Comparison on Excitation Methods for Natural Frequency Measurement of Blades

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Abstract: Aimed at practical demand of effective and precious measurement of blades' natural frequencies especially high-order natural frequencies in aero-engine and compressor etc, four different excitation methods, including hammer exciting method, piezoelectric ceramic based exciting method, shock exciting method and electrical-magnetic foundation exciting method are compared. Through the analysis of the stabilization diagram of blade vibration pickup and the identification of the natural frequencies, the effectively excited and recognized results in each excitation method are different in testing natural frequency of the blade, and the advantages and disadvantages of each exciting method are concluded. By comparing and analyzing the excitation method of the blade natural frequency test, the feasibility of obtaining more accurate natural frequency of the blade through experiments can be improved. The results show that each excitation method of the blade natural frequency test has its own different characteristics, and it needs to be utilized reasonably according to the blade mode orders of interest.

Keywords: Blade; Natural frequency; Excitation method; Frequency response function (FRF); Modal stability diagram

1 Introduction

Blades are important components widely used in aero-engine and compressor, which dynamic performance directly affects the safety of engine and compressor. Blade failure is one more common type of all kinds of faults of the aero-engine and compressor[1], mainly including blade crack or break, tenon teeth and shroud and flange cracks, blade tip wear or break and so on, mostly are caused by blade vibrations[2-4]. Therefore, conducting modal analysis of the blade to obtain natural frequency and mode of vibration is particularly important. In recent years, scholars have conducted a series of studies on the inherent characteristics of blade, and achieved good results. However, in the vast majority of literatures[5-8], the first few natural frequencies and mode shapes of blade are determined based on the tested and calculated modes, and there are relatively few studies on the vibration characteristics of high-order modes of blades. And the choices of excitation are relatively simple in the experimental modal analysis of blade, mostly

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only using hammer exciting or shock exciting method. However, in some cases by using of unreasonable exciting methods, some interested modes in certain frequency range may not be discovered, bad exciting method can directly lead to measurement errors of natural frequencies and wrong mode identification of the blades. The choice of excitation method influences the measured results to a great extent.

This paper compares four different excitation methods, including hammer exciting method, piezoelectric ceramic based exciting method, shock exciting method and electrical-magnetic foundation exciting method, applying to blade natural frequency measurement, elaborates the advantages and disadvantages of each excitation method, and finally the effective natural frequency ranges under four different excitation methods are obtained. It can provide a basis for the blade dynamic analysis and design.

2 Hammer exciting method

Hammering exciting method in modal test of blade is to use a hammer as a stimulus device to impact the blade and the vibration data of the blade are recorded. The method is simple and easy to use, and it does not affect the dynamic characteristics of the measured parts, which suitable for linear structure. But it often suffers from unexpected continuous strikes due to human operating skills and produces great errors of measurement results of natural frequencies. In addition, the hammering excitation energy is limited and the signal noise ratio (SNR) is not high, so it is difficult to accurately obtain high-order natural frequencies.

Figure 1 shows the photo of the blade natural frequency test via hammer exciting method. First of all, to use a fixture to restrain the blade root, and then to hit the planned excitation points with a hammer, and a laser or light acceleration sensor is used to pick up the vibration responses of the blade. And finally the natural frequencies of the blade are obtained by identification algorithm of modal analysis. Figure 2 shows the measured results of the steady-state diagram of mode analysis on blade, where the hammer hits at point 7 and the vibration response is picked at point 25 and point 13 with laser and an acceleration sensor. From the steady-state diagram of the blade, we can see that it is valid for natural frequency test of the blade in low and middle frequency range within 5000Hz, and when the frequency range above 5000Hz, the effect of stabilization diagram of the blade is not very well, therefore, it is difficult to obtain more precise natural frequencies due to the larger test data errors. Table 1 and Table 2 list the first eight order natural frequencies of the blade, which is obtained through the laser and light acceleration sensor picking up vibration responses respectively. Comparing the data of Table 1 and Table 2, it can be concluded that the natural frequencies of the vibration responses picked up by laser and light acceleration sensor are basically consistent, and the errors between them are very small, so the vibration responses picking up method has little influence on the natural frequency test of the blade.

