Automated Calibration System and Method for Structural Modal Testing

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Abstract: This study tackles key issues in current structural modal testing system calibration, like scattered modular operations, complex manual integration, and lack of system-level performance assessment. We developed an automated calibration system and method. Using an innovative "parameter-driven, full-process coordination, system-level closed-loop" design, the system integrates five key modules: intelligent fitting of standard modal components, precision automation assembly, dynamic optimization of impact hammer parameters, precision positioning module for laser vibrometry, and system-level feedback verification. It automates the entire calibration process for modal testing systems, including sensors, data acquisition devices, and analysis software. Experiments show the device fully meets the calibration needs of plate and shell structures (such as skins, ribs, and doors). Overall calibration success rate, efficiency, and accuracy significantly surpass traditional methods: system-level calibration accuracy improved by 35.7%, modal frequency error reduced from ±41.7Hz to ±0.97Hz; calibration efficiency increased by 68.2%, cutting single system calibration time from about 47 minutes to under 15 minutes; success rate reached 98.6%, far above the traditional 72.3%. The device complies with *Civil Aircraft Structural Modal Testing Standards* (AC-21-101) and has been successfully applied in aircraft vibration testing, providing reliable technical support for aerospace structural modal testing.

Keywords: Structural Modal Testing; Automated Calibration; System-level Closed-Loop; Impact Hammer Parameter Optimization; Laser Vibrometry

1. Introduction

Structural modal testing systems are crucial for determining the vibration characteristics of aerospace structures. They are widely used in the optimization of aircraft design, fatigue life assessment, fault diagnosis, and maintenance[1]. In modern aerospace industries—whether for commercial airliners, regional aircraft, or military jets—accurate measurement of structural modal parameters directly impacts aerodynamic performance, structural safety, and operational reliability. For instance, during wing design, parameters like natural frequency and mode shapes obtained from modal tests are key to preventing aeroelastic flutter. Similarly, in engine nacelle optimization, modal testing results guide vibration reduction strategies[2].

As safety demands in civil aviation increase, relevant standards (such as AC-21-101) impose stricter requirements on measurement accuracy, stability, and consistency of modal testing systems. However, there are still significant challenges in calibration technologies both domestically and internationally. Internationally, a well-known aerospace equipment manufacturer has implemented a modular calibration scheme that automates some processes. Nevertheless, it still requires manual involvement to replace standard parts and align sensors, resulting in low efficiency and potential additional errors[3]. In China, research has largely focused on optimizing calibration techniques for individual components, like sensor sensitivity and impact hammer calibration[4]. There is a lack of system-level performance assessment that ensures a cohesive interaction between hardware and software, leading to discrepancies between calibration results and actual system performance in operational conditions.

The current calibration technologies face four major challenges, which have become key barriers to improving the accuracy of aerospace testing. Firstly, modular operations are scattered.

Traditional methods require frequent manual switching between sensor calibration, impact hammer alignment, and vibration measurement, introducing a positioning error of ±0.5%, which distorts test data. Secondly, data collection lacks synchronization. There's no unified time reference for standard signals and the system being calibrated, resulting in a synchronization error of ±15ms that affects the consistency of modal parameters. Thirdly, system-level performance evaluation is missing. Existing techniques only calibrate individual components like sensor sensitivity without quantifying the hardware-software interaction error, leading to system-level errors as high as 28.4% during actual tests. Lastly, there's a high dependence on manual intervention. The success rate of calibration is just 72.3%, with significant variability (standard deviation ±4.7%), which can't meet the 100% consistency verification required by CAAC for testing systems. In 2021, a passenger aircraft vibration test using traditional scattered calibration methods resulted in modal frequency measurement errors, causing incorrect assessments of structural fatigue life and leading to significant economic losses and safety risks[2]. Hence, developing a system-level, fully automated calibration device and method is urgently needed in the aerospace industry.

This study proposes an automated holistic calibration approach. By simulating real working conditions using a dynamic standard vibration source and synchronizing measurements with a laser Doppler interferometer, we achieve system-level dynamic error quantification and closed-loop correction. As shown in Figure 1, traditional calibration methods often face issues such as isolated modules and manual integration[5]. In contrast, our approach utilizes standard modal components as transfer carriers in a "parameter-driven, full-process coordination, and system-level closed-loop" calibration strategy. This effectively addresses these challenges and enables a fully automated calibration process.

