

Research on Flow Field Calibration Method and Accuracy Improvement for the Aerodynamic Performance Test Rig of Aircraft Engine Compressors

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Abstract: The aerodynamic performance test rig for aircraft engine compressors serves as a core ground test facility for conducting aerodynamic design verification, performance evaluation, stability analysis, and flow mechanism research on compressors. The accuracy of its flow field measurement results directly determines the reliability of key conclusions, such as compressor characteristic curves, adiabatic efficiency, stability boundaries, and interstage matching relationships. In the context of developing a new generation of compressors with high load, high efficiency, and wide stability margins, traditional methods relying on empirical debugging and local calibration struggle to meet the requirements for high-precision aerodynamic testing. This paper takes an axial-flow compressor aerodynamic performance test rig as the research object, systematically elaborates on the typical process and mainstream methods of flow field calibration, analyzes the primary sources of error affecting measurement accuracy, and proposes an integrated strategy for improving accuracy from aspects such as probe calibration, flow rate calibration, flow field uniformity correction, installation and environmental compensation, and traceability of measurements. Furthermore, it provides a comparative analysis of calibration effects based on engineering test data. The research results indicate that through systematic flow field calibration and multi-dimensional error correction, the uncertainty in flow rate measurement can be reduced to better than $\pm 0.3\%$, with significant improvements in the measurement accuracy of total pressure and flow angle. The flow field non-uniformity is controlled within 3%, providing reliable data support for ground testing of high-performance compressors.

Keywords: Aircraft engine; Compressor; Test rig; Flow field calibration; Measurement accuracy; Error correction

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1. Introduction

The compressor of an aircraft engine is the core component for achieving air pressurization in the overall engine cycle, and its aerodynamic design level directly impacts the engine's thrust-to-weight ratio, fuel consumption rate, operational stability, and reliability [1]. As advanced engines continue to evolve towards higher pressure ratios, higher Mach numbers, and higher efficiency, the internal flow within the compressor exhibits strong three-dimensional, unsteady, and high-load characteristics, imposing extremely stringent requirements on the measurement accuracy, data consistency, and repeatability of ground tests. The compressor aerodynamic performance test rig, by simulating inlet conditions under real flight conditions, obtains key performance parameters of the compressor, such as flow rate, pressure ratio, efficiency, and surge margin, under varying rotational speeds, guide vane angles, and back pressures. It serves as an irreplaceable validation tool throughout the compressor's design, manufacturing, and finalization processes. During actual testing, flow field measurements can be influenced by various factors, leading to discrepancies between the measured results and the true flow field. If raw data is used directly without systematic calibration, it can result in systematic shifts in key parameters such as flow rate, total pressure, temperature, and flow angle, subsequently causing deviations in compressor efficiency assessments exceeding 1% and even leading to incorrect judgments of stability boundaries, severely impacting the progress of model development and technical decision-making. Therefore, establishing a complete, standardized, and traceable flow field calibration method to systematically enhance the measurement accuracy of the test rig is an important research area in modern compressor testing technology.

2. Calibration methods for the mainstream flow field of compressor test rigs

2.1. Probe calibration methods

Probes are the most commonly used sensors in compressor flow field measurements, including total pressure rakes, temperature rakes, three-hole probes, and five-hole probes. Probe calibration is primarily divided into two categories: wind tunnel calibration and on-line calibration.

Wind tunnel calibration is conducted in a dedicated standard calibration wind tunnel, where the incoming Mach number, flow pitch angle, and yaw angle are precisely controlled to measure the outputs from each pressure port of the probe. The corresponding relationships between the probe calibration coefficients and flow parameters are established, forming a calibration database. The core lies in calculating the pressure coefficient: (where p is the pressure at the measurement port, p_s is the central static pressure, and p_t is the incoming total pressure). During formal testing, the total pressure, static pressure, Mach number, and flow angle are determined through interpolation algorithms. Wind tunnel calibration can cover a wide range of Mach numbers and angles, serving as the foundation for high-precision probe measurements [2].

On-line calibration, on the other hand, involves comparing measurements taken by a standard probe and a probe under test at the same location and under the same operating conditions within the test rig's own flow field. This process yields a comprehensive correction amount for positional, installation, and systematic deviations. The core correction formula is: (where p_c is the calibrated total pressure, p_m is the measured value, Δp is the pressure deviation, C_a is the angle correction coefficient, and $\Delta \alpha$ is the angle deviation).

