Research on Automatic Test System of Engine Blade Natural Frequency

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(Received 8 April 2024; revised 16 August 2024; accepted 19 August 2024)

Abstract: Blades are one of the important components on aircraft engines. If they break due to vibration failure, the normal operation of the entire engine will be offected. Therefore, it is necessary to measure their natural frequency before installing them on the engine to avoid resonance. At present, most blade vibration testing systems require manual operation by operators, which has high requirements for operators and the testing process is also very cumbersome. Therefore, the testing efficiency is low and cannot meet the needs of efficient testing. To solve the current problems of low testing efficiency and high operational requirements, a high-precision and high-efficiency automatic test system is designed. The testing accuracy of this system can reach ±1%, and the testing efficiency is improved by 37% compared to manual testing. Firstly, the influence of compression force and vibration exciter position on natural frequency test is analyzed by amplitude-frequency curve, so as to calibrate servo cylinder and four-dimensional motion platform. Secondly, the sine wave signal is used as the excitation to sweep the blade linearly, and the natural frequency is determined by the amplitude peak in the frequency domain. Finally, the accuracy experiment and efficiency experiment are carried out on the developed test system , whose results verify its high efficiency and high precision.

Key words: blade; vibration failure; natural frequency; automatic test system

CLC number: TP273;TB52 **Document code:** A **Article ID:** 1005-1120(2024)04-0476-12

0 Introduction

Blades are one of the important components in aircraft engines. Their working environment is extremely harsh. In addition to bearing centrifugal loads during operation, they are also constantly subjected to alternating loads caused by airflow excitation, high temperatures, and atmospheric temperature differences. However, the most important factors affecting the service life of blades are vibration and fatigue[1-2]. These loads generate complex periodic forces on rotating blades. When the frequency of the excitation force is equal to an integer multiple of the blade's natural frequency, the blade resonates and is prone to fatigue fracture, which can affect the normal operation of the engine. According to statistics, vibration faults in aviation engines account for more than 60% of total engine failures, and blade vibration faults account for more than 70% of total vibration faults[3], indicating that the fault problems caused by blade vibration are very serious. To avoid resonance phenomena, it is necessary to conduct vibration testing on blades before installing them on the engine, and select blades with natural frequencies within the qualified range to reduce the occurrence of engine failures. The natural frequencies of the compressor rotor blades and turbine rotor blades of a certain type of aircraft engine are currently measured through manual testing systems, which have low testing efficiency and high requirements for operators, making it difficult to meet existing production needs.

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How to cite this article: LU Yonghua, LIU Jingjing, YANG Haibo, et al. Research on automatic test system of engine blade natural frequency[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2024, 41(4): 476-487.

http://dx.doi.org/10.16356/j.1005-1120.2024.04.005

The commonly used engine blade vibration testing systems can be mainly divided into two categories based on testing principles: Sweep frequency method and hammer impact method[4]. The hammering method[5] generally involves hitting the blade with a force hammer to generate a free vibration signal. The vibration sensor is used to collect this signal and perform modal analysis to calculate the multi order natural frequencies and vibration modes of the blade. According to different principles of natural frequency calculation, it can be divided into transmission function spectrum analysis method and self spectrum analysis method. The transfer function method is to identify the modal parameters of the excitation signal and vibration signal, obtain the transfer function of the system, and then obtain information such as the multi order natural frequencies and vibration modes of the blades. The self spectral analysis method[6] directly performs self spectral analysis on the vibration response signal, without the need to collect the excitation signal. However, its disadvantage is that it can only measure the natural frequency of the blade and cannot obtain information such as vibration mode. The sweep frequency rule is to use a sine wave frequency conversion signal that varies according to a certain pattern to excite the blade, and the blade will generate a forced vibration response[7]. When the excitation frequency is close to the natural frequency of the blade, the maximum vibration amplitude will be generated at the blade tip, and this response signal can be collected through contact or non-contact sensors. After noise reduction, Fourier transform, and other operations, the maximum amplitude during the forced vibration process of the blade can be obtained, and the frequency corresponding to the maximum amplitude can be considered as the natural frequency of the tested blade.

Donato et al.[8] first proposed the research of a non-contact dynamic frequency testing system, and successfully developed an online dynamic frequency testing system using eddy current sensors as pickups in the 1 990 s. The Liberty Technology Center has developed a STARS blade dynamic frequency testing system with sound sensors as the core[9], which can obtain real-time blade dynamic frequency information and detect the normal operation of engine blades online. MTU Corporation has successfully developed a complete blade vibration testing system[10] using the TP400 engine as the research object, and completed the testing work during flight. Japan, the United States and other countries have also developed corresponding blade dynamic frequency testing systems[11-12].

Wang et al.[13] proposed automatic tracking of the natural frequency in the time-frequency domain. Additionally, the mathematical principle of the inherent characteristic of multiple signal classification (MUSIC) to filter out synchronous frequency components was first mentioned and explored herein. Furthermore, simulations and experiments under variable rotating frequencies were conducted to show that the proposed method can track the natural frequency under variable operating conditions. Li et al.[14] proposed a structural monitoring method based on a fiber Bragg grating (FBG) sensing network. The results indicate that the strain-vibration testing method based on FBG can effectively monitor the blades response to wind pressure and vibration frequency, with an error range within 0.04 Hz, thus meeting the requirements for practical engineering applications.

