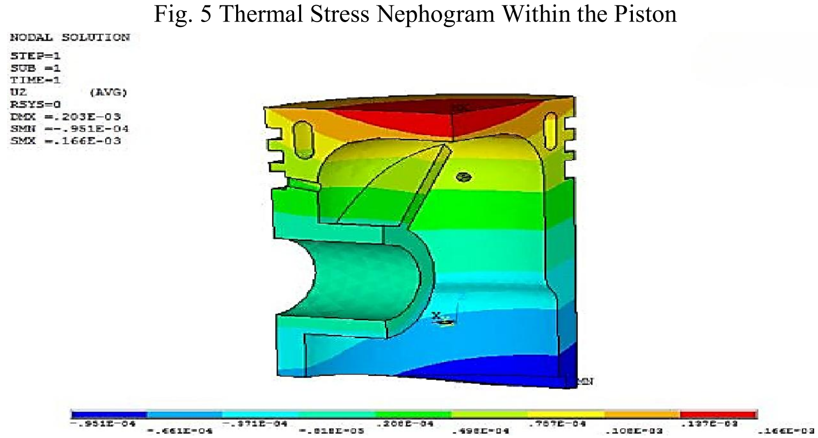

Fig. 6 Thermal Deformation of the Piston

Thermal Load and Mechanical Load Coupling Analysis to the Piston in Jet Engines

The interplay between temperature variations and mechanical stresses in the jet engine components is revealed by the thermal load and mechanical load coupling study. When the engines are working at very high temperatures and subjected to high rotation forces, the combined effects determine the material to deform, to have stress areas, and to be saturated for fatigue life. The realism of component life prediction, the reliability of failure prevention, and the optimisation of engine design for harsh operating conditions all rely on this understanding of the interaction.

- *Mechanical Load Analysis of the Piston*

The mechanical load on the piston is extremely high due to the gas pressure, which is susceptible to periodic changes. This can have a significant effect on the entire combustion engine during operation, and the resulting stress and deformation affect the piston's fatigue life and dependability. The working medium pressure inside the cylinder, the piston's inertia force, the bearing response force of the pin boss hole's inner surface, and the skirt's lateral pressure all contribute to the piston's mechanical load during operation. Analysing the piston's intensity at this point is crucial, since the piston's pressure, force, and deformation are at their highest during the cylinder's maximum explosion pressure, as illustrated in Fig. 7.

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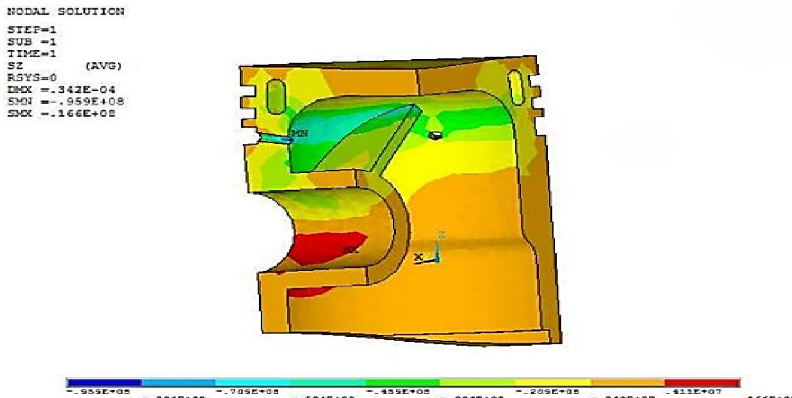

Fig. 7 Mechanical Stress Nephogram Within the Piston

- *Thermo-Mechanical Coupling Analysis of the Piston*

The piston is affected by thermal loads from high-temperature gases during operation, as well as by high-pressure gas, lateral pressure, friction forces, other mechanical loads, and the inertia force from high-speed reciprocating motion. Despite being two distinct types of stresses happening on the piston, the mechanical load and thermal load both have an impact on the piston's dependability and longevity. In order to better reflect the distribution of the stress field and the deformation condition of the piston under operating conditions, it is necessary to integrate the dual functions of the piston's mechanical stress and thermal stress in order to perform coupling analysis and solve the problem. Deformation of the piston occurs under the influence of the thermal load, and this deformation affects the transfer of heat, the thermal stress, and the mechanical stress. Fig 8 illustrates thermo-mechanical coupling.