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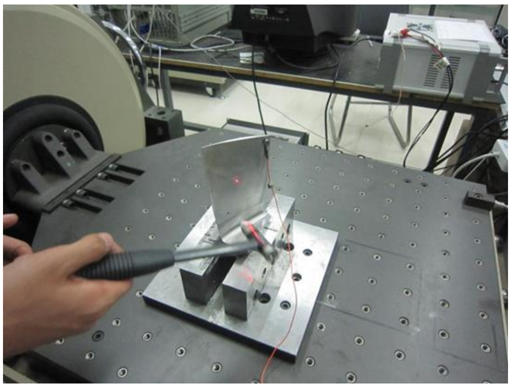

Fig.1. The photo of the blade natural frequency test via hammer exciting method

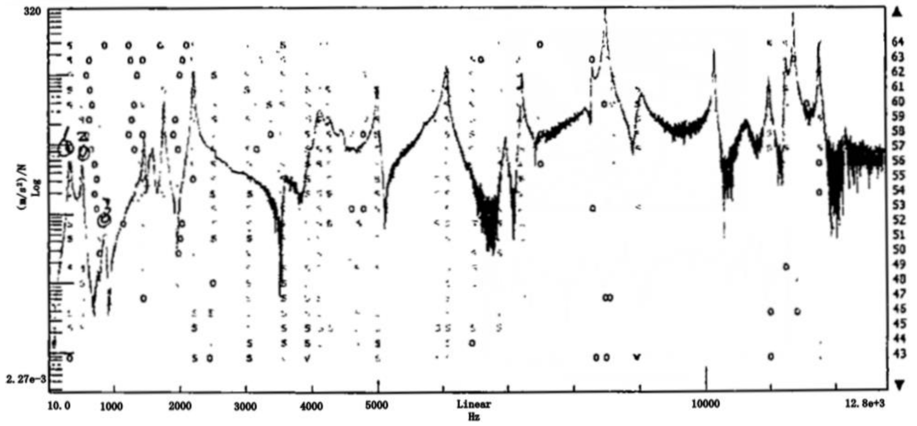

Fig.2. The steady-state diagram of mode analysis on blade, where the hammer hits at point 7 and the vibration response is picked at point 25 and point 13 with laser and an acceleration sensor

Table 1. Vibration response picked up by laser

Order	1	2	3	4
Frequency	332.81	523.44	1468.75	1594.53
Order	5	6	7	8
Frequency	1771.09	2224.22	4111.72	5009.38

Table 2. Vibration response picked up by light acceleration sensor

Order	1	2	3	4
Frequency	332.03	523.44	1467.19	1590.81
	332.03	522.66	1467.19	1593.75
Order	5	6	7	8
Frequency	1769.53	2218.75	4125.00	5010.94
	1769.53	2219.53	4110.94	5009.38

3 Piezoelectric ceramic based exciting method

Figure 3 shows that using piezoelectric ceramic based exciting method to test the natural frequency of the blade. Usually, it needs to determine the stickup position of the piezoelectric ceramics chip at first, and then use piezoelectric ceramics chip to excite the measured objects and pick up the vibration responses by the high-precision sensors. The effect of the excitation and vibration response pickup at different points is observed, then the natural frequencies and vibration modes of the blade are obtained[9]. Because of the piezoelectric ceramics itself has small volume, light weight, high accuracy and resolution, high frequency response etc, therefore using piezoelectric ceramics as the exciting method of natural frequency test of blade, also has many advantages. Piezoelectric ceramics, for example, are not affected by the geometry of the component and can be excited anywhere on the component, so it is more convenient to use; The piezoelectric ceramics exciter can produce stable single and multi-frequency exciting signal with specified frequency and amplitude, and also generate narrowband and broadband random signal; And its additional mass is very small as well. Piezoelectric ceramic vibration excitation system mainly consists of piezoelectric ceramic, BNC attenuator, drive amplifier of piezoelectric ceramic and excitation signal source.