The hammering method is a common solution to the measurement on natural frequency of solid components[15]. Due to the difficulty to directly measure the natural frequency of a rotating runner in the water, numerical simulation is widely applied to predict the runner behaviours. To verify how the influence coefficient of natural frequency differs in the water than that in air, specific measurements are taken on a model runner both in the water and air and a prototype runner by hammering method.

As summarized above, the current research on blade static frequency testing systems is not perfect, such as the inability to achieve automatic frequency scanning and cumbersome operation. The excitation and pickup modules have low efficiency and do not meet the requirements of batch testing. Usually only one type of blade can be tested, and its universality is poor. Therefore, this paper designs a high-precision and high-efficiency automatic blade vibration testing system for the compressor rotor blades and turbine rotor blades of a certain type of aircraft engine. It can accurately measure the first-order natural frequency of different types of blades, and screen out the blades whose frequency is not within the qualified range, which solves the problems of low test efficiency, cumbersome operation and single test object in the current vibration test system.

1 Overall Design of Automatic Test System for Engine Blade Natural Frequency

1.1 Analysis of natural frequency test principle

Due to the detachable nature of blades for individual testing, this article uses the frequency sweep method to test them. Considering factors such as the range of vibration testing and site limitations, the exciter is selected as the eddy current exciter from non-contact excitation equipment, and the vibration pickup sensor is selected as a piezoelectric accelerometer. The frequency sweep method is based on the principle of resonance for testing. When the excitation frequency is close to the natural frequency of the tested blade, the blade will produce the maximum vibration displacement or amplitude. The testing principle diagram is shown in Fig.1.

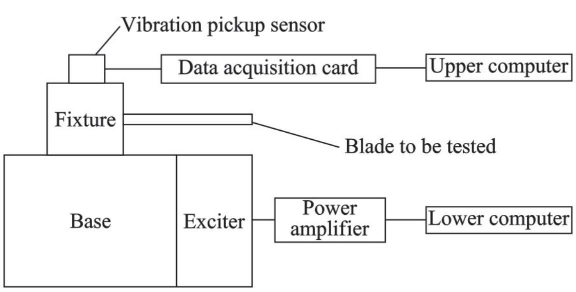

Fig.1 Principle diagram of blade natural frequency testing

The blade natural frequency testing process is as follows:

(1) The blades are fixed on the base through fixtures, with fixed support at the blade tenon and free vibration at the blade tip, forming an ideal cantilever beam structure.

(2) Sweep the frequency within the testing range of the blade to be tested, and the lower computer generates a sine wave signal of the corresponding frequency according to a certain pattern from small to large. The power amplifier of the exciter amplifies the sine wave to generate the excitation force of the current corresponding frequency at the blade tip.

(3) The vibration pickup sensor is pasted on the fixture to pick up the vibration signal of the blade under the current excitation force, and the time-domain signal is sent to the computer through data acquisition (DAQ) card. Due to the characteristics of blade resonance, the signal collected by the vibration sensor will peak at the natural frequency of the blade, and the computer can obtain the first-order natural frequency value of the blade through signal processing.

1.2 Overall system design

Starting from the requirements of large-scale and automated testing, an automatic testing system for blade natural frequency is proposed. The hardware part of the testing system is divided into a turntable module, a manipulator grasping module, and a testing module. The testing system software is divided into upper computer software and lower computer software. The former is responsible for human-computer interaction, system debugging and other functions and the latter is responsible for manipulator control. By analyzing the size and quantity information of blades, the size of the fixture used to place the blades can be determined, and thus the size of the turntable can be determined. The size of the turntable can be used to select servo motors, drivers, and the manipulator. By calibrating the position between the manipulator and the turntable, the positioning of blades is achieved, so that the manipulator can move the blades on the turntable to the testing area for testing through pneumatic grippers. The testing module uses a servo electric cylinder to compress blades and fix them on the base. An eddy current exciter is used to output an excitation force with a certain energy and adjustable frequency, which causes forced vibration of blades. A DAQ card and is used to collect signals from the accelerometer. After filtering, noise reduction, peak extraction, and other processing, the first-order natural frequency of blades can be obtained.

The hardware platform is built as shown in Fig.2, where the turntable module is mainly responsible for precise positioning of large quantities of blades. The manipulator[16] grabbing module is mainly responsible for the rapid loading of blades, that is, transporting blades from the turntable to the testing area. The testing module is responsible for vibration testing of blades. The hardware platform of the testing area is shown in Fig.3.