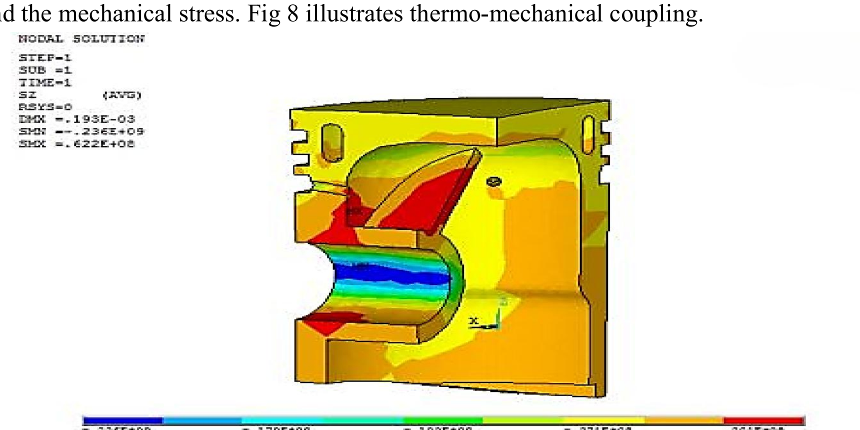

Fig. 8 Thermo-Mechanical Coupling Stress Nephogram of the Piston

IV. FATIGUE ANALYSIS IN JET ENGINES

Stress cycles lead to fatigue, a gradual failure condition. Under some circumstances, dynamics and resonance may drive these stress cycles, hence knowledge of resonance is necessary for fatigue life prediction. Stress cycles are the cause of fatigue, a gradual failure mode. Even if the stress magnitude is not high enough to result in collapse right away, if these stress cycles occur frequently enough, they may eventually lead to structural failure. Fatigue failure is caused by a combination of the number of repetitions and the magnitude of stress cycles. The cumulative change in stress, known as the stress range, is a typical way to describe the size of these stress cycles. Rainflow cycle counting is one method of counting the number of cycles seen in service.

The Stress Life (SN) Curve

The relationship between the ranges of stress and the number of applied cycles until a material breaks down is shown by a stress-life (SN) fatigue curve relative to that material. By subjecting material coupons to known cyclic loading and recording the failure time, an experimental SN curve is produced[19]. In order to comprehend the connection between stress and life, ten to twenty material coupons are usually broken. Fig 9 displays an example SN curve.

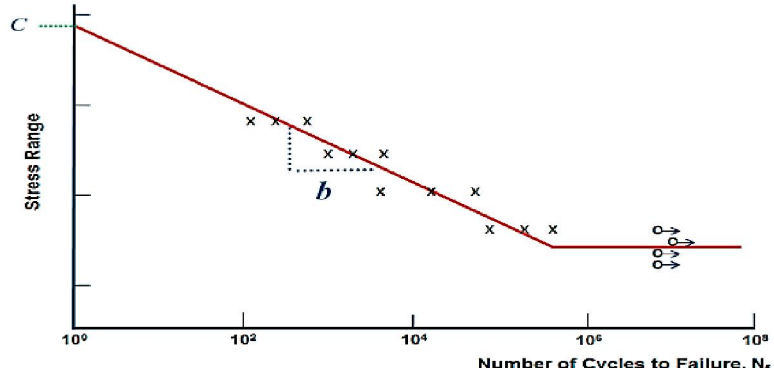

Fig. 9Stress-Life (SN) Curve

The Strain-Life (EN) Approach

The foundation of strain-life analysis is the concentration of stress in several crucial areas, such as notch roots, which clearly exhibit plastic deformation during cyclic loading prior to fatigue breakdown. The strain results obtained are elastic-plastic and are necessary for carrying out strain-life analysis.

