Effect of Pre-tension State Change and Loosening on High-order Modal of Wheel Disk Assembly

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Abstract: It is difficult to ensure the consistency of pre-tightening force state when assembling the disc components in the aeronautical rotor, which results in modal differences, thus affecting the vibration characteristics of the rotor and even the whole machine. In this paper, the finite element model and the solid model of the wheel disk simulation component are established, and the influence of pre-tension state change (loosening) on its higher natural frequency is analyzed by the finite element method and the experimental method, respectively. The results show that the lower natural frequencies and mode shapes of the wheel disk assembly do not change, while the higher natural frequencies and mode shapes have some changes when a bolt loosening at the installation side causes the change of the pretension state. With the change of pre-tightening force state, the axial and bending amplitude-frequency curves of the measuring points are basically unchanged in the frequency band of 0-3000Hz, while in the frequency band of 3000-6400Hz, the amplitude-frequency curves of the measuring point have a certain offset at some natural frequencies, which makes the axial and bending dynamic stiffness change. In addition, the change of pre-tightening force state is sensitive to the phase-frequency curve of the measured points.

Keywords: The wheel disk; Higher natural frequency; Amplitude-frequency curves; Dynamic stiffness

1 Introduction

There are the following phenomena in engineering: the same engine parts, according to the same assembly process and process parameters, different assembly times will produce different vibration level or response characteristics of the whole machine; a small deviation of individual assembly process parameters will even lead to significant changes in the vibration response of the whole machine. The main reason for the analysis is that the structure of the aero-engine rotor is complex, and the manufacturing and assembly errors of the components will lead to the change of the pre-tightening force state of the connecting bolts, which will have a great impact on the dynamic

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performance of the rotor, and further affect the vibration characteristics of the rotor and even the whole machine. Therefore, it is necessary to study the influence of bolt pre-tightening state change (loosening) on the dynamic characteristics of the rotor assembly, and to provide a basis for controlling the assembly quality of the rotor and making it have good dynamic performance.

As an important component of the aero-engine rotor, the parts of the wheel disk assembly are connected by a large number of high-performance bolts, resulting in a certain degree of discontinuity of wheel disk assembly, which will affect the dynamic characteristics of the rotor. If the connecting bolt of the disc-drum component is in the ideal uniform pre-tightening state, the transfer function of dynamic response of the structure is basically fixed in the linear conditions. When the pre-tightening force state of the bolt changes (loosening), the stiffness of the disc-drum component will be reduced to a certain extent, which will change the transfer function of the flange surface to be connected, thus leading to the change of its modal characteristics and vibration [1]. Many scholars have studied the influence of pre-tightening force changes on the dynamic characteristics of assembly components [2-8], but most of them are based on the analysis of low-order modes and low-order vibration characteristics of simple components with few bolts, which has no good guidance for the identification of pre-tightening force state of multi-bolted connection structures. According to the research of related literatures [1], for the complex structure of multi-bolt connections, the change of the pre-tightening state is not sensitive to the influence of low-order modes. With the progress of testing technology and the development of high-order modal theory, it is necessary to study the influence of pre-tightening state change (loosening) on its high-order natural frequency, and then find out a new method to identify the pre-tightening state of bolts on wheel disk assembly.

In this paper, the high-order natural frequencies of the wheel disk assembly, which is an important structure of the aero-engine rotor, are analyzed by the finite element method and the experimental method. The first 30 order natural frequencies, the sensitive mode shapes and the amplitude-frequency/phase-frequency curves of the measured points in the frequency band of 0-6400Hz under different preload conditions are obtained. Through the test and simulation analysis, the influence law of the pre-tightening state change (looseness) on its high-order natural frequency can be obtained, which can provide reference for identifying the pre-tightening state of the aero-engine rotor structure.

2 The finite element model of wheel disk assembly

2.1 The structure of wheel disk assembly

Fig. 1 shows the three-dimensional structure of the wheel disk assembly, which consists of left flange, right flange and bolt. The two connected parts are fitted with rabbet and 36 bolts are uniformly distributed in circumference to ensure good assembly quality.