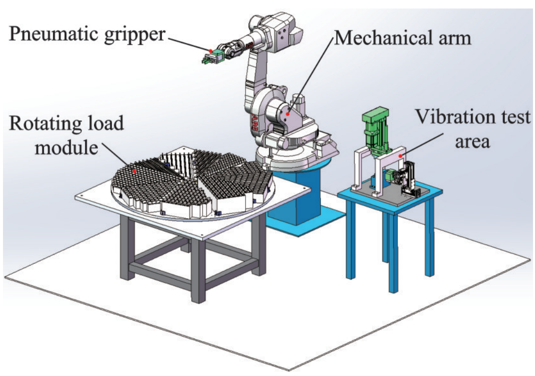

Fig.2 3D design of hardware platform for blade natural frequency test

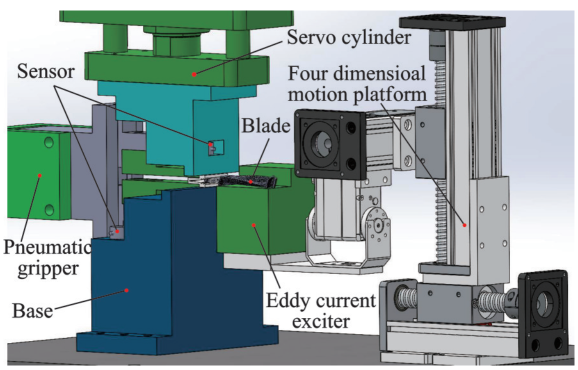

Fig.3 3D design of the test area

The test process of the test system includes: (1) The host computer plans the test process according to the input parameters, and sends rotation commands to the turntable module according to the area where the blade to be tested is currently located; (2) after the turntable is rotated to the specified area, the host computer finds the calibration data of the blade to be measured in the database and sends it to the robot arm; (3) after receiving the coordinate data of the blade to be measured, the robot arm will pick up the blade and transport it to the test area, and send the test signal to the upper computer; (4) after receiving the test signal, the upper machine controls the servo electric cylinder to press the blade tightly; (5) after the completion of the test, the servo electric cylinder will lift and reset, and send the test completion signal to the robot arm; (6) after the manipulator receives the signal of completion of the test, the blade is placed on the turntable, and a single test is completed. The complete control process is shown in Fig.4.

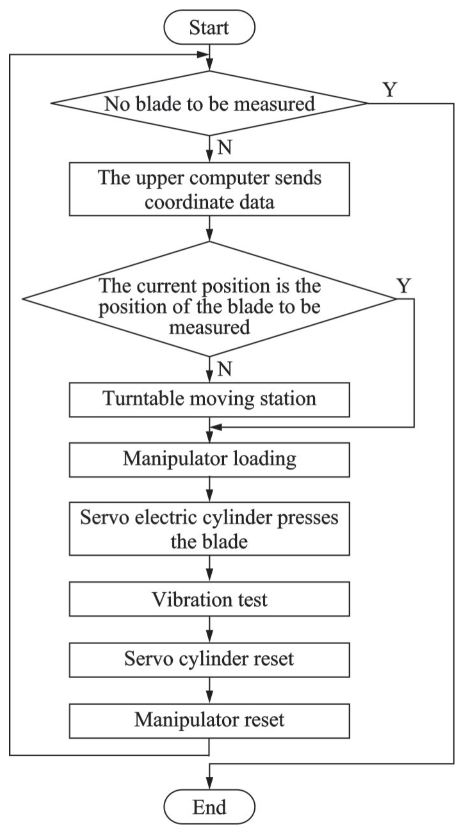

Fig.4 Motion control flow of blade natural frequency test

2 Calibration of Test System

There are two types of motion mechanisms in the testing area: Servo electric cylinder and four-dimensional motion platform. Through experiments, it can be concluded that these two types of motion mechanisms have a significant impact on the accuracy of test results. Therefore, it is necessary to calibrate these two types of motion mechanisms.

2.1 Servo electric cylinder calibration

Fig.5 shows the schematic diagram of the motion of servo electric cylinder. In position mode, the electric cylinder quickly moves from the initial position to position A above the fixture. At this time, the electric cylinder switches to torque mode, slowly presses down and uses clamping force. The clamping force has a significant impact on the accuracy of the blade natural frequency test and is also an important factor affecting the numerical stability of the measured blade natural frequency. In the experiment, the clamping state at the root of the blade should be consistent with the working state, usually close to the absolute clamping state, and the clamping state is influenced by the magnitude of the compressive force.

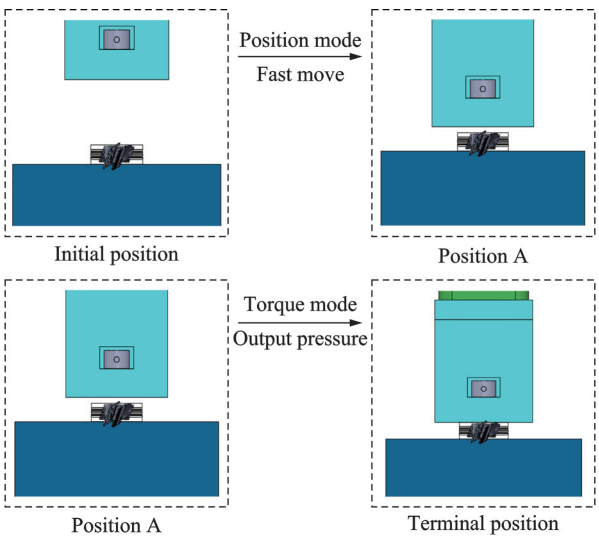

Fig.5 Motion diagram of servo electric cylinder

As shown in Fig.6, keeping all conditions of the entire experiment unchanged and only changing the magnitude of the clamping force, the natural frequency value of the blade slowly increases with the clamping force. When the clamping force increases

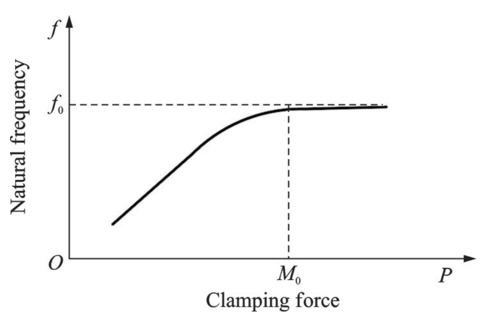

Fig.6 Relation between clamping force and frequency

to a certain value, the natural frequency of the blade basically remains unchanged. This state is the fixed state at the root of the blade, where M_0 is the critical clamping force and f_0 the true natural frequency of the blade. The calibration of the servo electric cylinder is the calibration of the critical clamping force.