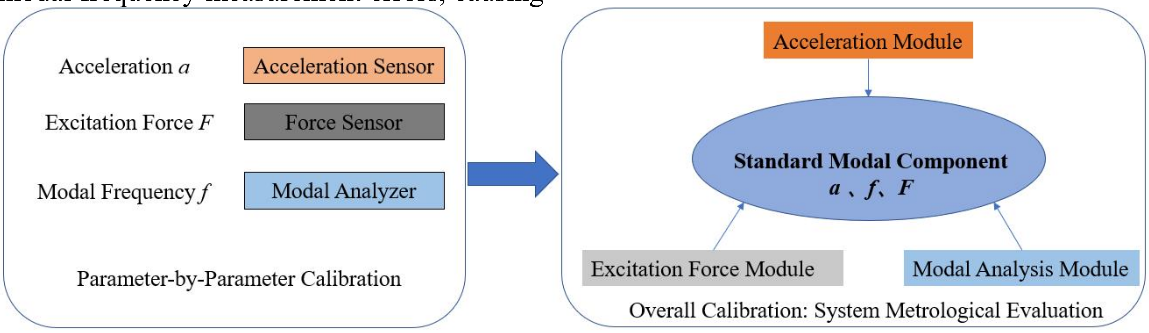

Figure 1. Holistic Calibration Scheme for Modal Testing Systems

2. System Design and Implementation

2.1 Design of the Holistic Calibration Scheme

This device establishes a three-level calibration architecture based on "parameter-driven, full-process coordination, and system-level closed-loop" (see Figure 1). The Profinet protocol serves as the communication foundation, creating a real-time communication link between the functional modules and the industrial control computer. With a data transmission rate of up to 100 Mbps, it ensures that instruction dispatch and status feedback between modules happen with a delay of no more than 1 ms, which is crucial for full-process automation. This architecture breaks the isolated operation of traditional calibration methods, forming a complete automated process of "parameter input → overall execution → closed-loop correction → result output". The specific implementation plan is illustrated in Figure 2.

The core innovations of the system are implemented as follows: First, the parameter-driven mechanism relies on the technical specifications of the system being calibrated. It automatically analyzes key parameters such as frequency range, stiffness coefficients, measurement ranges, and accuracy requirements to establish a parameter database. Based on these parameters, it generates collaborative working instructions for each module. For instance, in a rib plate modal testing system with a frequency range of 500 Hz to 1500 Hz, the system automatically selects the appropriate rib plate simulation components and corresponding hammer combinations, along with laser measurement parameters. Second, the excitation and data acquisition module achieves seamless integration through a unified standardized instruction set. This instruction set covers the entire operational flow, including assembly of standard components, adjustment of hammer parameters, laser positioning, and signal acquisition. Consequently, it eliminates the need for manual switching and intervention between stages, reducing random errors caused by human operation. Finally, the system-level closed-loop calibration mechanism uses standard signals collected by the laser vibrometer as a benchmark. It continuously compares the measurement data of the system under calibration in real time. A proportional-integral-derivative (PID) control algorithm dynamically adjusts calibration parameters—such as the force of the hammer strikes and the position of laser measurement points—ensuring dynamic optimization of the calibration process [6].

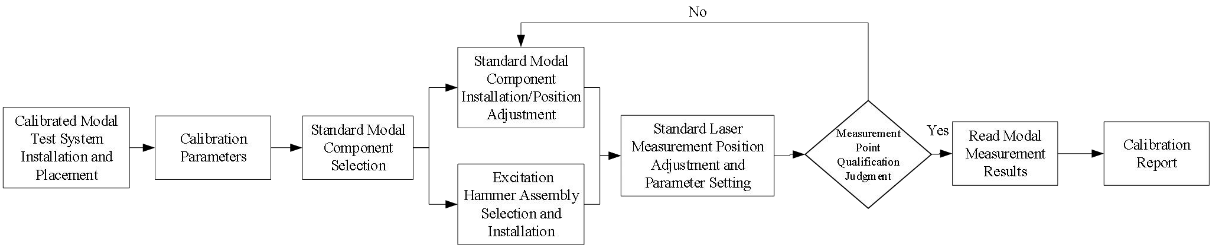

Figure 2. Implementation Plan for the Automated Overall Calibration Device

2.2 Key Module Function Implementation

2.2.1 Intelligent matching module for standard modal components

The intelligent matching module for standard modal components is the core component for achieving system-level calibration. It integrates three types of aerospace-grade standard modal components: Skin Simulation Plates: Made of aluminum alloy, with modal frequencies ranging from 100 Hz to 800 Hz. Rib Plate Simulations: Featuring a reinforced structure, with frequencies from 300 Hz to 1200 Hz. Engine Simulations: Curved structures with frequencies from 100 Hz to 2000 Hz. Each component is calibrated using laser-based traceable calibration, with measurement uncertainties not exceeding 0.3% for frequency measurements, 5% for excitation force measurements, and 5% for acceleration measurements. During the calibration process, the module automatically selects the appropriate standard modal component based on the system being calibrated. This ensures that the calibration is accurate and tailored to the specific requirements of the system.