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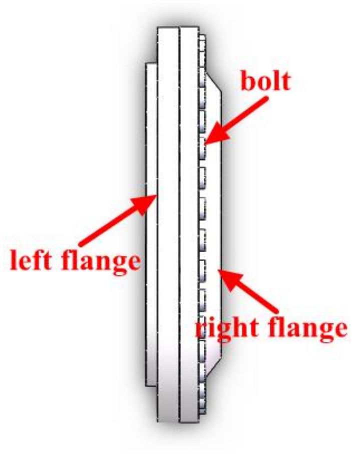

Fig. 1. Three-dimensional structure of disk assembly

2.2 Material Properties

The components of the wheel disk assembly are processed and manufactured with 45# steel. The bolts are made of high strength alloy steel, and their mechanical properties are equivalent to 45# steel. The material properties of the wheel disk assembly are shown in Table 1, including modulus of elasticity, density and Poisson's ratio.

Table 1. Material properties of the wheel disk assembly

Material	Modulus of elasticity/GPa	Density /Kg/m^3	Poisson's ratio
45#steel	201	7810	0.29

2.3 Contact Settings

The friction coefficient is defined as 0.2 by setting both the joint surface and the rabbet contact of the wheel disk assembly as friction contact. Contact pair settings in finite element software are shown in Fig. 2. The contacts between bolts and connected parts are defined as binding contact.

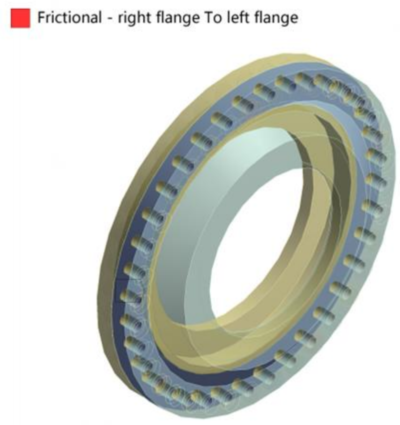

Fig. 2. Contact pair settings

2.4 Element Selection and Mesh Generation

The solid186 three-dimensional solid element in the software unit library is used in the calculation unit, which has good contact simulation ability and low calculation cost. The tetrahedral mesh generation method is adopted. The mesh quality is set to fine and the correlation degree is set to 100. The total number of meshes is 85086 and the number of nodes is 151856. The overall meshing of the wheel disk assembly is shown in Fig. 3.

Fig. 3. The meshing of wheel disk assembly

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2.5 Pre-tightening Force Model of Bolts

Check the table according to the bolt strength level 10.9 to determine the value of T, and according to the conversion formula T = 0.2Fd of tightening torque and pre-tightening force calculated that the pre-tightening force Fn of each bolt in the normal pre-tightening state is 35KN. Local coordinate system is established at the position of solid bolt, and preloading module is used for loading. It is set in two steps, the first step is to load the preload force value Fn = 35KN, and the second step is to lock it. The preload setting is shown in Fig. 4.

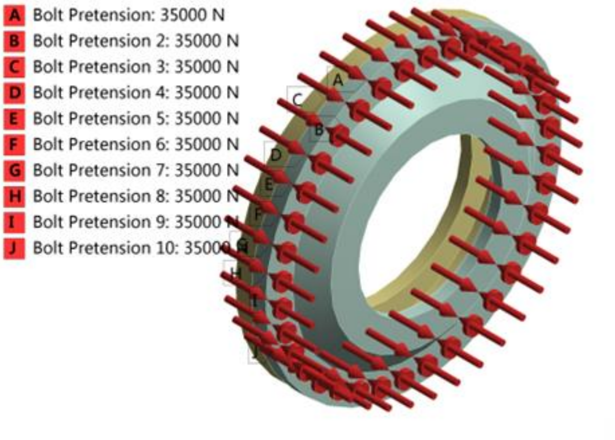

Fig. 4. Preloading settings

2.6 Boundary Conditions and Pre-tightening State Settings

The boundary condition of modal simulation of wheel disk assembly is defined as unconstrained state. Define the bolt number as shown in Fig. 5.