Taking the compressor rotor blades of stage Ⅱ as the test object, the eddy current exciter is adjusted in an appropriate position through a four-dimensional motion platform during the experiment, as shown in Fig.7.

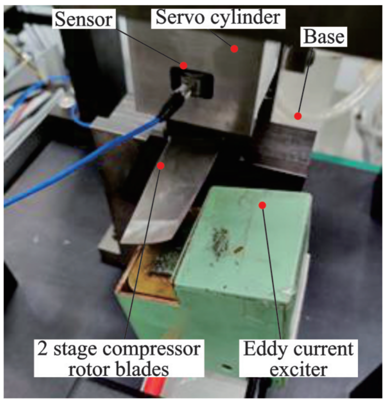

Fig.7 Test of compressor rotor blades of stage Ⅱ

Based on a clamping force of 1 kN, the test is conducted with an additional 1 kN per test, and the test results are shown in Fig.8. In the first seven tests, the measured natural frequency gradually increases with the clamping force. When the clamping force reaches 8 kN, the measured natural frequency tends to stabilize. Therefore, it can be concluded that the critical clamping force of the compressor rotor blades of stage Ⅱ is 8 kN, and the natural frequency is 928 Hz. The partial amplitude frequency curves during the experiment are shown in Fig.9,

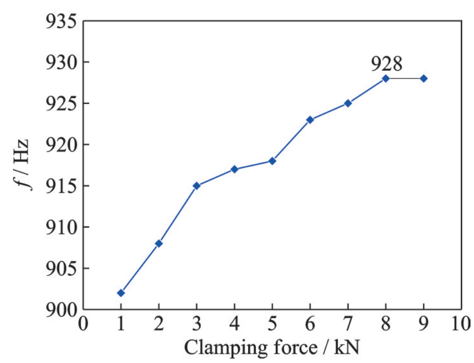

Fig.8 Relation between the clamping force and natural frequency of the compressor rotor blades of stage Ⅱ

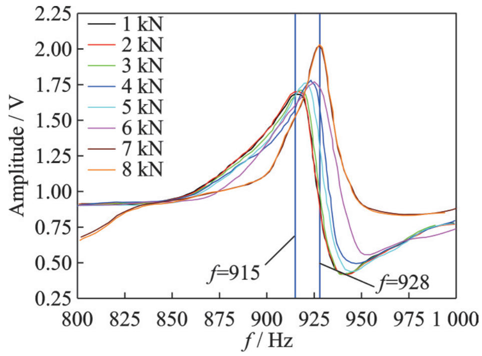

Fig.9 Amplitude-frequency curves during the test

and the remaining ten types of blades are also calibrated for the servo electric cylinder according to the above experimental method.

2.2 Calibration of four-dimensional motion platform

Through experiments, it is found that the position of the four-dimensional motion platform, i.e. the position of the exciter, has almost no effect on the position of the resonance peak, i.e. the magnitude of the resonance frequency. However, it has a significant impact on the height and amplitude of the resonance peak. In actual testing, the amplitude should be as large as possible to increase the algorithm's recognition probability of the resonance peak, which is also the basis for calibrating the four-dimensional motion platform. Fig.10 shows a schematic diagram of a four-dimensional motion platform equipped with an exciter, which has three degrees of freedom of movement in the x, y, and z directions, as well as rotational degrees of freedom around the x-axis.

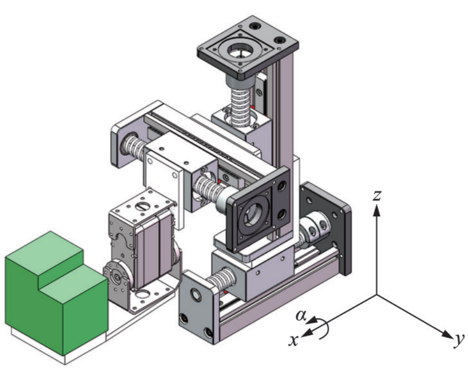

Fig.10 Four-dimensional motion platform equipped with exciter

During the calibration, each axis is individually calibrated. Taking the z-axis calibration as an example, the other three axes are adjusted to appropriate positions, gradually adjusting the z-axis position and ensuring that the clamping force output by the servo electric cylinder is constant. The amplitude is determined based on the amplitude frequency curve. During the test, certain positions on the z-axis and the corresponding amplitude frequency curve are shown in Fig.11. According to the test results, it can be concluded that as the distance between the exciter and the blade decreases, the measured natural frequency value remains unchanged but the amplitude increases. Therefore, in actual testing, the distance between the blade and exciter in the z-axis direction should be kept small, and the calibration method for the other three axes should be the same as the z-axis.