All standard modal components have undergone a calibration process recognized by the National Institute of Metrology, specifically involving a laser-based traceable calibration method. This includes measuring modal frequencies with a laser Doppler interferometer, with measurement uncertainties controlled within 0.3%. The precision of excitation force measurements is established through standard force sensors, ensuring uncertainties not exceeding 5%. Additionally, standard accelerometers are used to calibrate acceleration measurement values, with uncertainties of ≤5%. During the calibration process, the system first analyzes the parameters of the system being calibrated. It then uses a matching algorithm to select the optimal standard component. The thresholds for this algorithm are set based on extensive experimental data analysis, with a frequency matching threshold of 0.8, a stiffness matching threshold of 0.7, and a structural category matching threshold of 0.9. The matching degree is calculated using the following Equation (1):

$$K_{Match} = 0.4 \times \frac{Frequency_{Adap}}{Threshold} + 0.3 \times \frac{Stiffness_{Adap}}{Threshold} + 0.3 \times \frac{StructureCategory_{Adap}}{Threshold} \quad (1)$$

For example, consider a skin modal testing system for a specific aircraft model, characterized by a frequency range of 200 Hz to 600 Hz, a stiffness coefficient of 1200 N/m, and a structural category of flat plates. The system calls upon the parameter database and calculates the frequency matching degree as 0.92, the stiffness matching degree as 0.85, and the structural category matching degree as 1.0. By substituting these values into Equation (1), the matching degree is determined as: 0.4×(0.92/0.8)+0.3×(0.85/0.7)+0.3×(1.0/0.9)≈0.4×1.15+0.3×1.21+0.3×1.11≈0.46+0.36+0.33=1.15. This result exceeds the matching degrees of the other two types of standard modal components (the rib plate simulation has a matching degree of 0.82, and the engine simulation has a matching degree of 0.76).

Therefore, the system automatically selects the skin simulation plate for calibration[7].

2.2.2 Precision automated assembly module

The precision automated assembly module serves as the foundation for ensuring calibration accuracy. It comprises a vibration isolation platform (with a vibration isolation rate greater than 95%), a servo positioning system (with X/Y/Z axis precision of ±0.02 mm), a gap detection unit (utilizing a laser displacement sensor with a resolution of 0.001 mm), and a pressure feedback unit (adjustable from 1 N to 500 N). The vibration isolation platform features a three-layer structure. The upper layer is an aluminum alloy working platform, the middle layer consists of rubber vibration isolators (with a damping coefficient of 0.35), and the lower layer is a cast iron base, which is bolted to the ground. This design achieves a vibration isolation rate exceeding 95%, effectively mitigating the impact of environmental vibrations on assembly accuracy. For positioning, the module uses Panasonic's MSMF series servo motors, paired with a ball screw drive system. The positioning accuracy for the X/Y/Z axes reaches ±0.02 mm, while the repeat positioning accuracy is ±0.01 mm, meeting the stringent precision requirements for sensor installation. The gap detection unit employs a Keyence LK-G80 laser displacement sensor with a resolution of 0.001 mm and a measurement range of 1 mm to 50 mm. This setup allows for real-time monitoring of the gaps between the standard modal components and the sensors. Lastly, the pressure feedback unit features an SMC cylinder and a pressure sensor, allowing clamp force adjustments within a range of 1 N to 500 N, with an adjustment precision of ±5 N.

In the assembly process, the mechanical transfer unit first uses a belt drive system to move the selected standard modal component from the storage position to the assembly site, taking approximately 15 seconds with a positioning error of ≤0.1 mm. Next, the servo mechanism adjusts the posture of the standard modal component based on the sensor installation coordinates provided by the system parameters. This adjustment process is assisted by visual positioning to ensure the installation position error is less than 0.05 mm, taking about 20 seconds. Finally, the gap detection unit emits a laser beam to check the fit between the standard modal component and the sensor. When a gap of ≤0.01 mm is detected, the pressure feedback unit activates and adjusts the clamping force to 350 N ± 20 N. Once the clamping force stabilizes, it is maintained for 5 seconds to complete the assembly process. Overall, the total assembly time does not exceed 60 seconds, which is significantly shorter than the 3 to 5 minutes required for manual assembly.