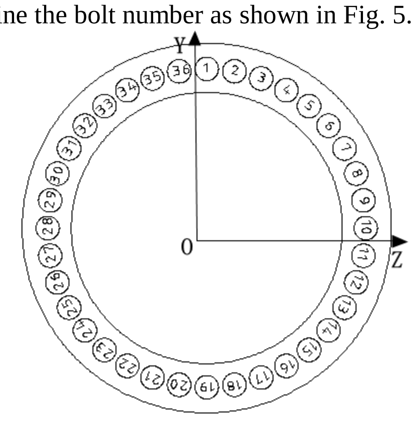

Fig. 5. The diagram of bolt number

The following two pre-tightening force states are established:

1) The bolt is in normal pre-tightening state, and the pre-tightening force Fn of each bolt is 8.3KN.

2) The 1# bolt is loosened, and the pre-tightening force Fn of the other bolts is 8.3KN.

3 Modal analysis of wheel disk assembly

Firstly, the static analysis of the wheel disk assembly under two pre-tightening conditions is carried out by using the finite element method. Then, the modal analysis with pre-stress is started based on the static results of the analysis, and the first 30 order modes of the wheel disk assembly are taken for modal truncation. List the first 30 order natural frequencies as shown in Table 2. Find out the sensitive order of natural frequencies and list the corresponding mode shapes, as shown in Figure 6. From the results of modal analysis, it can be seen that the change of pre-tightening force state (loosening) has no obvious effect on the low-order natural frequencies and mode shapes of the wheel disk assembly. The reason may be that when a bolt loosens, the local stiffness tends to decrease, but it has little effect on the overall stiffness of the wheel disk assembly, while the low-order mode is mainly the overall vibration, so the low-order natural frequencies and mode shapes are insensitive to the change of the preload state. In the high frequency band above 4000 Hz, there are some orders of natural frequency changes that are sensitive. For example, when the pretension state changes (loosening a bolt), the 13th order natural frequency is reduced by 14.6Hz, and the rate of change is 0.3%.

Table 2. The natural frequencies of the first 30 orders of the wheel disk assembly (unit: Hz)

order	The frequencies of fully-tightened	The frequencies of 1# bolt loosening	change
1	1515.2	1514.6	0.6
2	1515.5	1515.4	0.1
3	2459.3	2458.3	1
4	2459.7	2459.3	0.4
5	3747.1	3746.1	1
6	3747.6	3747.3	0.3
7	3800.3	3798.6	1.7
8	3801	3801.9	-0.9
9	3835.1	3833.4	1.7
10	3835.6	3835.2	0.4
11	4218.4	4215	3.4
12	5093.4	5085.7	7.7
13	5256.1	5241.5	14.6

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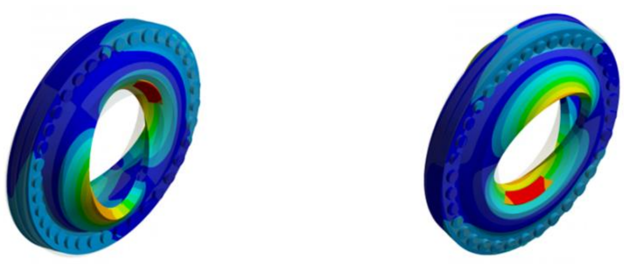
order	The frequencies of fully-tightened	The frequencies of 1# bolt loosening	change
14	5258.6	5254.5	4.1
15	5452.1	5450.6	1.5
16	5452.5	5453	-0.5
17	5920.8	5916.9	3.9
18	5922.6	5921.3	1.3
19	5963.3	5959.4	3.9
20	5963.6	5963.3	0.3
21	6402.8	6388.9	13.9
22	6408.9	6404.3	4.6
23	6883.6	6883.4	0.2
24	7971.8	7966.9	4.9
25	7973	7971.1	1.9
26	7991.6	7989.3	2.3
27	7992.1	7992.6	-0.5
28	8293.3	8281	12.3
29	8300.4	8295.7	4.7
30	8624.8	8624.8	0