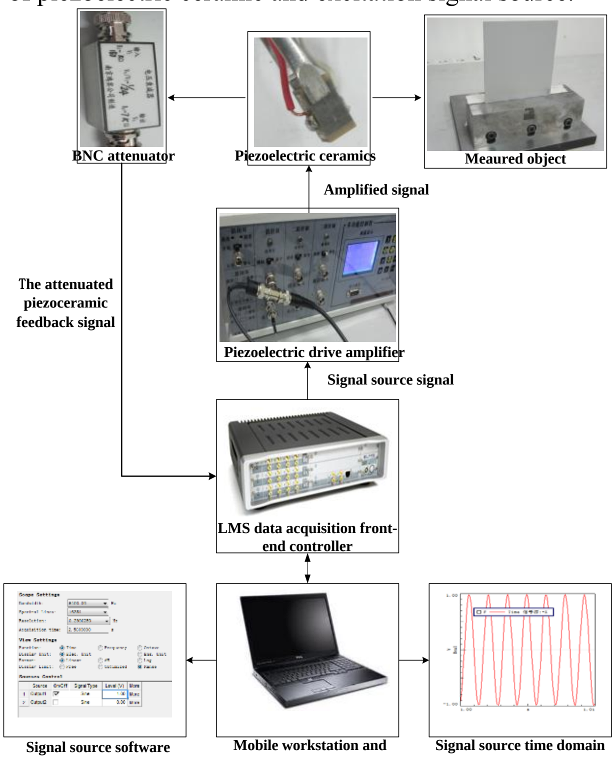

Fig.3. The photo of the blade natural frequency test via piezoelectric ceramic based exciting method

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3.1 Piezoelectric ceramic

The open-loop piezoelectric ceramic P-885.10, which is imported from German PI company, is selected for this measurement. Its overall dimension is 5*5*9mm, and it can withstand the bias voltage from 2.5V to 50V. Its electrostatic capacity is 0.6uf, and the maximum output force is 660N. It has advantages of small volume, light weight (only 2g), high resolution, fast response, large output force, high energy conversion efficiency, no heat generated, and its drive circuit is relatively simple. Under the excitation of 25KHz frequency, the maximum displacement of vibration response is close to 0.65um, which can satisfy the demand of the high frequency vibration test from 0 to 20KHz.

The selected piezoelectric ceramic can only work in a positive voltage environment.

3.2 Drive amplifier of piezoelectric ceramic

Drive amplifier of piezoelectric ceramic is mainly used to amplify the signal of the signal source and drive the piezoelectric ceramic to produce micro-nanometer displacement changes. It can drive three route piezoelectric ceramics at the same time, and has excellent frequency responses and very low static ripples. There is a 24-bit main controller on the drive amplifier of piezoelectric ceramic, the analog input impedance of the amplifier is less than 100KΩ, and the voltage output resolution is 5mV. The amplifier has a communication rate of 9600Bps, using liquid crystal display (LCD) to display, and it can monitor the output voltage in real time.

(1) Power amplification

Through the test software, the computer makes LMS signal source to send out analog signals, and after the analog signal source is amplified by 24 times through the drive amplifier of piezoelectric ceramic, then loading it on the piezoelectric ceramic. The energy of vibration produced by the piezoelectric ceramic will be transmitted to the test pieces, and the vibration excitation of the test pieces will be realized.

(2) Voltage bias

At the same time, due to the piezoelectric ceramic's own performance characteristics, the drive amplifier of piezoelectric ceramic provides a bias voltage to ensure that the piezoelectric ceramic always works in the positive voltage range. It can provide high stability and high resolution bias voltage for piezoelectric ceramic, for example, the bias voltage of 75V or 50V or 25V or other commonly used can be quickly loaded.