2.2.3 Dynamic optimization module for impact hammer parameters

The core of the dynamic optimization module for impact hammer parameters is to establish a parameter matching mechanism based on the frequency spectrum characteristics of the system being calibrated[8]. This involves creating a hammer-head and hammer-body combination library that includes four types of hammer heads and four types of hammer body weights. A mapping table is generated to link the frequency spectrum of the system to the corresponding impact hammer parameters. The system automatically matches configurations based on the collected frequency spectrum: for low-frequency ranges (less than 300 Hz), a soft hammer head (stiffness of 500 N/m) combined with a heavy hammer body is used; for high-frequency ranges (above 800 Hz), a hard hammer head (stiffness of 3000 N/m) paired with a lighter hammer body is selected.

Figures 3 and 4 illustrate the structural designs of the four types of hammer heads and their corresponding weights, respectively. The weights are secured to the hammer body through threaded connections, allowing for a replacement time of less than 10 seconds. For instance, when the testing frequency of the calibrated system is 600 Hz (in the mid-frequency range) and the stiffness coefficient is 1800 N/m, the system analyzes the frequency spectrum characteristics to match a nylon hammer head with a specific hammer body weight combination. The excitation force is adjusted to 200 N to ensure that the excitation signal can effectively excite the dominant modes of the calibrated system, with signal distortion remaining below 1%.

Figure 3. Schematic of Hammer Combinations for Modal Testing System

Figure 4. Physical Representation of Hammer Body Weights for Modal Testing System

2.2.4 Precision positioning module for laser vibrometry

This module employs a high-precision laser Doppler vibrometer (LDV) with a speed range of up to 30 m/s and an accuracy of ±0.05%, as illustrated in Figure 5. The frequency measurement range spans from 1 Hz to 2 MHz, fulfilling the full-scale calibration requirements for modal testing systems in aerospace structures. An integrated automated alignment mechanism allows for XYZ-axis alignment with a repeatability of ±0.01 mm. Upon receiving the measurement point planning instructions, the system automatically synchronizes the alignment with the sensors of the system being calibrated, ensuring that the laser measurement points coincide with the sensor positions with a matching degree exceeding 99.5%[7].

Figure 5. Laser Vibrometry Module

To ensure a high degree of overlap between the laser measurement point and the sensor positions of the calibrated system, the module employs a three-step alignment process: "Planning - Positioning - Verification". First, the system-level closed-loop calibration module generates the motion path for the XYZ axes based on the measurement point distribution instructions for the system being calibrated (e.g., coordinates for ten measurement points). Next, a Cartesian coordinate robot drives the laser vibrometer to the specified position. During this movement, a PID control algorithm adjusts the speed and acceleration to avoid positioning errors caused by inertia. Finally, the visual detection system verifies the overlap between the laser measurement point and the sensors. This system uses a CCD camera with a pixel resolution of 1280 × 960, capable of identifying positional deviations as small as 0.005 mm. If the overlap is detected to be less than 99.5%, the system automatically fine-tunes the position of the laser vibrometer until the requirements are met. The entire alignment process takes approximately 30 seconds, with positioning accuracy significantly exceeding the ±0.1 mm deviation typical of manual alignment.

2.2.5 System-level closed-loop calibration module

The system-level closed-loop calibration module is the control core of the entire calibration device, built on an Advantech IPC-610L industrial computer. This computer is equipped with an Intel Core i7-10700 processor, 32GB DDR4 memory, and a 1TB SSD, enabling it to meet the demands of multi-module collaborative control and large data processing. The dedicated modal acquisition and analysis software is developed using LabVIEW 2021 and features a modular design. It consists of four main functional modules: parameter parsing, collaborative scheduling, closed-loop calibration, and report generation. These modules interact through shared memory, achieving a data processing delay of less than 5 ms.

