Research on compressor blades fatigue life test under thermal-vibration combined load

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Abstract. Contrapose the fatigue life of compressor blades under thermal-vibration combined load, this article is described to carry out the fatigue life test of blades under the thermal-vibration load, the test device is designed in this article, the test conditions are determined, and the test results are analysed to obtain the conclusion that resonant frequency decreases gradually as fatigue life time goes on, and the extent of blades damage could be quantitatively described by calculating the drift distance of resonant frequency. It can also provide data support for life prediction.

1. Introduction

Compressor blades usually operate in high temperature, high pressure, high rotational speed, so its working environment is complex and harsh. Blades deformation may occur due to severe high temperature, and produce thermal stress, also considering the vibration excitation caused by high speed, the structure swings back and forth relative to its balance position, thus rapid destruction happens. When the incentive frequency of thermal-vibration combined load is consistent with the natural frequency of blades, the structure can produce significant stress and strain, and with the blade operating in the resonance environment for a long time, complex alternating stress can produce crack in the stress concentration parts of the structure, which results in changes in structure, and then, its service life is reduced. Therefore, in order to reduce the failure rate of compressor blades in operation and ensure the high reliability and long service life of blades, it is urgent to study the fatigue life of blades under thermal-vibration combined load.

In the field of thermal-vibration coupling and fatigue life research, For LED headlight, Wang [1] established thermal-vibration coupling analysis model and simulated the strain caused by an independent vibration and thermal-vibration coupling respectively. The results showed that maximum reduction of the coupling analysis compared to the independent vibration situation is nearly 6.2%. Zhao etc. [2] applied the Coffin-Manson equation to calculate the fatigue damage caused by random vibration in different temperatures, then weighted average of the random vibration damage and the thermal cycling damage were summed to obtain a total damage and subsequently to obtain the fatigue life. Yao etc.[3] found that the thermal-acoustics-vibration coupling stress induces a deformation of thin-wall blades greater than that induced by any single factor. Sha [4] carried out the thermoacoustic fatigue experiment of GH188 board fixed thin-walled, then the frequency response, dynamic stress, possible dangerous location and fatigue life were obtained. Cui [5] analyzed the turbine blades stress and strain under thermal, centrifugal and pressure loads using ANSYS, got the influence of each factor...
on the stress and strain of blades. D. Holländer, D. Kulawinski [6] studied the low-cycle fatigue test of the blades of industrial gas turbines at 850 °C, and then the performance degradation caused by the change of microstructure was observed, based on the determined fatigue data, the residual fatigue life of the blades could be estimated. For fatigue life of composite tidal turbine blades, Ciaran R Kennedy, Vesna Jaksic [7] studied the influence of seawater intrusion on blade composite material, design and service life, obtained that the fatigue life of tidal turbine blades was damaged by seawater immersion, which could be compensated by increasing the thickness of blade layer.

In summary, there is less research on the fatigue life of blades under thermal-vibration combined load. Therefore, this article is described to carry out the fatigue life test of compressor blades under the thermal-vibration combined load, the test device is designed in this article, the test conditions are determined, and the test results is analyzed to obtain the degradation law of blade fatigue life, and can provide data support for life prediction.

2. Design of test device

There is no ready-made test device available for carrying out fatigue life test under the thermal-vibration combined load. Based on the Temp/Humid/Vibration Chamber, we designed a test device of thermal-vibration integration, which not only saves time but also reduces costs.

2.1. The overall diagram of the test device

The thermal-vibration combined test device is composed of four major sub-systems. An automatic temperature control system can control the temperature of the product during the test in real time. A stress and strain measurement system measures the strain response using strain gauges attached to the blade. A temperature measurement system mainly measures the temperature of the blade and the test fixture, and then compares them to determine the setting temperature of the sensor on the test fixture. A vibration control system realizes a closed-loop control by using a “M + P” controller, a power amplifier, an accelerometer, and a charge amplifier. The four sub-systems cooperate with each other to complete the fatigue life test of the blade under the thermal-vibration combined load. The diagram of the test device is shown in Figure 1.

![Figure 1. The diagram of the thermal-vibration combined test device.](image-url)

2.2. The diagrams of each part of the test device

2.2.1. The automatic temperature control system. The automatic temperature control system is a device that provides high temperature for the blade. It is composed of thermocouple (copper-constantan), infrared lamps, SR23 temperature controller, program-controlled power supply, serial port server and temperature control software (IFIX). The setting program is loaded into the computer...
by IFIX, and then transferred to the temperature controller through the serial port server, the temperature controller sends instructions to drive the power supply, the temperature measured by thermocouple is fed back to the temperature controller, and then the data is transferred to the computer. Thus, a closed-loop temperature control system is built. The automatic temperature control system is shown in Figure 2a.

2.2.2. The stress and strain measurement system. The stress and strain measurement system (Figure 2b) is a key part of the blades fatigue life test under the thermal-vibration combined load. It is composed of a strain gauge, a coupling box, a data acquisition instrument, a program-controlled strain amplifier, and a LMS acquisition software. The strain response of the compressor blades under vibration is converted into electrical signal by the strain gauge, and then passed through a strain amplifier, data acquisition instrument and transferred to a computer finally. The LMS acquisition software is used to obtain the vibration spectrum diagram of the blades, so that fatigue characteristics can be analyzed.