Further study the mode shapes corresponding to the natural frequencies of these sensitive orders, as shown in Fig. 6. It can be seen from the figure that when the pretension state caused by the loosening of 1 # bolt changes, the mode shapes of some sensitive orders have obvious changes. The main manifestation is that the mode shapes slip along the circumferential direction at a certain angle.

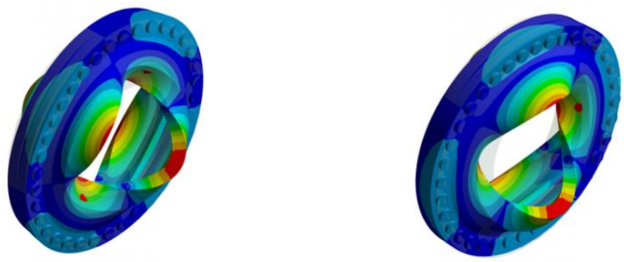
Ideal pre-tightening state　　1# bolt loosening

(a) 12th order



Ideal pre-tightening state 1# bolt loosening

(b) 13th order



Ideal pre-tightening state 1# bolt loosening

(c) 21th order

Fig. 6. Contrast nephogram of sensitive order modes of the wheel disk assembly in two pre-tightening states

4 Test analysis

4.1 Test Method

Three hammering points are set on the wheel disk assembly, and the direction of hammering is X, Y and Z, respectively. Four sensors, one light accelerometer and three ordinary accelerometers with magnetic base, are arranged. The hammering position and the installation position of the sensor are shown in Fig. 7. The measuring point 1 is a light acceleration sensor, and the measuring point 2, 3 and 4 are ordinary acceleration sensors with magnetic seat.

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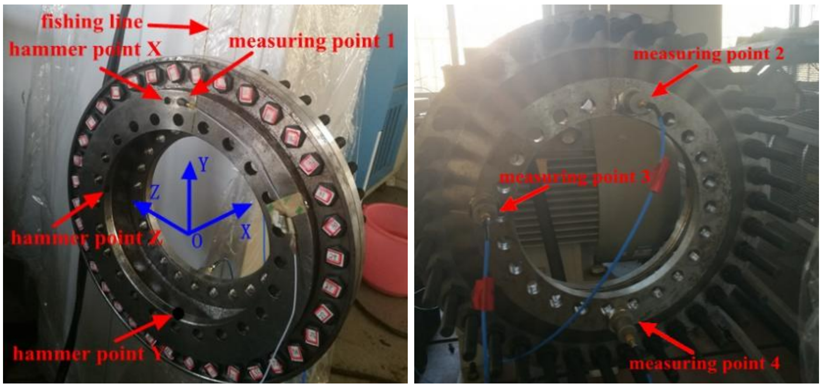
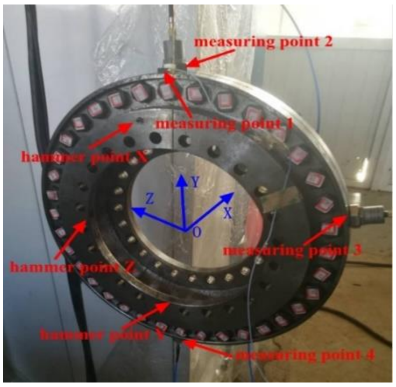


(a) Vibration pickup in X direction



(b) Vibration pickup in Y and Z directions

Fig. 7. The photos of excitation points and sensor arrangements

Two preload states are defined:

State 1: Torque wrench is used to apply 70N.m torque to 36 circumferentially uniformly distributed M10 connection bolts on two mounting edges, which is called full tightening for short.