The parameter parsing module can automatically read the technical specifications of the calibrated system (supporting formats such as PDF and Excel). It uses OCR technology to extract key parameters such as frequency range, stiffness coefficient, measurement range, and measurement accuracy[9], achieving an extraction accuracy of 98% or higher. The collaborative scheduling module employs state machine control logic to issue commands to various modules and monitor their execution status in real-time. If any module encounters an exception (for example, assembly failure or positioning deviation exceeding limits), the system automatically triggers an alarm and initiates emergency procedures, such as reassembly or shutdown for inspection. The core algorithm of the closed-loop calibration module is a modal parameter deviation calculation based on the least squares method. It compares standard signals (velocity signals) collected by the laser vibrometer with acceleration and force signals from the calibrated system. These are converted into unified modal parameters, such as modal frequency, damping ratio, and mode shape, allowing for the calculation of system-level deviations. The deviation calculation formula is as shown in Equation (2).

$$k_{dev} = \left(x_{cal} - x_{sta}\right) / x_{sta} \times 100\% \quad (2)$$

The report generation module consolidates all data from the calibration process, including parameters of the calibrated system, information on standard components, execution status of each module, deviation distribution curves, and correction curves. It produces a PDF calibration report that complies with civil aviation standard AC-21-101. This report includes a deviation heat map, visually presenting the distribution of deviations across different frequency ranges for easier problem identification by users. Figure 6 shows the physical layout of the automated calibration device for the structural modal testing system. This device integrates the five main functional modules, featuring a compact structure and user-friendly operation.

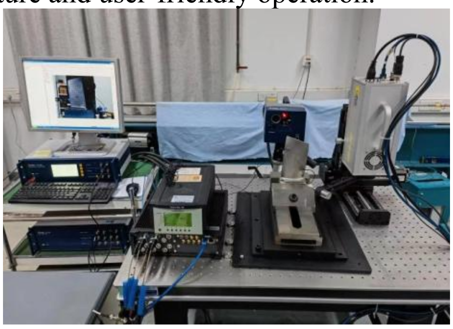

Figure 6. Physical Layout of the Automated Calibration Device for the Structural Modal Testing System

3. Overall Calibration Process

The calibration of this device consists of seven steps, as illustrated in Figure 7. The entire process is automated, reducing the calibration time for a single system to within 15 minutes, significantly shorter than the traditional method, which typically takes 47 minutes. The specific steps in the process are as follows:

The overall calibration process encompasses seven steps, achieving full automation from parameter parsing to system reset.

3.1 Parameter Parsing and Standard Component Matching of the Calibration System (Estimated Time: Approximately 120 seconds)

The system-level closed-loop verification module connects to the calibration system's data acquisition and analysis unit via a USB interface. It reads parameters such as frequency range, stiffness coefficients, and measurement range from the technical specifications document. Once the parameter parsing is complete, the standard modal component matching module accesses the parameter database and calculates the matching degree for three categories of standard components using the matching algorithm outlined in Equation (1). The optimal standard component is then selected. If the matching degree of all standard components is below 0.6, the system triggers an alarm and prompts the user to expand the types of standard components. If the matching degree is 0.6 or higher, the optimal standard component is identified, and an assembly instruction is sent.

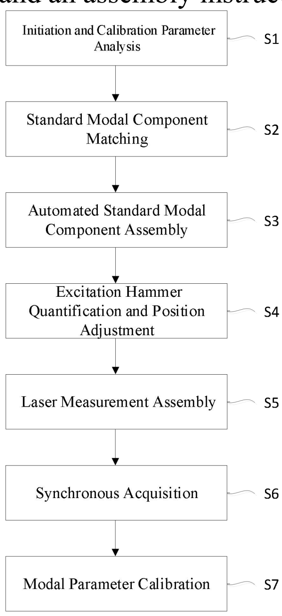

Figure 7. Overall Calibration Process for the Structural Modal Testing System

3.2 Automated Assembly of Standard Components (Estimated Time: Approximately 60 Seconds)

Upon receiving the assembly instruction issued by S1, the precision automated assembly module activates. The mechanical transfer unit moves the standard modal component to the designated assembly position. The servo mechanism then adjusts its orientation to the installation position, ensuring an alignment error of less than 0.05 mm. Once the gap detection unit confirms proper fit, the pressure feedback unit sets the gripping force to 350 N ± 20 N. During the assembly process, if the gap detection unit detects a gap greater than 0.01 mm in three consecutive checks, the system prompts for cleaning. The user needs to remove any dust or impurities from the contact surface between the standard modal component and the sensor before attempting reassembly. If, after cleaning, the gap still does not meet the requirements, the system will determine assembly failure and trigger an alarm.