3.3 BNC attenuator

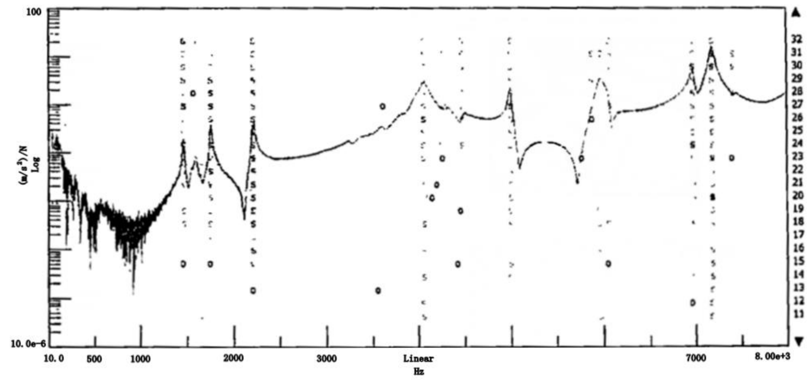
Obtaining the excitation force of component is the key to the modal test and response test of the component. However, the high voltage of the piezoelectric ceramic can not be input to the data collector. In order to obtain the excitation signal, BNC attenuator is selected to use, which has two main functions of voltage attenuation and voltage anti-bias.

One end of the BNC attenuator is used to connect with two pins of the piezoelectric ceramic. First, making the bias voltage of working of the driving amplifier of piezoelectric ceramic to anti-bias, and adjusting the voltage to the reference 0V.Then, the high-voltage signal loaded on the piezoelectric ceramic is attenuated by 24 times and converted into a low-voltage signal, which is fed back to the front end of the LMS data collector via the BNC joint to realize the real-time acquisition of exciting voltage of piezoelectric ceramics.

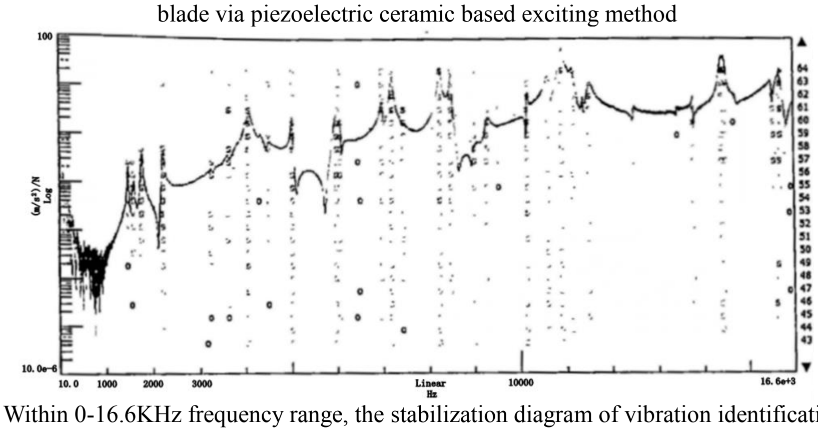
3.4 Signal source

The 16-channel LMS acquisition front-end is selected, which can provide steady-state sinusoidal and random excitation signal.

Figure 4 shows the stabilization diagram of vibration identification of blade via piezoelectric ceramic based exciting method. From Figure 4(a), we can see that in the 0-1500Hz frequency range, it is almost impossible to identify the peak of the frequency response function (FRF) from the stabilization diagram, that is to say, the identification ability of the low order natural frequencies of the blade is poor. However, the natural frequencies of the blade above 1500Hz can be easily identified. Figure4 (b) shows the stabilization diagram of high-order vibration identification of blade via piezoelectric ceramic based exciting method, combined with the data of table 3 and table 4, we know that the piezoelectric ceramic based exciting method is used to test the natural frequencies of blades, which can accurately obtain the higher order natural frequencies above 10KHz.



(a) Within 0-8KHz frequency range, the stabilization diagram of vibration identification of blade via piezoelectric ceramic based exciting method



(b) Within 0-16.6KHz frequency range, the stabilization diagram of vibration identification of blade via piezoelectric ceramic based exciting method

Fig.4. The stabilization diagram of vibration identification of blade via piezoelectric ceramic based exciting method

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Table 3. Identification of natural frequency of blade via piezoelectric ceramic based exciting method

Order	1	2	3	4
Frequency	337.598	520	1462	1591.42
	335.94	521.88	1463.28	1586.33
Order	5	6	7	8
Frequency	1759.38	2212		
	1758.98	2212.05	4064.06	4991.02

Table 4. Identification of high-order natural frequency of the blade via piezoelectric ceramic based exciting method