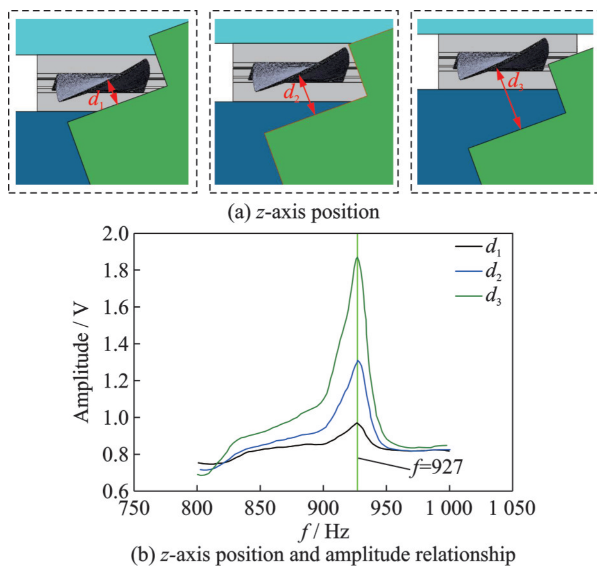

Fig.11 Process of z-axis calibration

3 Vibration Measurement Based on Resonance Method

3.1 Implementation of sweep signal

The sweep frequency signal used in this system is a frequency converted sine wave signal, which means that within a certain frequency band, a constant amplitude sine wave signal is input to the exciter, and the exciter outputs a frequency changing sine wave excitation signal, causing the measured blade to vibrate. The commonly used frequency sweep methods currently include linear sweep and logarithmic sweep.

When using linear sweep, increasing frequency in a certain proportion (forward sweep) or decreasing frequency over time (backward sweep), the relationship between frequency and time is

$$\frac{\mathrm{d}f}{\mathrm{d}t}=\beta(\text{constant}) \tag{1}$$

When using logarithmic sweep, there will be a proportional increase in the logarithmic frequency over time, which is

$$\frac{\mathrm{d}(\ln f)}{\mathrm{d}t}=\beta(\text{constant}) \tag{2}$$

In this system, linear sweep is used as the sweep strategy, and the sine sweep signal output by the upper computer is as follows

$$x(t)=A_{\mathrm{m}}\sin\left[2\pi t\left(f_{\mathrm{s}0}+\left(\frac{t}{\Delta T_{\mathrm{s}}}\right)\Delta f_{\mathrm{s}}\right)\right] \tag{3}$$

where A_{m} is the amplitude of the signal; Δf_{s} the sweep interval frequency; $f_{\mathrm{s}0}$ the initial sweep frequency; and ΔT_{s} the steady-state sweep time for each frequency. This system performs rounding operations on frequency. Due to accuracy requirements, the testing frequency does not need to be precise to one decimal place. It can only be tested within the integer range to achieve the goal, while also improving the reliability and efficiency of testing.

3.2 Implementation of sweep vibration test

Based on the principle of structural dynamics, the differential equation of motion for a damped single degree of freedom system under harmonic loads can be obtained as

$$\ddot{y}(t)+2\xi\omega\dot{y}(t)+\omega^2 y(t)=\frac{p_0\sin(\theta t)}{m} \tag{4}$$

where $y(t)$ is the displacement equation of the system; $\dot{y}(t)$ the system velocity equation; $\ddot{y}(t)$ the system acceleration equation; ω the system frequency; and ξ the damping ratio. The full solution is

$$y(t)=\bar{y}(t)+y^*(t)=$$
$$\mathrm{e}^{-\xi\omega t}(C_1\cos(\omega_d t)+C_2\sin(\omega_d t))+A\sin(\theta t-\varphi) \tag{5}$$

where C_1 and C_2 need to be calculated according to the initial conditions. The system assumes that at time $t=0$, the system displacement is y_0 and the velocity is $\dot{y}_0$. The following characteristics can be obtained by analyzing the results.

(1) The frequency of system vibration is equal to the frequency of external load excitation.

(2) The amplitude of forced vibration is independent of the initial conditions and does not change over time. The amplitude of vibration A is

$$A=y_{\mathrm{st}}\beta=\frac{p_0}{k\sqrt{\left(1-\gamma^2\right)^2+\left(2\xi\beta\right)^2}} \tag{6}$$

where y_{st} is the static displacement of the system under load p_0; β the dynamic coefficient (dynamic amplification coefficient); k the system stiffness; and γ the frequency ratio. According to Eqs.(3—6), the amplitude frequency response curve of the system is obtained as shown in Fig.12. When $\xi\neq 0$, the extremum point can be obtained as $\gamma=\sqrt{1-2\xi^2}$, and the system will generate the maximum vibration amplitude. The blades to be tested in this system belong to a small damping system, i.e. the value of ξ is small. Approximately, when frequency ratio $\gamma=1$, the system generates the maximum vibration amplitude, which is the resonance phenomenon.