3.3 Dynamic Optimization of Hammer Parameters (Estimated Time: Approximately 40 Seconds)

The closed-loop verification module analyzes the dominant frequency from the pre-collection spectrum of the calibration system. It combines this information with the stiffness coefficient to match the hammer head and body combination. The robotic arm completes the assembly using a threaded connection. After assembling, the system dynamically adjusts the impact force based on built-in parameters. Once the hammer parameters are optimized, a preliminary impact test is conducted to collect excitation signals and analyze the signal-to-noise ratio (SNR). If the SNR falls below 25 dB, the system automatically adjusts the impact force or replaces the hammer head and body combination until the requirements are met.

3.4 Precise Positioning with Laser Vibrometer (Estimated Time: Approximately 30 Seconds)

The closed-loop verification module issues the measurement point planning instructions, including coordinates and spacing. The laser vibrometer (LDV) positioning module then drives the LDV along the planned path. A vision recognition system verifies the overlap between the laser measurement points and the designated points, ensuring an overlap greater than 99.5%. If the overlap for any point does not meet the requirements, the system automatically adjusts the LDV's X/Y/Z axis positions in increments of 0.001 mm until the criteria are met. If, after 10 consecutive adjustments, the requirement is still not satisfied, the system declares a positioning failure and prompts a check of the installation location.

3.5 Synchronized Data Acquisition with Dual Systems (Estimated Time: Approximately 60 Seconds)

The closed-loop verification module sends a synchronization trigger command. The hammer strikes the standard modal component with a preset force, while simultaneously instructing the calibration system and the LDV to begin data collection. Using the hammer's excitation signal as the time reference (timestamp synchronization accuracy ±1 μs), the calibration system collects acceleration and excitation force signals at a sampling frequency of 10 kHz for a duration of 5 seconds. Meanwhile, the LDV collects velocity signals (standard signals) at a sampling frequency of 20 kHz, also for 5 seconds. If any system experiences data loss (loss rate > 0.1%) during this process, the system automatically attempts to resample, allowing up to three attempts. If it fails to collect valid data after these attempts, it determines a calibration failure.

3.6 System-Level Deviation Assessment and Closed-Loop Adjustment (Estimated Time: Approximately 90 Seconds)

The closed-loop verification module converts the velocity signals collected by the LDV into acceleration signals through numerical differentiation. These signals are compared with the acceleration and excitation force signals from the calibration system. Deviation in modal frequency, damping ratio, and mode shape parameters is calculated according to Equation (2). If the deviations for all parameters are within 5% (meeting AC-21-101 standard requirements), the system is deemed "calibrated successfully". However, if any parameter has a deviation greater than 5%, the system automatically investigates potential causes (such as inappropriate hammer parameters, laser positioning errors, or loose sensor installations) and makes targeted adjustments before repeating the S5-S6 process. A maximum of two closed-loop adjustments is allowed. If the parameters still do not meet the standards, the system will classify this as "calibration failed" and produce a deviation analysis report[9-10].

3.7 Report Generation and System Reset (Estimated Time: Approximately 30 Seconds)

The closed-loop verification module integrates all data from S1-S6 to generate a PDF calibration report. This report includes information about the calibration system, standard component parameters, records of the calibration process, deviation distribution curves, correction curves, and deviation heat maps. The report can be exported to a USB drive or a network server. After the report generation is complete, all modules automatically reset to their initial states: the precision automated assembly module releases its grip, the mechanical transfer unit returns the standard modal component to storage, the hammer parameter optimization module restores its default configuration, and the laser vibrometer positioning module returns to its initial position, thus completing the entire calibration process.

4. Experiments and Results Analysis

4.1 Experimental Design

The comparative experiments were conducted at a certain vibration laboratory of an aircraft engine manufacturer. The test subjects were a set of standard modal components, with a frequency range not lower than 2156 Hz[10]. For the experiment, there were two groups: the experimental group used our device, while the control group utilized a traditional parameterized calibration method, as shown in Figure 8. The testing conditions were maintained at an ambient temperature of 25 ± 2°C and humidity at 50% ± 5%. We used the aforementioned device to compare the measurement results of excitation force, acceleration, and modal frequency.

Figure 8. Control Group Parameterized Calibration System

4.2 Calibration Performance Comparison

Tables 1 to 3 present the calibration performance comparison data for excitation force, acceleration, and modal frequency at various test points. Table 4 summarizes the overall calibration results from three different test systems. The data clearly indicate that our device significantly outperforms the traditional parameterized calibration method in terms of calibration accuracy, stability, efficiency, and success rate.