Order	1	2	3	4	5
Frequency	335.94	521.88	1473.36	1757.33	2214.87
			1465.192	1758.50	2213.71
Order	6	7	8	9	10
Frequency	4067.75	4998.78	5963.96	6971.34	7179.10
	4063.39	4995.095	5956.34	6969.69	7176.29
Order	11	12	13	14	15
Frequency	8233.96	8481.22	10148.6	10614.3	10904.6
	8233.95	8484.40	10148.18	10612.84	10904.9
Order	16	17	18	19	20
Frequency	11152.45	12475.36	13779.48	14465.89	15607.09
	11165.36	12470.92	13775.92	14474.89	15660.47

In addition, the piezoelectric ceramic has obvious advantage in the high-frequency vibration excitation relative to the hammer, shaker and other equipment, but due to the small excitation energy, it usually needs to use high-precision sensor to pick up the vibration response. Although the piezoelectric ceramic' additional mass is very small, it will still affect other modal parameters to identify, leading to the shift of the FRF , and the test results of modal parameters such as natural frequency and damping ratio will be generated errors[9].

4 Shock exciting method

Compared with the hammer exciting method, the excite energy of shock exciting method is larger, and it is more evenly distributed, we can obtain higher quality data through the shock exciting method. Shock exciting method is used to the modal test of complex or non-linear structures has obvious advantage. However, it is difficult to install and operate for the exciter, and it has great additional mass. And the top bar of the exciter is always in contact with the structure, which may bring about the influence of bending stiffness or the coupling of the top bar and the structure.

As shown in Figure 5, the shock exciting method is used to test the natural frequency of the blade. First, to arrange the number and position of the measuring points on the blade reasonably and to use a fixture to constrain the blade root, and to install the exciter and to select the appropriate fixed point to excite, then to use the light acceleration sensors to pick up the vibration responses of the blade, and to process the experimental data to obtain the natural frequencies and vibration modes of the blade. Figure 6 shows the steady-state diagram of mode analysis on blade, where the exciter excites at point 3 and the vibration response is picked at point 25 with a light acceleration sensor. It can be seen from the diagram that in the low frequency range of 0-300Hz, the natural frequency cannot be accurately identified, presenting the phenomenon of signal aliasing in the frequency response curve. From the data listed in Table 5 we can get the conclusion that the medium and low natural frequency of the 300-6000Hz of the blade can be accurately identified via shock exciting method. However, the test results inevitably have some errors due to the impact of additional mass.