State 2: On the basis of State 1, a moment wrench is used to loosen the 1# bolt at the installation side near the end of the short shaft disc, which is abbreviated as 1# bolt loosening.

The hammering test is carried out by using LMS test software. Sampling frequency is defined as 12800 Hz, corresponding sensors and hammer point are arranged, simple signal debugging is conducted, vibration tests are carried out on the two pre-tightened states of specimen respectively, and the vibration characteristic curves in X, Y and Z directions of the measured points are obtained. Each excitation point is hammered 3 times for averaging, and the software can directly obtain the amplitude-frequency curve and phase-frequency curve of the measuring points. The test site is shown in Fig. 8.

(a) fully-tightened (b) 1# bolt loosening

(c) Testing system

Fig. 8. The photos of test site

4.2 Test results

The influence of bolt loosening on the vibration characteristics of wheel disc test pieces is studied by X-direction excitation, axial acceleration vibration response picked up by measuring point 3 and Y-direction excitation, bending acceleration vibration response picked up by measuring point 2 and 4.

4.2.1 Analysis of the influence of pre-tension state change (loosening) on the axial vibration characteristics of disk assembly

The amplitude-frequency/phase-frequency curves of acceleration under two pre-tightening force states obtained by X-direction excitation measuring point 3 are shown in Fig. 9. From the amplitude-frequency curve of point 3, it can be seen that when the pre-tightening force state changes, there is no obvious change in the 0-5000Hz frequency band, whether linear or log amplitude-frequency curve; but in the 5000-6400Hz frequency band, the amplitude-frequency curve has obvious change, and with the pre-tightening force state changes, the offset of frequency response curve is obvious. That is to say, in low frequency band, the change of pretension state does not affect the

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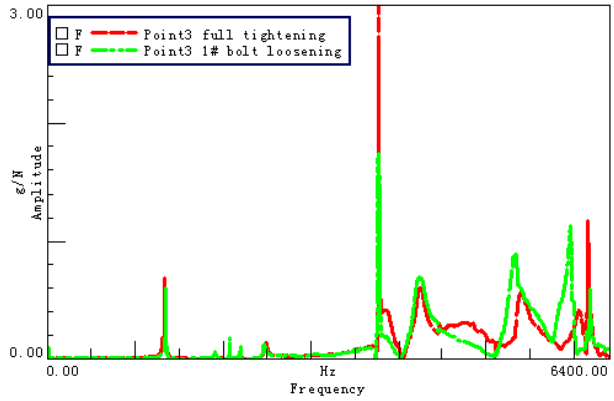
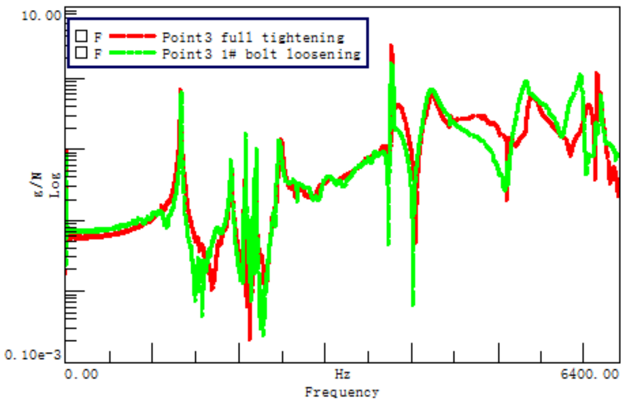
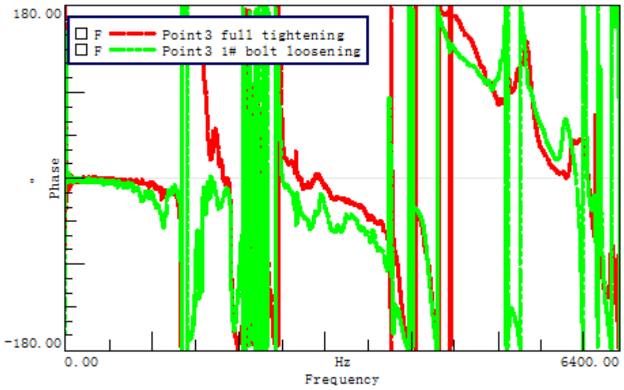
axial dynamic stiffness of the wheel disk assembly, but in high frequency band, when the pretension state changes, the axial dynamic stiffness of the wheel disk assembly will be reduced to a certain extent. From the phase-frequency curve of point 3, it can be seen that the phase of point 3 varies sensitively in some frequency bands in the frequency band of 0-6400Hz.