Creep Fatigue Analysis

Creep is a phenomenon that occurs when an external force is applied to a solid material, causing it to change in stress and deformation over time. As a consequence, the relationship between the deformation, stress, and external force is no longer linear in nature. This deformation cannot be reversed, even below the yield limit of the stress [20]. Creep may occur in materials such as metals, minerals, and polymers at any temperature[21]. Although the material's creep strain is minimal at low temperatures, it becomes too significant to ignore after extended exposure to high temperatures.

V. LITERATURE REVIEW

This review discusses the latest advances in thermal stress and fatigue analysis of jet engines, particularly in modelling, fatigue testing, material selection, and cooling strategies, which are key factors for higher structural reliability and engine performance.

Ye, Wang and Li (2025) investigated the effects of Reynolds number, impingement aperture, impingement height, and flow channel layout are investigated to achieve a cooling rate that meets the requirements of the thermal compression bonding process. It is a rapid thermal cycling bonding head system developed on the principle of jet impingement cooling. It incorporates a multi-microhole impingement cooling structure that imparts air jets onto the bonding head surface, effectively increasing the heat transfer coefficient and thus rapid cooling [22].

Vanhee et al. (2024) suggested a multiphase CFD model to examine heat transmission in the hairpin end-windings of electric motors cooled by oil jets. A cutting-edge electric motor hairpin winding's crown-end and weld-end end-windings are included in the model with realistic end-winding geometry. A set of heat transfer coefficients is obtained by analyzing the cooling method's convective heat transfer. A multi-sectorial lumped-parameter model of the stator imports these heat transfer coefficients [23].

Vanteddu et al. (2024) provided a co-design model that was intended to enhance the control performance of their robot as well as the mechanical design. They specifically highlight the robot linkages that are crucial to the operation of control. The geometry nature of these links is optimized and parameterized with the help of a multi-objective evolutionary algorithm to provide the optimum control performance. Additionally, an automated Finite Element Method (FEM) analysis is incorporated into the scheme to reduce the number of options that fail to achieve the required structural safety margin. By using it to improve the mechanical design for the jet-powered humanoid robot iRonCub's flying performance, they verify the framework[24].

Dong, Chen, and Shi (2023) analysed multi-level variable-load experimental test data to evaluate the fatigue life and reliability of the nose landing gear. The results indicate that the fatigue life and reliability of the landing gear are severely affected by variable load impact, and this research has practical significance for improving the reliability of aircraft and accident prevention [25].

Diab, Diab, and Al Hosari (2023) included data from 15 healthy participants and used a variety of coupling techniques, including Granger causality, imaginary coherence, nonlinear correlation coefficient, mean phase coherence, and nonlinear indices. These contrasted with the median frequency, which is the gold standard for fatigue monitoring. As anticipated, a steady decline in the electromyography signal's median frequency is shown by data analysis, signifying the existence of muscle tiredness. The best method for modelling temporal variation in relation to muscle exhaustion among the studied methodologies is Granger causality (GC)[26].

Jones-Jackson, Azer, and Emadi (2022) compared jet impingement with a baseline cooling system in their steady-state and transient studies. The device's maximum steady-state temperature was reduced by 48 degrees Celsius thanks to jet impingement cooling. Furthermore, during the drive cycle, the same jet impingement system lowered the temperatures of the diode junction and the MOSFET. Additionally, the maximum MOSFET junction temperature was reduced by 11 °C, enabling safer operation [27].

