

Research Progress on Tip Clearance Measurement Technology for Aero-Engines: From Traditional Methods to Innovations in Laser Self-Mixing Interference

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Abstract:

This paper systematically reviews the current development and research progress of tip clearance measurement technologies for turbine blades in aero-engines. Firstly, it defines tip clearance as the tiny radial distance between the tip of rotating blades and the inner wall of stator casings, emphasizing its critical role as a core parameter affecting engine aerodynamic efficiency, operational stability, and safety. By examining the principles and characteristics of traditional measurement techniques (e.g., capacitance method, eddy current method, and microwave method), the paper analyzes their limitations under extreme operating conditions such as high temperatures ($>1000^{\circ}\text{C}$) and high rotational speeds ($>15000\text{ r/min}$), including poor anti-interference capability and insufficient precision (with errors typically exceeding $22\mu\text{m}$). The focus is placed on elaborating the innovative breakthroughs of Laser Self-Mixing Interference (LSMI) technology: the three-mirror F-P cavity model enables dynamic synchronous measurement of rotational speed and clearance; the combined algorithm of wavelet denoising and windowed FFT reduces dynamic measurement error to $23\mu\text{m}$ and static error to $12\mu\text{m}$; and the technology features non-contact operation, high-temperature resistance, and a compact structure. Applications in ground tests, airborne monitoring, and industrial machinery are discussed, highlighting its value in improving fuel efficiency (a 1% reduction cuts large airliner annual costs by \$200,000), preventing blade rubbing, and supporting active control. Finally, the development trends of various technologies are summarized, providing theoretical references and technical support for the efficient and safe operation of aero-engines and their localized research and development.

Keywords: Aero-engine; tip clearance measurement; laser self-mixing interference technology.

1. Introduction

As the “heart” of an aircraft, the aero-engine directly affects flight safety [1], fuel efficiency, and operational costs. Tip clearance, a critical dimensional parameter between the rotor blades of core components such as compressors and turbines and the stator casing, exerts a decisive impact on the engine’s aerodynamic efficiency, vibration characteristics, and service life. Studies have shown that for every 0.1mm increase in tip clearance, turbine efficiency can decrease by 1% to 2% [2], which in turn leads to a 3% to 5% rise in fuel consumption rate. Conversely, an excessively small clearance may cause friction and collision between the blades and the casing, potentially resulting in catastrophic failures. Therefore, achieving high-precision, real-time, and non-contact measurement of tip clearance has long been a core issue in the design, manufacturing, and maintenance of aero-engines. The development of tip clearance measurement technology has gone through an evolution from static to dynamic, and from contact to non-contact methods. In the early days, limited by technical conditions, contact measurement methods such as mechanical probes were mainly used. Although they could obtain static clearance data, they were prone to interfering with the flow field and could not adapt to dynamic working conditions. In the mid-20th century, with the development of electromagnetics and sensing technology, non-contact technologies such as the capacitance method and eddy current method gradually emerged, realizing dynamic monitoring of rotating blade clearance and becoming mainstream solutions in the industry. However, these technologies have insufficient stability in extreme environments such as high temperature and high pressure. For example, the accuracy of eddy current sensors decays significantly in environments above 650°C, and the capacitance method is susceptible to interference from oil contamination and humidity. Since the late 20th century, optical measurement technologies have come to the fore. Laser triangulation, laser Doppler velocimetry, and other technologies have provided new ideas for clearance measurement, but their complex optical path design and shortcomings in anti-interference ability have restricted their engineering applications. Over decades of development, traditional tip clearance measurement technologies have formed a contact or near-field measurement system represented by the capacitance method, eddy current method, and microwave method. Among them, the capacitance method, with its advantage of high response speed (up to 1MHz), is widely used in static calibration. However, it is susceptible to environmental factors such as temperature, humidity, and oil contamination, with measurement errors often exceeding 5%.

The eddy current method is suitable for detecting metal components but is sensitive to changes in the electrical conductivity of blade materials, leading to significant accuracy attenuation in the measurement of high-temperature alloy blades. Although the microwave method has strong penetrability, its spatial resolution is relatively low (usually >1mm), making it difficult to meet the micron-level measurement requirements of modern high-bypass ratio engines. These technical bottlenecks, especially the insufficient adaptability under extreme working conditions such as high temperature (>1000K), high pressure (>2MPa), and high-speed rotation (>15000r/min), have driven academia and industry to explore new-generation measurement methods.