2.2.3. The vibration control system. The vibration control system is composed of a 5t shaker, “M + P” controller, a power amplifier, a charge amplifier and acceleration sensors. The “M + P” controller drives the shaker through the power amplifier, and the acceleration sensor on the shaker transmits the vibration response through the charge amplifier to the “M + P” controller and then forms a closed-loop control system to ensure that the vibration applied can following the settled spectral pattern. The vibration controller is shown in Figure 2c.

2.2.4. The temperature measurement system. The temperature measurement system mainly measures the difference between the temperature of the test fixture and of the blade. It is composed of thermocouple, a multi-channel data acquisition instrument and an acquisition software. The test interface of the temperature measurement system is shown in Figure 2d.

Figure 2. Each subsystem of the test device.
3. Blades fixing and measuring points

3.1. Blades fixing
A special test fixture is needed to carry out the compressor blades fatigue life test on a vibration table. Considering that the vibration response of two blades on one fixture will affect each other during the testing, only one compressor blade is installed in each fixture in order to ensure the accuracy of the test. During the testing, the blades are heated by infrared lamps. If the blades are directly heated, the moving frame of shaking table may probably be overheated, which will lead to alarm shutdown. Therefore, we design a thermal insulation device showed in Figure 3 below. It uses a reflective screen to surround the infrared lamp, and makes a hole in the middle of the reflective screen. The blade is placed directly below the hole, which can not only meet high temperature requirements of the blade, but also protect the shaking table from being overheated and shutdown.

![Figure 3. Installation position of a blade and insulation plate.](image)

3.2. measuring points of blades
The fatigue life test under the thermal-vibration combined load needs to measure both the strain and the temperature of the blade during the test. After modal analysis of the blade, it can be seen that the highest stress appears in the middle position of the root on the suction surface, so the strain gauge should be pasted in the middle position of the root on the suction surface using high temperature glue. Because of small size of the blade, it is difficult to paste the thermocouple in the middle position of the root on the suction surface as well, so the temperature of the blade can be maintained by controlling the temperature on the fixture. The measuring points of blades is shown in Figure 4.

![Figure 4. The position of a strain gauge and temperature measurement point.](image)
4. Determination of the test conditions and test parameters

4.1. Test conditions
The blade fatigue life test contains three parts: the sweep frequency test, the constant frequency test, and test time.

4.1.1. The sweep frequency test. The frequency range is 250 Hz ~ 2500 Hz, test level: 3 g, sweep rate: 1 Oct/min, test times: 3 times. Finally, the frequency response curve of the blade is obtained.

4.1.2. The constant frequency test. The first-order resonant frequency obtained from the sweep frequency test was set as the frequency of the constant frequency test, test level: 63 g (actual operating level), temperature: 150°C ± 2°C (For small compressor blades of missile, 150°C is the actual operating temperature). During the preexposure test, the blade and fixture were separated pasted thermocouples to measure their temperature. The temperature on the fixture was set to 140°C, while the blade actual temperature was 150°C. Therefore, during the test, as long as the temperature of the thermocouple on the fixture is controlled at 140°C, the blades requirement of 150°C is met.

4.1.3. Life test time. The compressor blade material is 1Cr11Ni2W2MoV. We investigated the material characteristics of the blade, which are shown in Table 1.

| Temperature | Elastic Modulus | density | Poisson's ratio | tensile strength | Yield Strength |
|-------------|-----------------|---------|----------------|-----------------|---------------|
| 20°C        | 196GPa          | 7800kg/m3 | 0.31          | 932MPa          | 804 MPa       |
| 100°C       | 188GPa          | 7800kg/m3 | 0.31          | 879MPa          | 758 MPa       |
| 200°C       | 180GPa          | 7800kg/m3 | 0.31          | 826MPa          | 712 MPa       |

According to the theory of structural fatigue, fatigue life can be considered as infinite if it is more than $10^7$. Therefore, only the fatigue life within $10^7$ is considered. According to the mass of the blade and the elastic modulus at room temperature, the theoretical resonant frequency of the blade was calculated to be 1100 Hz, and the test time of the blade fatigue life was calculated to be about 2.5 h by referring to the fatigue life of $10^7$.

4.2. Test parameters
The fatigue life test level of the compressor blade is relatively large under the thermal-vibration combined load, and the lead diameter of the strain gauge is small, so it is very easy to break under the condition of a large level, and the strain cannot be measured. According to relationship between resonant frequency and fatigue damage [8-11], we can measure the resonant frequency after each life test, and calculate the frequency drift relative to the initial state, then study the development trend of fatigue life.