Table 1 summarizes recent studies on Thermal Stress and Fatigue Analysis in Jet Engines. The studies highlight improved research focus, methods and approach, key findings and broader significance to the topic

Table 1: Review of Recent Studies on Thermal Stress and Fatigue Analysis in Jet Engines

Author, Year	Research Focus	Methods / Approach	Key Findings	Broader Significance
Ye, Wang & Li (2025)	Optimization of jet impingement cooling for thermal compression bonding	Investigated effects of Reynolds number, impingement aperture, impingement height, and flow-channel layout; designed a rapid thermal cycling bonding head with multi-microhole jet impingement	Multi-microhole jet impingement significantly enhances the heat-transfer coefficient and enables rapid cooling that meets bonding process requirements	Demonstrates jet impingement's capability for high-rate cooling in precision thermal manufacturing
Vanhee et al. (2024)	Heat transfer in the end-windings of electric motors that are cooled by oil jets	A multiphase CFD model with intricate end-winding geometry was created; derived heat-transfer coefficients and integrated into a lumped-parameter stator model	Generated accurate convective heat-transfer coefficients and improved understanding of stator thermal behaviour under oil jet cooling	Advances thermal modelling accuracy for electric motors, supporting improved EV cooling strategies
Vanteddu et al. (2024)	Co-design framework for improving robotic control and mechanical design	Parameterized geometric characteristics of robot links; optimized design using a multi-objective evolutionary algorithm; integrated automated FEM analysis to ensure structural safety; validated using the jet-powered humanoid robot iRonCub	Identified optimal link designs improving control performance while maintaining structural safety	Provides an integrated approach to enhancing robotic performance through simultaneous control–mechanical optimization
Dong, Chen & Shi (2023)	Reliability and fatigue life of	Analyzed multi-level variable load experimental	Variable load impact severely reduces fatigue	Supports more accurate fatigue

	aircraft nose landing gear under varying loads	data	life and reliability; findings critical for accident prevention and aircraft reliability improvement	assessment and safety improvements in aerospace engineering
Diab, Diab & Al Hosari (2023)	EMG-based muscle fatigue detection using multiple coupling methods	collected 15 patients' EMGs and evaluated nonlinear indices, Granger causality, imaginary coherence, phase coherence, and nonlinear correlation to median frequency	Median frequency decreased progressively with fatigue; Granger causality was most effective at capturing temporal fatigue patterns	Demonstrates that advanced coupling metrics can enhance physiological fatigue monitoring
Jones-Jackson, Azer & Emadi (2022)	Jet impingement cooling vs. baseline cooling for power electronics	Conducted both steady-state and transient analyses for MOSFET and diode temperatures	Jet impingement decreased the MOSFET junction temperature by 11 °C and the highest steady-state temperature by 48 °C throughout driving cycles	Highlights jet impingement as a highly effective method for improving thermal management in power electronics

IV. CONCLUSION AND FUTURE WORK

The temperature and pressure of the gas at the combustion chamber's exit increase as aero-engine performance improves, with higher flow rates and thrust-to-weight ratios. The study illuminates the influential factors in the design and reliability of jet engines, namely critical heat stresses, mechanical forces, and fatigue mechanisms. The investigation not only presented the simultaneous operating conditions of the gears and component lifetimes but also identified such situations through the engine parts, power-setting systems, and monitoring practices, along with thorough thermal, mechanical, and coupled-load effects analyses. The investigation of fatigue models such as stress-life, strain-life, and creep-fatigue has, though indirectly, consequently increased the demand for precise prediction tools and exhaustive material testing. The outcomes are interrelated and thus require enhancing diagnostic techniques, developing new design methodologies, and modifying load management as primary measures to prolong engine life, prevent failures, and ensure efficient aviation operations.

Future studies need to focus on high-fidelity thermomechanical models, real-time diagnostic systems, and the use of advanced materials with improved temperature and fatigue resistance. In addition, more experimental validation under realistic engine conditions is essential to improve life-prediction methods and make jet engine components more reliable and efficient.

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