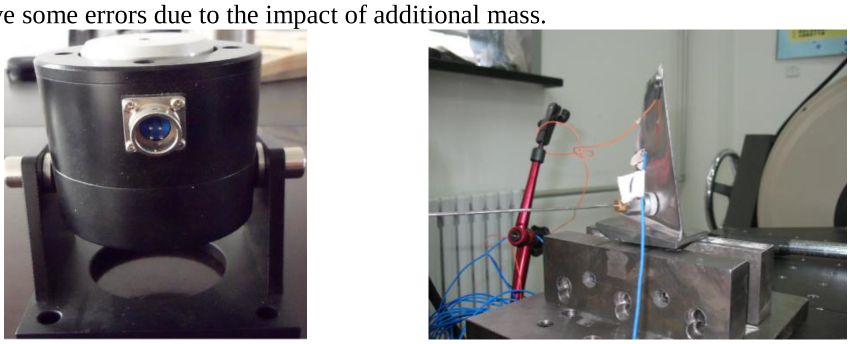

Fig.5. The photo of the blade natural frequency test via shock exciting method

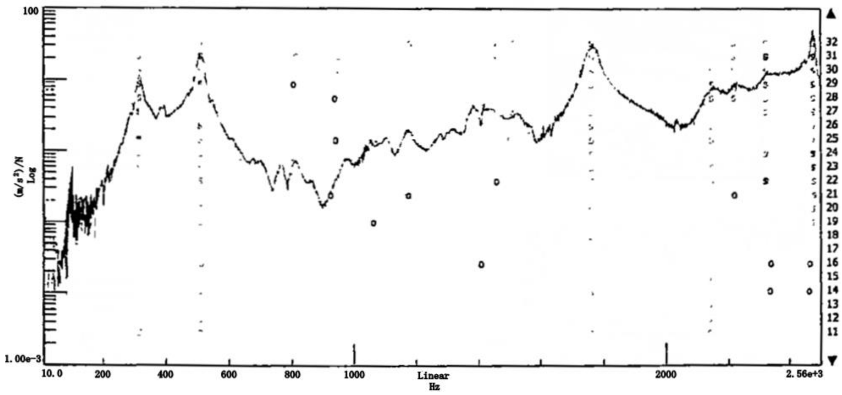

Fig.6. The steady-state diagram of mode analysis on blade, where the exciter excites at point 3 and the vibration response is picked at point 25 with a light acceleration sensor

Table 5. Shock exciting method to identify the natural frequency of the blade

Order	1	2	3	4	5
Frequency	312	507	1387		1769
	315.43	506.64	1382		1760
Order	6	7	8	9	10
Frequency	2469	4231	5022	5359	5981
	2471	4170	5032	5353	5966

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5 Electrical-magnetic foundation exciting method

Figure 7 is the photo of the natural frequency test of blade via electrical-magnetic foundation exciting method. To connect the exciter to the fixture, and to drive the fixture to excite the natural frequency of the blade on the fixture. The interface force between the test-piece and the fixture can be obtained during the modal test of structures by electrical-magnetic foundation exciting method. But it is also very difficult to accurately measure the interface force, because the force measuring device is connected in series between the test-piece and the fixture, connection and calibration are a bit troublesome[10].

The steady-state diagram of mode analysis on blade as shown in Figure 8, where electrical-magnetic foundation exciting method is used to excite and the vibration response is picked at point 25 with a light acceleration sensor. From the steady-state diagram we can see that in the low frequency range of 0-300Hz and in the middle and high frequency range above 2000Hz, the natural frequency of blade cannot be accurately identified. It can also be seen from the data listed in table 6 that electrical-magnetic foundation exciting method can only excite the natural frequency of blade effectively in the lower frequency range.

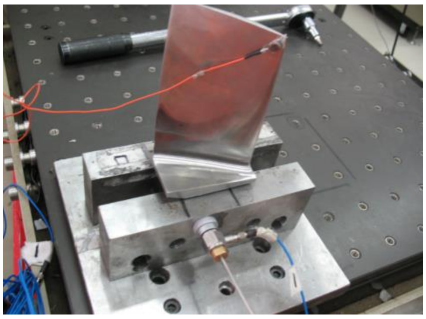

Fig.7. The photo of the natural frequency test of blade via electrical-magnetic foundation exciting method

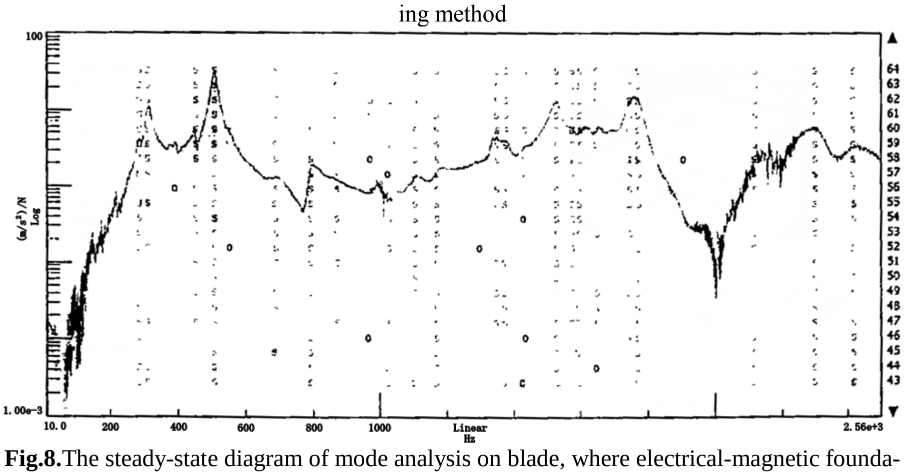

Fig.8. The steady-state diagram of mode analysis on blade, where electrical-magnetic foundation exciting method is used to excite and the vibration response is picked at point 25 with a light acceleration sensor