Therefore, the fatigue life test of blades is divided into two procedures. First, a blade is swept at 3g level and room temperature to obtain the first-order resonant frequency. Considering the first-order resonant frequency as the constant frequency, the fatigue life test at the level of 63g is carried out, and the sweep frequency is conducted separately after each interval of 10min, 40min, 70min, 100min, 150min at room temperature, and then all resonant frequencies are measured. Another blade is also swept separately at 3g level at room temperature and high temperature, in order to obtain their resonance frequency under their respective conditions. The resonant frequency obtained at high temperature is taken as the constant frequency, and then the fatigue life test under thermal-vibration combined load is carried out, by setting different time intervals of 2 min, 5 min, 20 min, 50 min, 90
min, 150 min, the resonance frequencies of the blade at the room temperature after each interval are measured, which provides basic data for calculating frequency drift.

5. Results and discussions

5.1. Consistency analysis of sweep test results
In order to exclude the change of the first-order resonant frequency of compressor blades caused by accidental factors, three sweeps were carried out for each sweep test, and the results obtained were basically same, as shown in Figure 5.

![Figure 5. Frequency response curves of three sweeps.](image)

5.2. Time drift characteristics of frequency response curve
First the sweep frequency test on a selected blade is carried out at room temperature to obtain a first-order resonant frequency. Based on the resonant frequency, fatigue life tests at intervals of 10min, 40min, 70min, 100min and 150min were carried out respectively. Then, sweep frequency was also conducted to obtain the spectrum response diagram of each test, as shown in Figure 6.

Another blade was swept separately at room temperature and high temperature of 150°C. The first-order resonance frequency obtained at 150°C was taken as the constant frequency. Fatigue life tests at intervals of 2min, 5min, 15min, 30min, 1h and 2.5h were carried out respectively. After each intervals of the life test, the blade temperature drops to 20°C, the measured spectrum response diagrams obtained from each test are shown in Figure 7.

As can be seen from Figure 6 and Figure 7, the resonance frequency will decrease with gradually extending of the life test time. It is because the resonance frequency is directly affected by the elastic modulus (\(\omega = \sqrt{k/m}\)). The change amount of the elastic modulus reflects the damage degree of the product. When the resonance frequency reaches a certain threshold, the product will crack and sequentially break quickly. Therefore, it is not necessary to completely break the product in the fatigue life test, the dropping of the resonant frequency to a certain value can be considered as the damage standard, which can greatly shorten test time and improve test efficiency.
5.3. Frequency drift at high temperature and room temperature
When the fatigue life test of compressor blades is carried out at room temperature, the resonant frequency decreases gradually as time goes on. Compared with the drift of blade resonant frequency under 150°C and vibration combined load, the drift distance is relatively small. Therefore, it can be proved that the fatigue life test is significantly affected by temperature, as shown in Figure 8. Moreover, as time goes on, the percentage of frequency drift increases more and more slowly, which indicating that the damage of life test tends to be stable after 150min.

Figure 6. Spectrum response diagrams after each interval life test of 20°C.

Figure 7. Spectrum response diagrams after each interval life test of 150°C.
5.4. The change of blades before and after life test

After 150 min fatigue life test under thermal-vibration combined load, the resonance frequency of the compressor blade has a marked drift, but the appearance of suction surface has no obvious change before and after test (Figure 9). Therefore, resonance frequency drift characteristics can be used to obtain the blade damage characteristics that cannot be seen by the naked eye, and the damage degree can be better quantitatively described. For further study, the actual change inside the compressor blades can be inspected by fluorescence penetrant [12-15]. (fluorescence penetrant inspection is to apply the osmotic fluid containing fluorescent substances on the surface of the detected part for imaging).

6. Conclusions

In this paper, a set of thermal-vibration combined test equipment is designed for the fatigue life test of compressor blades, and further the development law of blade fatigue life is studied, finally the following conclusions are drawn.

1) A thermal-vibration combined test system is built by making change to the test box, which not only realizes the automatic control of temperature, but also avoids the influence of high temperature on the over-temperature shutdown of the shaking table, and perfectly solves the difficult problem of blades fatigue life test under the thermal-vibration combined load in the project.

2) The test result shows that the resonant frequency of compressor blades would gradually decrease as life time goes on. Therefore, the degree of blades damage could be quantitatively described by calculating the drift distance of resonant frequency.
3) In the blade life test designed in this paper, the resonant frequency drift is logarithmic increase with time going on at room temperature and high temperature. (20°C: \( y = 1.6277\ln(x) - 2.7943 \); 150°C: \( y = 1.2077\ln(x) + 2.3135 \)), but the drift distance at 150°C is much larger than that at 20°C, which indicating that temperature has a significant impact on the life of blades. Therefore, temperature load cannot be ignored in blades fatigue life test.

However, the resonance frequency will continually decreases during the blade life test time after the blade is damaged, the blade does not continue to be in the most better resonant state because the excitation frequency is fixed, which causes that the damage become small in the later stage of the life test, consequently brings certain errors. It is expected that in the future, intelligent devices can be used to monitor the resonance frequency in real time and adjust the excitation frequency at any time to make the obtained curve more perfect.

Acknowledgement
Thanks to the funding supports from the PLA (Grant No. 41402010103) and National Natural Science Foundation of China (Grant No. 51805038).

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