Laser Self-Mixing Interference (SMI) technology, an emerging optical measurement method in the past two decades, has provided a brand-new solution for tip clearance measurement with its significant advantages of compact structure (high optical path integration), strong anti-interference ability (coherent filtering characteristics), and high measurement accuracy (up to the nanometer level). Its core principle is to convert clearance changes into detectable light intensity modulation signals through the interference effect between the laser beam reflected on the surface of the measured object and the intracavity light, enabling non-contact measurement without complex optical path calibration. In recent years, with the maturity of semiconductor laser technology and breakthroughs in signal demodulation algorithms, SMI technology has made key progress in dynamic range (achieving a 0-5mm measurement range), high-temperature adaptability (realizing measurement in 800°C environments through sapphire windows), and anti-vibration performance (adopting adaptive filtering algorithms), gradually moving from laboratory research to engineering applications.

This paper systematically sorts out the development context of aero-engine tip clearance measurement technologies, focuses on comparing the principle characteristics, technical bottlenecks, and application scenarios of traditional methods and laser self-mixing interference technology, deeply analyzes the innovative breakthroughs of SMI technology in high-temperature environment compensation, high-speed dynamic response, multi-blade synchronous measurement, etc., and combines the needs of aero-engine design and maintenance to look forward to the development trends of future measurement technologies, providing theoretical reference and technical support for the research and development of high-precision tip clearance control technologies.

2. Basic Overview of Tip Clearance

2.1 Definition of Tip Clearance

As shown in Fig.1, the main structure of a modern turbofan aero-engine includes a fan, high and low pressure compressors, a combustion chamber, high and low pressure turbines, a tail nozzle, an accessory transmission device, and auxiliary systems. Among them, the core components of the rotor of the compressor and turbine consist of blades [3], a wheel disc, and a rotating shaft. The rotor

rotates at a very high speed during operation, converting chemical energy into mechanical energy through interaction with airflow (air or gas) to drive the engine. The gaps between the rotor and stator inside the engine are divided into radial gaps and axial gaps according to direction. The small radial distance between the tip of the rotating blade and the inner wall of the stator casing is called the tip clearance (Tip Clearance) [4], where d shown in the Fig.2 is the tip clearance value.

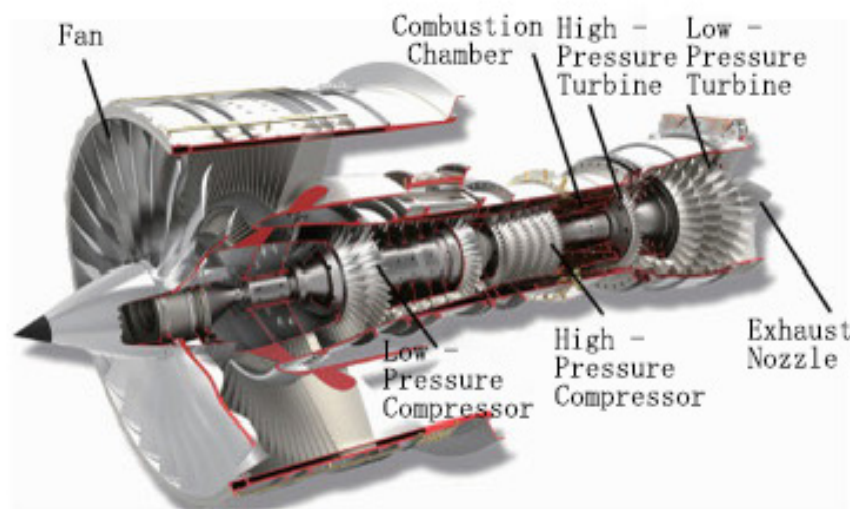


Fig. 1 Diagram of an aeroengine.

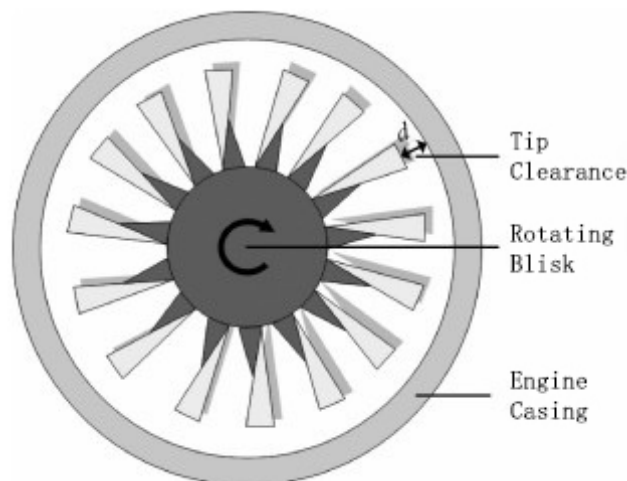


Fig. 2 Diagram of blade tip clearance.