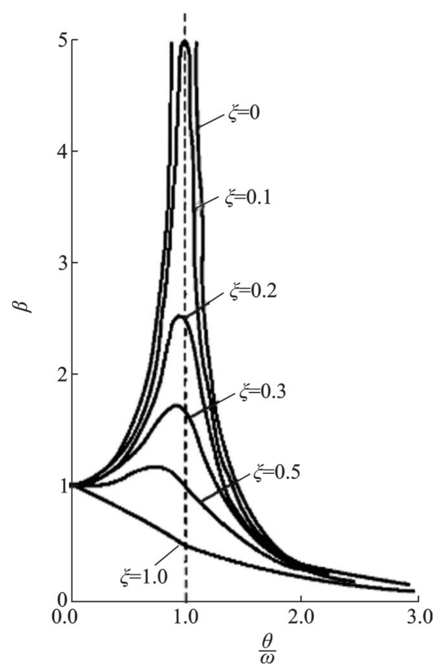

Fig.12 System frequency response curves

There are two commonly used methods to determine whether the current tested blade is in resonance state:

Method 1 Real time collection of blade vibration signals, and obtaining the corresponding vibration amplitude of the current frequency through methods such as discrete Fourier transform. When the amplitude is at its maximum, the current frequency can be recognized as the natural frequency.

Method 2 Making Lissajou figure by real-time collected blade vibration signals and upper computer sweep frequency signals. When the figure is elliptical, the corresponding frequency is the natural frequency of the blade.

This system uses Method 1 as the evaluation standard, and Method 2 assists operators in verification. Firstly, the upper computer uses the lower computer to collect the vibration signal of the tested blade, performs discrete Fourier transform on it, and extracts the peak value of its frequency domain graph to obtain the vibration amplitude corresponding to the current frequency. By repeating the above steps and using amplitude as the Y-axis and frequency as the X-axis, the amplitude frequency graph of the tested blade within the entire frequency range can be obtained. The position of the resonance peak in the graph can be determined using the extremum method, and the corresponding frequency of the resonance peak is the natural frequency of the tested blade. Fig.13 shows the amplitude frequency response curve obtained from a certain set of tests.

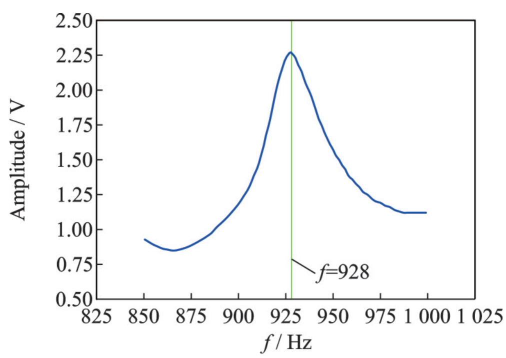

Fig.13 Amplitude frequency curve

4 Experiment and Analysis of Natural Frequency Automatic Test System

4.1 Efficiency experiment

The engine blades tested in this system are divided into 11 types, totaling 806 pieces. To verify the testing efficiency of the system, the engine blades are used for testing in actual production environments.

The testing process of blades can be divided into two parts, namely motion control and vibration testing. The motion control mainly includes turntable control, manipulator control, and clamping module control. During the entire testing process, the turntable only needs to complete one rotation, which is relatively short and can be ignored. The manipulator and clamping module have complete forward and backward movements during each blade test, which takes relatively more time. In a single test, the average round-trip time of the manipulator is $T_r = 30$ s, and the average round-trip time of the clamping module $T_y = 15$ s.

The average testing time varies greatly for different types of blades, and the specific testing time is shown in Table 1.

Table 1 Blade test schedule

Blade type	Number	Single blade testing time/s
Compressor rotor blades of stage Ⅰ	37	19.83
Compressor rotor blades of stage Ⅱ	43	20.05
Compressor rotor blades of stage Ⅲ	59	20.05
Compressor rotor blades of stage Ⅳ	67	21.19
Compressor rotor blades of stage Ⅴ	73	22.59
Compressor rotor blades of stage Ⅷ	89	27.08
Compressor rotor blades of stage Ⅻ	89	21.25
Turbine rotor blades of stage Ⅰ	133	23.33
Turbine rotor blades of stage Ⅱ	101	24.09
Turbine rotor blades of stage Ⅲ	64	23.05
Turbine rotor blades of stage Ⅳ	51	25.21

Based on the above data, it can be calculated that the time required for single engine test T is

$$T = \sum_{i=1}^{11}\left[\left(T_r + T_y + T_i\right)N_i\right] = 15.2 \tag{7}$$

where T_i is the testing time for the ith type of blade; N_i the number of the ith type of leaves. At present, it takes at least 24 h to manually complete a single engine blade test. The testing time of this system meets production needs, which is much lower than the time required for manual testing, and has greatly improved efficiency.

4.2 Accuracy experiment

To verify the accuracy of the blade natural frequency testing system designed in this article, the testing system is used to test engine blades in actual production environments. The blades used for testing are standard blades with known natural frequencies. By analyzing the differences between the test results and the standard values, the accuracy of the system testing is verified.

The vibration testing is conducted on eleven standard blades, with only one standard blade placed in each blade box and the rest of the test being the same as normal testing. The formula for calculating the relative error in the experiment is as follows

$$P_{\Delta i}=\frac{\Delta u_i}{t_i}\times 100\% \tag{8}$$

where Δu_i is the absolute error of the ith group; t_i the true value; and $P_{\Delta i}$ the relative error of the ith group. The final test results are shown in Table 2, and Fig.14 shows the amplitude frequency response curves of some tests.