(a) The curve of linear amplitude frequency



(b) The curve of log amplitude frequency



(c) The curve of phase frequency

Fig. 9. Amplitude-frequency/phase-frequency curves of axial vibration at X-direction excitation measuring point 3 under two pre-tightening conditions

4.2.2 Analysis of influence of pre-tightening force state change (loosening) on flexural vibration characteristics of disk assembly

Amplitude-frequency/phase-frequency curves of acceleration under two pre-tightening conditions obtained by Y-direction excitation and vibration pickup at measuring point 2 and 4 are shown in Fig. 10 and Fig. 11, respectively. From the amplitude-frequency curves of points 2 and 4, it can be seen that when the pre-tightening force state changes, there is no obvious change in both linear and log amplitude-frequency curves in the frequency band of 0-3000Hz, but in the frequency band of 3000-6400Hz, the amplitude-frequency curves have obvious changes. The main manifestations are as follows: due to the change of pre-tightening force state (loosening one bolt), the vibration acceleration response of measuring point 2 and 4 increases obviously in the middle and high frequency band above 3000Hz, especially in the frequency band above 5000Hz, the increasing trend of vibration acceleration response of measuring point 4 is more intense. That is to say, in the low frequency band, the change of pretension state does not affect the bending dynamic stiffness of the wheel disk assembly, but in the high frequency band, when the pretension state changes, the bending dynamic stiffness of the wheel disk assembly will be reduced to a certain extent. It can be seen from the figure that the phase-frequency curves of bending vibration at measuring points 2 and 4 change obviously in the whole frequency band due to the loosening of a bolt.

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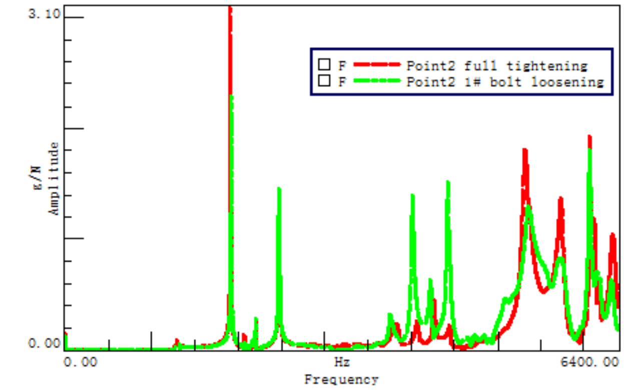
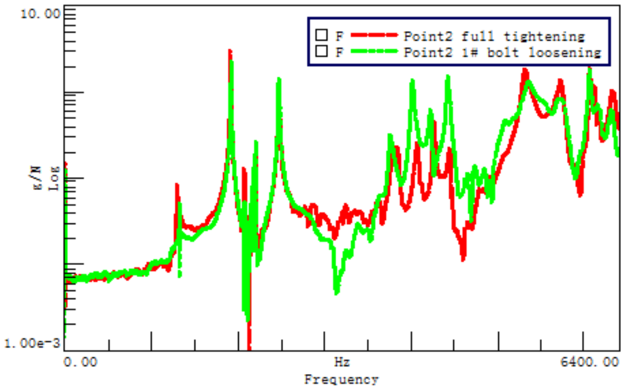
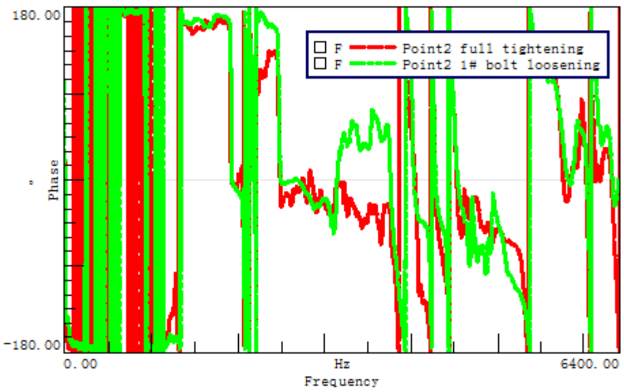