On-line calibration reflects the impact of the actual installation environment on flow field measurements, making it suitable for condition monitoring and periodic calibration during long-term testing. After systematic calibration, the measurement error of the flow angle can be controlled within 1° , and the measurement errors of total pressure and static pressure are significantly reduced, meeting the measurement requirements for complex

flow fields between stages of multi-stage compressors.

2.2. Flow rate calibration methods

Flow rate is the most fundamental input parameter in compressor characteristic curves, and its accuracy directly determines the reliability of all performance results^[3]. Currently, high-precision compressor test rigs commonly employ sonic nozzle calibration methods and flow tube real-flow calibration methods.

Sonic nozzles utilize the principle of critical flow, where the flow rate is solely dependent on the upstream total pressure, total temperature, and nozzle geometric parameters when the pressure ratio between the downstream and upstream of the nozzle falls below a critical value. The core formula is: (where C_d is the discharge coefficient, A is the throat area, γ is the specific heat ratio, and R is the gas constant). Sonic nozzles offer high stability and precision, with uncertainties typically better than $\pm 0.2\%$, making them suitable as primary flow standards.

Flow tubes, characterized by their simple structure and ease of use, calculate cross-sectional flow rates by measuring wall static pressure and total pressure. However, their measurement results are influenced by factors such as boundary layer blockage, wall roughness, and inlet flow field quality, necessitating real-flow calibration to determine the discharge coefficient. During calibration, sonic nozzles serve as the reference, and multi-point tests are conducted on the flow tube under different Reynolds numbers and Mach numbers to fit a correction formula for the discharge coefficient, thereby significantly improving measurement accuracy.

In engineering applications, sonic nozzles and flow tubes are often used in combination to ensure both reference accuracy and ease of use, enabling the system flow uncertainty to meet the requirements of high-precision testing.

2.3. Flow field uniformity calibration methods

Flow field uniformity is a key indicator for evaluating the inlet air quality of a test rig and directly affects the inlet attack angle distribution and efficiency calculation of the compressor^[4,5]. Flow field uniformity calibration is typically conducted without a test specimen, using an electric scanning mechanism to drive a standard probe to perform grid scanning of the measurement section. This process obtains the radial and circumferential distributions of parameters such as total pressure, static pressure, and total temperature. The core calculation involves determining the total pressure non-uniformity: (where N is the total number of measurement points, p_i is the total pressure at the measurement point, and \bar{p} is the mean total pressure), which is then used to assess flow field non-uniformity, turbulence intensity, and distortion index. If the flow field uniformity does not meet requirements, improvements can be made by optimizing the inlet bend, adding honeycomb structures and damping screens, adjusting boundary layer suction devices, and improving the length of the straight pipe section. After systematic debugging and calibration, the flow field non-uniformity in the core inlet region of the compressor can be controlled at a low level, ensuring that the inlet flow approaches uniform and undistorted conditions^[6].

2.4. System cascade calibration methods

After completing single-point and subsystem calibrations, a full-system cascade calibration is also necessary^[7]. System cascade calibration typically employs methods such as comparing standard test specimens or cross-comparing multiple test rigs. Measurement results are compared under the same operating conditions, rotational speeds, and pressure ratio points to isolate systematic deviations caused by rig resistance, exhaust interference, acquisition system delays, and environmental correction models. The core consistency evaluation formula is: (where C_c is the consistency coefficient, x_i and x_j are measurement values from different rigs, and \bar{x} is the mean value). Through system

cascade calibration, data consistency relationships between rigs can be established, ensuring that test results for the same compressor on different test rigs and at different times are comparable. This provides a stable and reliable data foundation for model development and iterative optimization.

3. Analysis of main error sources in flow field measurement

The error sources in flow field measurement on compressor test benches are complex and can generally be classified into four categories as follows:

- (1) The first category comprises errors inherent to the sensors and probes themselves, including insufficient probe machining accuracy, deviations in tip shape, errors in measuring hole positions, surface roughness, temperature cross-sensitivity, linear errors and zero drift in pressure sensors, among others. These errors are intrinsic systematic errors that can be mitigated through precision machining and rigorous calibration;
- (2) The second category involves installation and positioning errors, such as insufficient probe insertion depth, radial and circumferential positional offsets, bent measuring rods, excessively long or leaking pressure leads, and sensor installation stresses. Installation deviations can directly alter the flow field structure near the probe, causing significant measurement offsets that must be strictly controlled in high-precision tests;
- (3) The third category encompasses inherent flow field distortions and duct influences, where secondary flows generated by intake bends, strut wakes, boundary layer thickening on duct walls, vortices and leaks within the duct can cause the flow field at the measurement cross-section to deviate from an ideal uniform state ^[8]. Without calibration and correction, these factors can lead to overall higher or lower flow field parameters;
- (4) The fourth category involves environmental and systemic errors, where fluctuations in ambient temperature, pressure, and humidity can alter gas constants and physical property parameters, while asynchrony in the acquisition system, insufficient sampling rates, noise interference, and simplified data processing models can introduce additional errors.