Table 2 Accuracy experiment results of blade natural frequency test system

Blade type	Standard value/Hz	Test value/Hz	Relative error/%
Compressor rotor blades of stage Ⅰ	727	726	−0.14
Compressor rotor blades of stage Ⅱ	928	928	0.00
Compressor rotor blades of stage Ⅲ	936	935	−0.11
Compressor rotor blades of stage Ⅳ	1 090	1 084	−0.55
Compressor rotor blades of stage Ⅴ	1 568	1 578	−0.64
Compressor rotor blades of stage Ⅷ	2 543	2 538	−0.20
Compressor rotor blades of stage Ⅻ	4 833	4 870	0.77
Turbine rotor blades of stage Ⅰ	1 294	1 295	0.08
Turbine rotor blades of stage Ⅱ	877	881	0.46
Turbine rotor blades of stage Ⅲ	538	535	−0.56
Turbine rotor blades of stage Ⅳ	299	287	−2.97

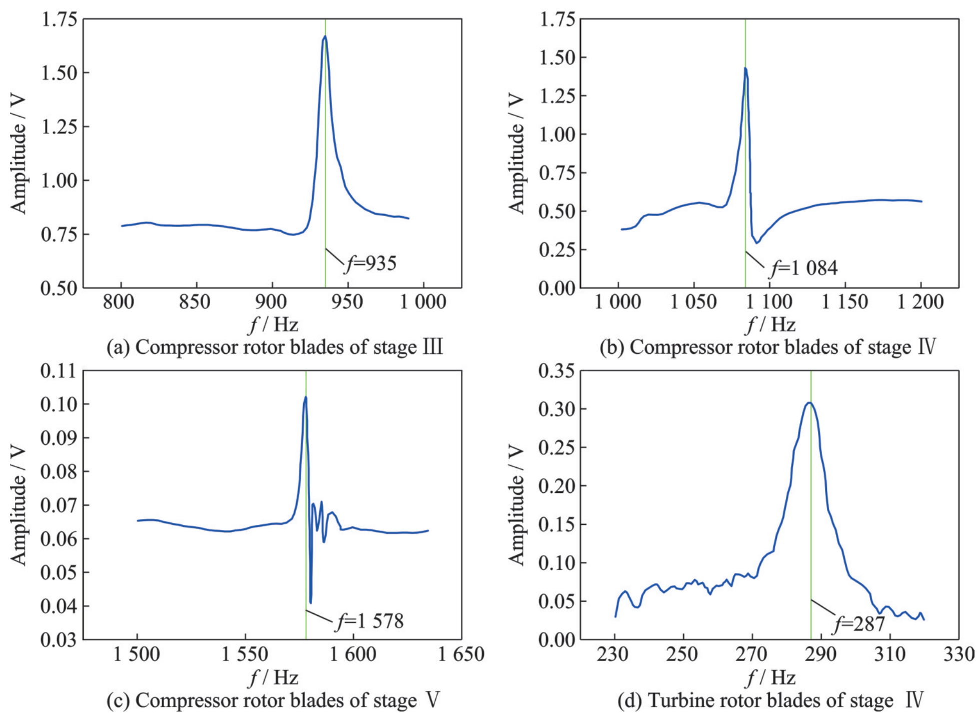

Fig.14 Partial amplitude-frequency response curves of accuracy experiment

The accuracy experiment shows that except for the turbine rotor blades of stage Ⅳ, the test values of other blades are within the range of standard values ±1%, which meets the requirements of system accuracy.

4.3 Measurement error analysis

Due to the significant relative error measured during vibration testing of the turbine rotor blades of stage Ⅳ, the error analysis is conducted on this type of blade. Fig.14(d) shows the amplitude frequency response curve of the standard turbine rotor blades of stage Ⅳ. The resonance peak of this amplitude frequency curve is obvious, so the first consideration is whether there is an error in the testing system. Due to the fact that the standard values of the standard blades used in the test are measured by the original manual testing system, the differences between the two testing systems are analyzed.

The manual testing system shown in Fig.15 has passed the relevant frequency performance verification.

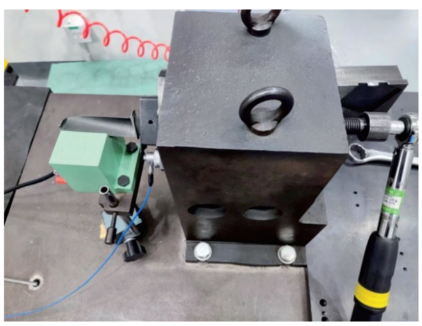

Fig.15 Manual test system

The eddy current exciters used in the two testing systems are consistent, and the position of the exciters has almost no effect on the natural frequency values. Therefore, the difference in the application of clamping force between the two testing systems is analyzed. The automatic testing system applies a clamping force through a servo electric cylinder, with the direction of the force perpendicular to the tenon plane, as shown in Fig.16(a). The manual testing system applies a tightening force through a torque wrench, with the direction of the force parallel to the tenon plane, as shown in Fig.16(b).