Table 6. Electrical-magnetic foundation exciting method is used to excite the blade and using a light acceleration sensor to pick up the vibration response at point 25

Order	1	2	3	4	5
Frequency	312.11	505.08	1341	1527.3	1741.02
	313.67	505.47	1344.53	1526.58	1757.81
Order	6	7	8	9	10
Frequency					
	2314	4226			

6 Comparison and analysis of excitation methods of natural frequency test of blade

Through the comparison and analysis of the characteristics of excitation methods of natural frequency test of blade above, the following conclusions can be drawn:

(1) From the viewpoint of installation and additional mass we can know: the device of hammer exciting method is simple and easy to move, and this method has no effect of additional mass, hence it is suitable for the simple blade structure; piezoelectric ceramic based exciting method produces very small additional mass, and the installation position of piezoelectric ceramic can be chosen flexibly , so it is used to excite the special points of the blade; The shock exciting method and electrical-magnetic foundation exciting method are more applicable to the exciting of large and complex structures, due to the inconvenience of installation and the effect of additional mass, while the exciting effect for blade is not ideal.

(2) For the excitation and picking up vibration responses: If you need to obtain the higher natural frequency above 5000Hz of the blade, especially the natural frequency above 10KHz, give priority to using piezoelectric ceramic based exciting method; if you want to obtain natural frequency within 5000Hz of blade, it is supposed to adopt hammer exciting method; the low-middle natural frequency of blade can be accurately excited via shock exciting method and electrical-magnetic foundation exciting method. The natural frequency within 6000Hz of blade can be obtained via using shock exciting method, while electrical-magnetic foundation exciting method is usually used to excite the natural frequency within 2000Hz of blade. Therefore, in the natural frequency test of the blade, the frequency range of interest needs to be determined combined with the results of the finite element modal analysis, and then the exciting method is selected reasonably to obtain more accurate natural frequencies.

7 Conclusions

In order to improve the accuracy of the inherent frequency test of aero-engine and compressor blades, and considering the lack of targeted research on exciting methods of blade natural frequency test, this paper systematically expound the advantages and disadvantages of natural frequency test of blade, which is excited by hammer exciting

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method, piezoelectric ceramic based exciting method, shock exciting method and electrical-magnetic foundation exciting method, from the angle of excitation method. By comparison and analysis of these four exciting method, the effective natural frequency ranges of the blade which can be identified by each method are discussed. Usually, the frequency range of interest needs to be determined combined with the results of the finite element modal analysis, and then select appropriate exciting method according to the interesting frequency range and the characteristics of each method, thus the more accurate natural frequencies and vibration modes can be obtained. It is necessary to further study the exciting method of natural frequency of the blade in the following two aspects:

(1) For the accurate identification of high-order natural frequency of the blade, by analyzing each excitation method, we can realize that only piezoelectric ceramic based exciting method can effectively excite natural frequency above 10KHz of the blade, while natural frequency above 6000Hz of the blade cannot be effectively acquired via the other three excitation methods. The engineering practice has shown that high-order vibration of blades can cause faults such as fall of corner and crack of blades, etc, therefore, it is particularly important to obtain the high-order natural frequency of the blade accurately through experiments. As one of the few excitation methods to identify the high-order natural frequency of blades, the accuracy of the piezoelectric ceramic based exciting method is still to be verified. Therefore, it is necessary to find more excitation methods to assure the accuracy of the high-order natural frequency of blades by comparison. Currently, the gas exciting method is applied in the natural frequency test of blades to obtain high-order natural frequency, but the degree of accuracy of test needs further study.

(2) Better methods of excitation and vibration response picking up for testing the natural frequency of blades are needed. With the development of science and technology and new materials, there will be more and more excitation methods and vibration response picking up methods used for the natural frequency test of the test-piece. In order to obtain true natural frequency of blades as far as possible, it is necessary to study the new excitation methods and vibration response picking up methods, which are used for other subjects or fields, and apply these methods to the natural frequency test of the blade.

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