Without systematic calibration, the superposition of various errors can cause measurement deviations in flow rate, pressure, temperature, and flow angle to exceed allowable limits, resulting in distorted efficiency calculations and inaccurate stability boundary determinations, seriously undermining the credibility of experimental conclusions.

4. Strategies for improving flow field calibration accuracy

To achieve high-precision flow field measurement on compressor test benches, an integrated accuracy improvement system must be established encompassing hardware, methods, software, and management.

4.1. Optimizing measurement cross-section and probe point layout

Measurement cross-sections should be selected to minimize the influence of flow disturbances. Specifically, locations should be positioned sufficiently far from components such as elbows, valves, and structural supports, while ensuring adequate straight pipe lengths to allow full flow development and stabilization. At key cross-sections, a high-density probe arrangement integrating both radial and circumferential distributions is recommended to improve the representativeness of the measured flow field. In addition, high-precision electric

scanning mechanisms should be employed to enhance probe positioning accuracy and repeatability, thereby reducing random errors associated with manual operation ^[9].

4.2. Establishing a full-process probe calibration system

A comprehensive three-tier calibration framework should be implemented, consisting of factory calibration, periodic recalibration, and on-site calibration. During factory calibration, probes should undergo full Mach number and full angular range testing in a standard wind tunnel to establish a complete correction database. Periodic recalibration should be conducted by returning probes to the manufacturer to ensure long-term accuracy. Prior to each test, on-site procedures such as zero-point calibration and comparative calibration should be carried out to correct real-time drift errors. Furthermore, data processing should incorporate corrections for compressibility effects, angular nonlinearity, and temperature variations to enhance the accuracy of flow parameter inversion.

4.3. Achieving high-precision calibration of the flow measurement system

A combined calibration approach utilizing a reference sonic nozzle and a working flow tube should be adopted. The sonic nozzle serves as the primary standard, enabling multi-point calibration of the flow tube under actual operating conditions and facilitating the derivation of correction relationships for flow coefficients across varying regimes. Concurrently, strict sealing performance tests should be performed on the test bench. Pressure-holding tests under maximum operating conditions are necessary to ensure leakage remains within acceptable limits, thereby guaranteeing the reliability of flow reference measurements.

4.4. Multi-dimensional data correction and compensation

To improve measurement accuracy, multi-dimensional correction techniques should be incorporated into data processing. These include boundary layer blockage corrections for near-wall probe measurements, computational fluid dynamics (CFD)-assisted corrections to account for probe interference, and environmental compensation based on real-time measurements of total temperature, total pressure, and flow conditions. Additionally, filtering techniques and outlier detection algorithms should be applied to mitigate the effects of turbulence and measurement noise ^[10]. The integration of these correction methods can significantly reduce both systematic and random errors.

4.5. Establishing a comprehensive system traceability

A complete traceability framework should be established for all test bench parameters. Sensors measuring pressure, temperature, rotational speed, torque, and displacement must be calibrated in accordance with national measurement standards to ensure traceability and reproducibility. In parallel, detailed calibration records should be maintained, including calibration dates, equipment used, applied correction factors, and associated uncertainties. This systematic documentation supports long-term stability and reliability of the measurement system.

5. Experimental verification and result analysis

This paper takes the aerodynamic performance test bench of a certain open-type axial-flow compressor as the object, applying the aforementioned flow field calibration methods for systematic calibration and accuracy verification.

5.1. Test bench and calibration scheme

The test bench mainly consists of an intake device, flow measurement section, pressure stabilization chamber, test section, and data acquisition system, as shown in **Figure 1**. During calibration, a reference sonic nozzle serves as the flow reference, and a high-precision five-hole probe performs grid scanning of the inlet measurement cross-section, completing probe calibration, flow calibration, flow field uniformity evaluation, and system joint calibration.