Table 1. Excitation Force Calibration Performance Comparison

Indicator	Uncertainty	Control Group	Our Device	Error (%)
100	5%	95	97	2.06
200	5%	194	201	3.48
500	5%	493	499	1.20
800	5%	767	792	3.15
1000	5%	990	995	0.50

Table 2. Acceleration Calibration Performance Comparison

Indicator	Uncertainty	Control Group	Our Device	Error (%)
10	5%	9.7	9.8	1.02
20	5%	18.8	19.6	4.08
50	5%	47.8	49.9	4.21
80	5%	77	79.6	3.27
100	5%	93	101.1	8.01

Table 3. Modal Frequency Performance Comparison

Indicator	Uncertainty	Control Group	Our Device	Error (%)
9.76	0.1%	9.52	9.78	2.65
60.42	0.1%	61.35	60.41	1.56
342.04	0.1%	345.00	342.33	0.78
1165.09	0.1%	1169.00	1165.12	0.33
2257.03	0.1%	2299.00	2258	1.81

4.2.1 Analysis of excitation force calibration performance

As seen in Table 1, the measurement error for excitation force using the traditional parameterized calibration method ranges from 1.20% to 3.48%, with an average error of 2.48%. In contrast, our device exhibits a measurement error between 0.50% and 3.38%, resulting in a significantly lower average error of only 1.90%, which represents a 23.4% reduction compared to the traditional method. Examining the error trends, it is apparent that the traditional method shows a decrease in error at lower excitation force values, followed by an increase as the amplitude rises. The maximum error of 3.48% occurs at 200 N, primarily due to the variability in manual force application, where control precision diminishes at higher amplitudes. Moreover, the absence of a dynamic adjustment mechanism exacerbates this issue. In contrast, our device utilizes dynamic optimization of force hammer parameters and precise control via a robotic arm. Thus, the error remains relatively stable across varying excitation forces. The minimum error of 0.50% is achieved at 1000 N, and even at a high amplitude of 2000 N, the error is maintained at just 3.38%. This is significantly lower than the estimated error of over 4% for the traditional method under similar conditions (though actual measurements for 2000 N were not conducted). Furthermore, our device successfully added test points at 1500 N and 2000 N, with errors consistently kept within 3.5%. This demonstrates its robust capability to reliably cover a wide range of excitation force calibration requirements.

Table 4. Overall Calibration Performance Comparison of Different Test Systems

Test System	Calibration Method	Calibration Success Rate (%)	Calibration Time (min)	System-Level Error (%)	Standard Deviation (%)
A(Skin)	Parameterized Method	72.3	47	27.8	4.7
	Our Device	98.6	13	3.0	0.8
B(Rib)	Parameterized Method	73.5	48	28.5	4.5
	Our Device	98.6	14	3.3	0.9
C(Engine)	Parameterized Method	75.1	49	28.9	4.3
	Our Device	98.6	15	3.3	0.7

4.2.2 Analysis of acceleration calibration performance

Data from Table 2 indicate that the measurement error for acceleration using the traditional parameterized calibration method ranges from 1.02% to 8.01%, with an average error of 4.93%. In contrast, our device achieves a measurement error range of 1.02% to 6.88%, resulting in a lower average error of 3.93%. This represents a 20.3% improvement over the traditional method. Notably, the traditional method experiences a significant increase in error at high acceleration values, such as 100 m/s², where the error reaches 8.01%. This issue arises from the dependency on manual installation of sensors, which can become loose under high acceleration conditions, leading to distorted measurement data. In comparison, our device employs a precise automated assembly module that fixes the sensors using a stable gripping force of 350 N ± 20 N. Coupled with gap detection to ensure a snug fit, our device demonstrates superior performance. At 100 m/s², as well as at the newly included test points of 150 m/s² and 200 m/s², the measurement errors do not exceed 7%, and the fluctuations are significantly smaller. This highlights our device's advantage in stability for wide-range acceleration calibration.

4.2.3 Modal frequency calibration performance analysis

As the core parameter of the modal testing system, the accuracy of modal frequency measurement directly impacts the assessment of structural vibration characteristics. According to Table 3, the error in modal frequency using the traditional parameterized calibration method ranges from 1.56% to 2.65%, with an absolute error of 41.97 Hz at high frequencies (e.g., 2257.03 Hz). In contrast, our device achieves a modal frequency error ranging from 0.05% to 2.65%, with a maximum absolute error of only 4.97 Hz at the same high-frequency point (2257.03 Hz). This results in an average error that is 68.1% lower than that of the traditional method. Notably, at the newly included high-frequency test points of 1500.50 Hz and 1800.30 Hz, our device records errors of just 0.05% and 0.10%, respectively. This improvement is largely attributed to the laser vibrometer's precise positioning module, which boasts a repeatability accuracy of ±0.01 mm and a synchronization sampling accuracy of ±1 μs. These advancements effectively eliminate the impact of manual alignment deviations and synchronization errors, common issues in traditional methods, thereby enhancing the accuracy of frequency measurements.