Through the previous calibration experiment, it can be concluded that the clamping force has a significant impact on the natural frequency value, and

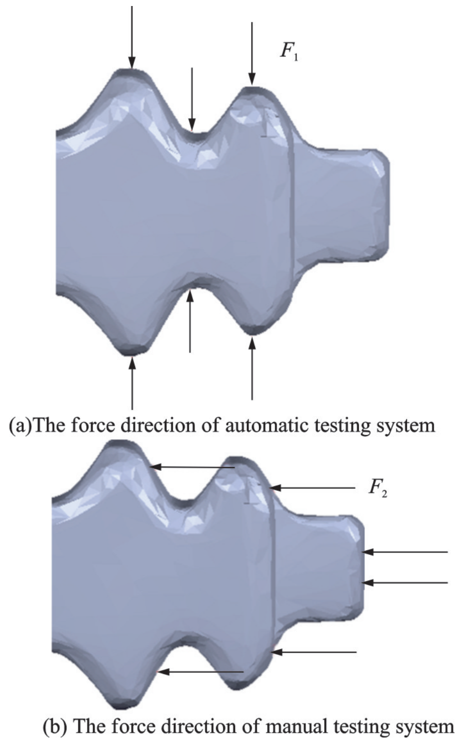

Fig.16 Difference of clamping force application modes between two test systems

there is a significant difference in the way the clamping force is used between the two testing systems. Therefore, it is considered that there is a systematic error in the two testing systems. Five hundred turbine rotor blades of stage Ⅳ are taken as the test objects, and the natural frequency is measured through two sets of testing systems to ensure that the position of the exciter is consistent during testing. The final test results are shown in Fig.17. The difference in natural frequencies measured by the two testing systems follows a normal distribution, with 95% of the blade natural frequency difference in the range of 7—12 Hz. Therefore, it can be considered that there is a systematic error in the two testing systems.

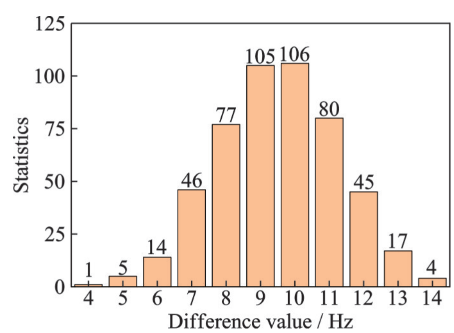

Fig.17 Statistics of natural frequency difference of two test systems

Add 10 Hz to the test results of the automatic testing system for error compensation, and the compensated data statistics are shown in Table 3. Finally, more than 95% of the blade natural frequency test results are within ±1%.

Table 3 Relative error statistics after error compensation

Relative error	Within 1%	Between 1%—1.5%	Over 1.5%
Number	473	18	9

5 Conclusions

The research object of this article is all types of blades of a certain aircraft engine, with the aim of automatically testing the first-order natural frequency of the blades and screening abnormal blades that do not meet the requirements based on the test results. This article selects the sweep frequency method as the testing method based on the shape and vibration characteristics of the blades, designs and builds a hardware platform for the natural frequency testing system of the blades, and develops corresponding testing software.

The automatic test system has the following innovations: Firstly, the blade is positioned by the linkage mode of multiple motion modules such as mechanical arm, servo motor and electric cylinder, which can achieve the automatic positioning, loading and fixing of large quantities of blades, replacing the current manual operation, and solving the problems of cumbersome disassembly and disassembly of blade batches, low test efficiency, low test consistency and high human resource consumption. Secondly, the electric cylinder is used with the corresponding compression module to achieve rapid compression of a fixed torque, and the corresponding compression torque is set for different types of blades to ensure the accuracy of blade testing. Finally, the eddy current exciter is used to quickly and automatically sweep the blade frequency, and the test process does not require manual participation, achieving complete automation. Compared to manual testing, there is a significant improvement in efficiency, with a testing error within ±1%, meeting the requirements of natural frequency testing.

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Acknowledgements This work was supported by the National Natural Science Foundation of China (No.51975293), Aeronautical Science Foundation of China (No.2019ZD052010) and Postgraduate Research & Practice Innovation Program of NUAA (No.xcxjh20230502).

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Competition interests All authors declare no competition interests.

(Production Editor: WANG Jing)

发动机叶片固有频率自动化测试系统研究

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摘要：叶片是航空发动机上的重要零部件之一，若因振动失效而断裂会影响整个发动机的正常工作，因此需在将叶片安装到发动机上之前检测其固有频率，避免共振现象发生。目前大多数叶片振动测试系统均需操作人员手动操作，对操作人员要求较高，测试过程也十分繁琐，因此测试效率较低，无法满足高效测试的需求。为解决目前存在的测试效率低、操作要求高等问题，设计了一套高精度、高效率的自动化测试系统。该系统的测试精度可达±1%，相比于人工测试效率提升37%。首先，通过幅频曲线分析压紧力、激振器位姿对固有频率测试的影响，从而对伺服电缸、四维运动平台进行标定；其次，选用正弦波信号作为激励对叶片进行线性扫频，通过频域内的振幅峰值确定固有频率；最后，研制的测试系统进行了准确性实验和效率实验，验证了系统的高效率、高精度。

关键词：叶片；振动失效；固有频率；自动化测试系统