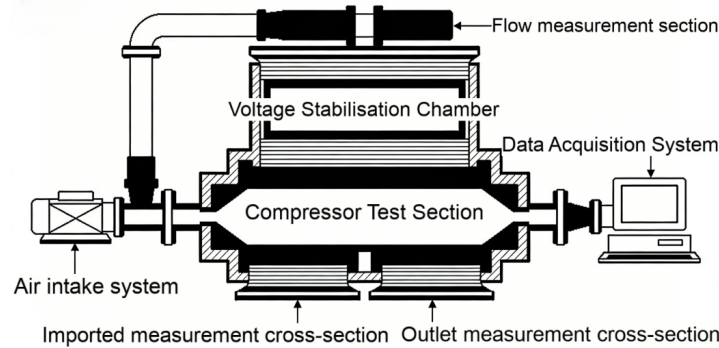


Figure 1. Schematic diagram of the flow field calibration system for the compressor aerodynamic performance test bench. Note: On the left side are the air intake inlet and flow straightening device, in the middle are the flow measurement section and pressure stabilization section, and on the right side are the compressor test section and the inlet and outlet measurement cross-sections. The probe is inserted radially into the measurement cross-sections, forming a complete flow field calibration and measurement layout.

5.2. Calibration results and accuracy comparison

Table 1 presents a comparison of the measurement accuracy of the main parameters before and after system calibration of the test bench.

Table 1. Comparison of the accuracy of main measurement parameters before and after flow field calibration

| Measurement parameter | Pre-calibration accuracy level | Post-calibration accuracy level | Accuracy improvement |
|--|--------------------------------|---------------------------------|----------------------|
| Flow Measurement Uncertainty | $\pm 1.2\%$ | $\pm 0.28\%$ | Better than 77% |
| Total Pressure Measurement Uncertainty | $\pm 0.65\%$ | $\pm 0.18\%$ | Better than 72% |
| Flow Angle Measurement Error | $\pm 2.3^\circ$ | $\pm 0.85^\circ$ | Better than 63% |
| Inlet Flow Field Non-Uniformity | 6.8% | 2.7% | Better than 60% |
| Efficiency Calculation Uncertainty | $\pm 1.8\%$ | $\pm 0.65\%$ | Better than 64% |

From the comparison results, it can be seen that after systematic flow field calibration, all indicators of the test rig have reached the level of high-precision rigs: the uncertainty in flow rate is better than $\pm 0.3\%$, the flow field non-uniformity is less than 3%, the error in flow angle is controlled within 1° , and the accuracy of efficiency calculation has been significantly improved, meeting the development requirements of advanced compressors.

5.3. Result analysis

The full-process calibration of probes effectively reduces angle and pressure measurement errors; real-flow

calibration and leakage control significantly enhance the accuracy of flow rate benchmarks; flow field uniformity optimization and multi-dimensional data correction further suppress systematic deviations; and full-system metrological traceability ensures long-term stable and reliable data. Overall, the calibration methods and accuracy enhancement strategies proposed in this paper have demonstrated remarkable effectiveness in engineering applications and can serve as a direct reference for similar test rigs.

6. Conclusion

This paper has systematically studied the flow field calibration methods and accuracy enhancement techniques for the aerodynamic performance test rig of aero-engine compressors, forming a complete technical system encompassing probe calibration, flow rate calibration, flow field uniformity assessment, system cascade calibration, error correction, and metrological traceability. Flow field calibration is a prerequisite for ensuring the accuracy and reliability of ground test data for compressors. Test rigs without systematic calibration exhibit significant errors and cannot meet the development requirements of new-generation high-performance compressors. The combination of probe wind tunnel calibration and online comparison, sonic nozzle and flow tube real-flow calibration, and cross-sectional grid scanning and flow field optimization are core means of enhancing flow field measurement accuracy. Measurement errors primarily stem from four aspects: sensors, installation positioning, flow field distortion, and environmental systems, and can be effectively suppressed through multi-dimensional correction and compensation.

Engineering tests demonstrate that after adopting the calibration methods proposed in this paper, the uncertainty in flow rate is better than $\pm 0.3\%$, the flow field non-uniformity is less than 3%, and the overall measurement accuracy meets the requirements of high-precision aerodynamic tests.

Future research can be further deepened in the following directions: developing joint calibration techniques combining non-contact optical measurement with traditional probe measurement to achieve high-resolution flow field calibration across the entire domain; constructing machine learning-based dynamic error compensation models to enhance adaptive correction capabilities under complex operating conditions; establishing digital twin test rigs to integrate flow field simulation with virtual calibration; and improving cross-rig and cross-unit data consistency standards to promote the standardization and shared application of test data.

With the continuous advancement of flow field calibration techniques, the ground test capabilities for aero-engine compressors in China will continue to improve, providing more solid experimental support for the independent development of advanced aero-engines.

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Disclosure statement

The author declares no conflict of interest.

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