2.2 The Research Significance and Engineering Value of Tip Clearance Measurement.

When an aero-engine is working, due to the different temperature and force deformation conditions of various

components, the movement between the rotor and stator is complex. The displacement magnitude and direction of parts in different positions in the radial and axial directions vary greatly, and this difference also changes with different engines [5]. There is an “optimal” gap between

the tips of the fan, compressor, and turbine and the casing. Excessively large or small gaps are detrimental to the engine [6]. Since the factors affecting the change of the rotor tip clearance are various and quite complex, it is difficult to determine only by calculation and analysis. It is necessary to measure the gap in real-time during the test to find the “optimal” gap. Therefore, tip clearance measurement is of great significance in the development and use of aero-engines.

The tip clearance is negatively correlated with turbine efficiency. For every 1% reduction in the ratio of tip clearance to blade height, the isentropic efficiency increases by approximately 0.8% [7]. By optimizing the gap with micron-level precision, a dynamic balance between maximizing fuel efficiency and minimizing the risk of friction and wear can be achieved. For example, a 1% reduction in fuel consumption rate can reduce the annual operating cost of a large airliner by \$200,000; a 2%-3% increase in high-pressure turbine efficiency can equivalently reduce the specific thrust fuel consumption rate by 1.5%.

Blade deformation at high speeds may cause friction between the blade tip and the casing, leading to fracture accidents. Dynamic measurement technology can provide real-time early warning of abnormal gaps and support active control with data. In addition, the operating temperature of aero-engines can reach above 1000°C, where traditional sensors are prone to failure. However, the laser self-mixing interference (LSMI) technology has the characteristics of non-contact, high-temperature resistance, and anti-electromagnetic interference, making it suitable for such harsh environments.

3. The Development Context of Tip Clearance Measurement Technology

Tip clearance measurement technology serves as a cornerstone for optimizing aero-engine performance and ensuring operational safety. Its evolutionary trajectory reflects the aviation industry’s unceasing drive to enhance precision and adaptability under increasingly extreme operating conditions. This progression can be delineated into three distinct phases, each marked by technological breakthroughs and shifting engineering priorities.

3.1 Contact-based Detection (1960s–1990s)

The early stage of blade tip clearance measurement was dominated by mechanical probe methods, which relied on direct physical contact with the blade tip to achieve measurements. These probes operated on the discharge principle, detecting voltage changes generated upon contact to determine the minimum clearance. However, their appli-

cation was severely constrained by inherent limitations: Temperature tolerance limited to $\leq 600^{\circ}\text{C}$, rendering them unsuitable for high-temperature zones of engines. Dynamic measurement accuracy of only $\sim 100\text{ }\mu\text{m}$, applicable solely to static or low-speed scenarios (rotational speed $\leq 6000\text{ rpm}$) [7]. Probes were prone to contamination by oil, debris, and particulates, leading to frequent measurement failures in actual engine environments.

As engine performance requirements escalated, these limitations propelled the industry toward non-contact solutions.

3.2 Non-Contact Measurement (2000s–2010s)

As aero-engines evolved toward higher thrust-to-weight ratios and thermal efficiency, non-contact measurement methods became mainstream. This era featured two key technologies:

3.2.1 Capacitance Method

As the primary technique for bench testing, this method achieved an ideal balance between performance and reliability. It utilizes the capacitance formed between a probe embedded in the casing and the blade tip, which act as two electrodes. The measured capacitance is a function of electrode geometry, inter-electrode distance, and dielectric properties of the medium. By fixing geometry and dielectric constants, a direct “capacitance–clearance” relationship is established. Due to the minuscule clearance scale (typically $\sim 0.01\text{ pF}$) [8], the capacitance is integrated into an oscillator circuit; clearance changes modulate capacitance, causing frequency shifts that translate into precise clearance readings. With a temperature tolerance of 1400°C and accuracy of $15\text{ }\mu\text{m}$ [9], it became indispensable in laboratory and production testing.

3.2.2 Fiber Optic and Eddy Current Methods

Both technologies offered distinct advantages but faced significant limitations: The Fiber Optic Method delivered the highest precision ($10\text{ }\mu\text{m}$) among peers but required strict environmental controls. Sensitive to contamination and thermal deformation, it was confined to clean, low-temperature environments (turbine inlet temperature $\leq 900^{\circ}\text{C}$). The Eddy Current Method, valued for robustness in harsh environments, enabled measurements through thin casing walls and exhibited strong anti-pollution capabilities. However, its large probe size restricted installation flexibility in compact engine designs.

3.3 Intelligent Integration Phase (2020s to Present)

Microwave and laser interferometry technologies have progressively matured, advancing towards multi-sensor

fusion and high-temperature adaptability(>1500°C).