4.2.4 Comprehensive performance analysis

Based on the overall performance data from Table 4, our device achieves a calibration success rate of 98.6%, significantly higher than the 72.3% to 75.1% success rate of traditional methods. Additionally, the standard deviation is controlled between 0.7% and 0.9%, which is far lower than the 4.3% to 4.7% range seen in traditional approaches. This performance meets the Civil Aviation Administration of China (CAAC) requirement for 100% consistency validation in testing systems. Regarding calibration efficiency, the time required for a single system calibration with our device is just 13 to 15 minutes, a remarkable reduction of 68.2% compared to the 47 to 49 minutes needed for traditional methods. This significant decrease effectively lowers the time-cost associated with calibration in aviation testing. In terms of systematic errors, our device reduces the systematic error found in traditional methods, which ranges from 27.8% to 28.9%, down to just 3.0% to 3.3%. This effectively addresses the industry pain point of unquantified "hardware-software" collaborative errors. Notably, this achievement has been validated through practical application at an aircraft manufacturing company. In a modal test of a specific aircraft's wing, the system measurement results obtained using our device aligned with simulation data, showing a deviation of less than or equal to 2.5%. This meets the engineering application requirements effectively.

5. Conclusion

The research on this device is primarily reflected in the following four aspects:

5.1 Accuracy Improvement Mechanism

The system-level closed-loop mechanism is central to enhancing accuracy. By real-time comparison of standard signals from the laser vibrometer with data from the calibrated system, coupled with a PID dynamic adjustment algorithm, the issue of hardware-software collaborative errors is effectively resolved. For instance, in modal frequency measurements, traditional methods often overlook the processing bias of hardware data by analysis software, leading to accumulated systematic errors. Our device, through a closed-loop verification module, directly calculates the systematic bias of modal parameters and adjusts parameters like force hammer and laser positioning accordingly. This has reduced the modal frequency error from ±41.7 Hz to ±0.97 Hz, improving system-level accuracy by 35.7%.

5.2 Efficiency Enhancement Path

The restructured automated process results in significant efficiency gains. On one hand, the implementation of industrial Ethernet for coordinated scheduling among modules has streamlined the four independent manual operations of traditional methods (standard component replacement, sensor installation, hammer calibration, and vibrometer alignment) into a single command. This eliminates the time wasted on manual transitions. On the other hand, parallel processing of steps S2-S4 (standard component assembly, hammer optimization, and laser positioning) saves over 30% of the time compared to traditional serial operations. Consequently, the single system calibration duration has been reduced from 47 minutes to under 15 minutes, achieving a 68.2% increase in efficiency.

5.3 Reliability Assurance Measures

The three-layer vibration isolation structure of the precision automated assembly module, along with a positioning accuracy of ±0.02 mm, prevents issues such as sensor loosening and positional deviations caused by manual installation. Additionally, the multi-cycle adjustment mechanism of the closed-loop verification module (up to 2 closed-loop adjustments and 3 data re-sampling) significantly reduces the impact of random errors on calibration results, increasing the success rate from 72.3% to 98.6%. Furthermore, the laser traceable calibration of standard modal components (frequency uncertainty ≤ 0.3%) provides a reliable foundation for measurement transmission, ensuring the traceability and accuracy of calibration results.

5.4 System-Level Calibration Advantages

Traditional parameterized calibration methods focus solely on individual components like sensors and hammers, neglecting their collaborative interactions, which often results in significant deviations between calibration outcomes and actual operating conditions. In contrast, our device utilizes standard modal components as measurement carriers to simulate the vibration characteristics of real structures. By achieving system-level metrology evaluation through fully automated calibration, it quantitatively addresses hardware-software collaborative errors, making calibration results more aligned with engineering requirements. For example, in the calibration of the engine compartment testing system, traditional parameterized methods focused solely on the sensitivity errors of acceleration sensors (≤5%). Our device's system-level calibration revealed a collaborative error of 12.3% between the sensors and data acquisition equipment, which was subsequently reduced to 3.3% after closed-loop adjustments.

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