4. Core Breakthroughs in Laser Self-Mixing Interference Technology

Laser Self-Mixing Interferometry (SMI) is a precision measurement technology based on the optical feedback principle. Its physical process is manifested as follows: The coherent light beam emitted by the laser is reflected/scattered by the target surface, and then part of the light wave carrying the target displacement information is reversely coupled into the laser resonant cavity and interferes with the original laser field inside the cavity. This optical feedback effect will cause periodic modulation of the laser output power and frequency, and its modulation parameters have a strict mapping relationship with the target motion state (displacement, velocity).

4.1 Technical Principle and Model Innovation

By leveraging this unique interference mechanism, the laser self-mixing interference technology converts the gap change into a detectable light intensity modulation signal through the interference effect between the laser beam reflected on the surface of the measured object and the intracavity light, enabling non-contact measurement without complex optical path calibration. The proposed three-mirror F-P cavity self-mixing interference model realizes the dynamic synchronous measurement of rotational speed and tip clearance for the first time. This innovative model addresses the issues of easy interference and low precision of traditional methods under high-temperature and high-speed conditions, providing a more stable and accurate measurement solution for complex working environments of aero-engines.

4.2 Signal Processing and Optimization Algorithms

A combined algorithm of wavelet denoising + band-pass filtering + windowed FFT is developed. Hard threshold wavelet denoising (Coif5 basis function) increases the signal-to-noise ratio from 11.86 dB to 25.07 dB. Hanning window FFT suppresses spectrum leakage, reducing the dynamic measurement error from 32 μm before optimization to 23 μm , with a static error of 12 μm . This technology breaks through the limitations of traditional static measurement and maintains high precision even at a high rotational speed of 1365.4 rpm [10], demonstrating excellent adaptability in dynamic measurement scenarios.

4.3 Technical Advantages and Experimental

Verification

Experimental verification shows that the 1% rotational speed relative error and 23 μm gap error of the laser self-mixing interference technology are better than those of the capacitance method ($\pm 50 \mu\text{m}$) and eddy current method ($\pm 22 \mu\text{m}$) [10]. It has strong high-temperature interference resistance, and frequency measurement is not affected by the surface roughness of the blade, providing reliable data for active engine gap control. In addition, the system has a simple structure (single laser + detector) and low power consumption, overcoming the defect that capacitance/microwave sensors require complex cooling systems. This series of advantages makes laser self-mixing interference technology show great potential in the field of aero-engine tip clearance measurement.

5. Practical Application Scenarios and Prospects

5.1 Ground Bench Test

This technology can be used for design verification of new engines and optimization of tip clearance control strategies, providing accurate measurement data support for engine development.

5.2 Onboard Real-Time Monitoring System

In the future, it can be integrated into the Engine Health Management (EHM) system to realize active gap control during flight, improving the safety and reliability of the engine during flight.

5.3 Extension of Micro-Precision Measurement

The technology can be extended to gap monitoring of other rotating machinery (such as gas turbines, compressors), improving the energy efficiency of industrial equipment and having broad application prospects.

6. Conclusion

The evolution of tip clearance measurement technology for aero-engines mirrors the aviation industry's unceasing pursuit of higher efficiency, safety, and adaptability under extreme conditions. From the mechanical probe methods of the 1960s–1990s, which laid the foundational understanding of clearance measurement despite their limitations in high-temperature and high-speed scenarios, to the non-contact innovations of the 2000s–2010s—such as the capacitance method, fiber optic method, and eddy current method—each stage has addressed critical engineering challenges while exposing new technical frontiers.

The capacitance method, with its balance of accuracy ($15\mu\text{m}$) and high-temperature tolerance (1400°C), remains a cornerstone in bench testing, underscoring the value of reliable, environment-adaptive solutions. Meanwhile, the fiber optic method's exceptional precision ($10\mu\text{m}$) and the eddy current method's robustness in harsh environments highlight the trade-offs between performance metrics, guiding the development of application-specific technologies.

Today, the era of intelligent integration is redefining possibilities. Multi-sensor fusion, combining the strengths of capacitance, laser, and microwave technologies, is overcoming individual method limitations, enabling redundant measurements and adaptive error correction in complex operating conditions. Breakthroughs in high-temperature materials and cooling systems, allowing measurements above 1500°C , are aligning with the demands of next-generation high-pressure turbines.

These advancements not only enhance real-time monitoring capabilities but also support proactive maintenance strategies, reducing operational risks and fuel consumption. As aero-engines continue to push the boundaries of thermal efficiency and power density, the evolution of tip clearance measurement technology will remain integral to unlocking their full potential, ensuring safer, more efficient flight for decades to come.

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