(a) The curve of linear amplitude frequency

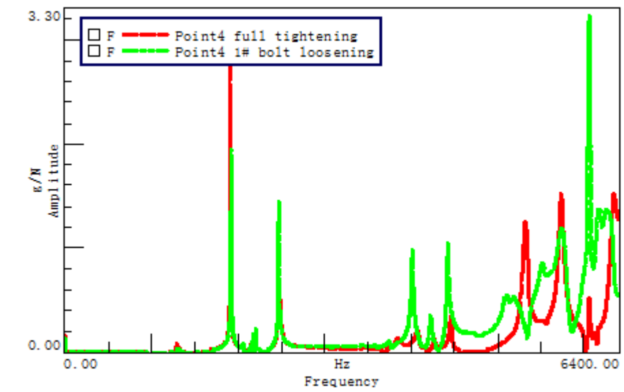


(b) The curve of log amplitude frequency

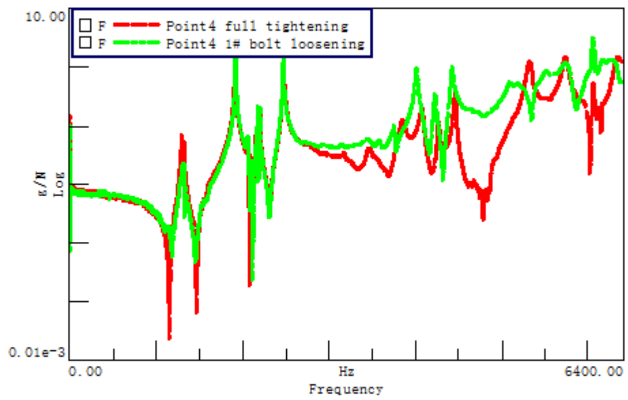


(c) The curve of phase frequency

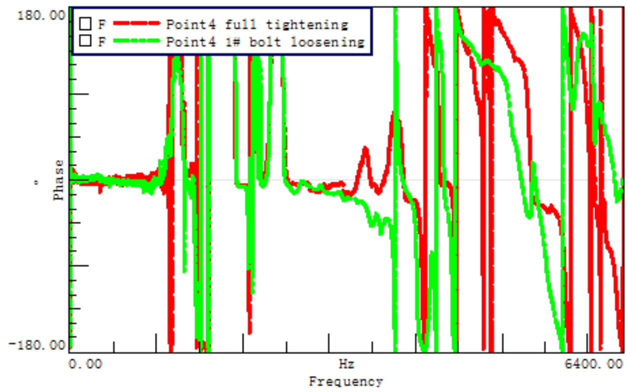
Fig. 10. Amplitude-frequency/phase-frequency curves of bending vibration at Y-direction excitation measuring point 2 under two pre-tightening conditions



(a) The curve of linear amplitude frequency



(b) The curve of log amplitude frequency



(c) The curve of phase frequency

Fig. 11. Amplitude-frequency/phase-frequency curves of bending vibration at Y-direction excitation measuring point 4 under two pre-tightening conditions

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5 Conclusion

Based on the results obtained from the above simulation and experimental analysis, the following conclusions can be drawn:

(1) Compared with the ideal pre-tightening state, when there is a bolt loosening at the installation side leading to the change of pre-tightening force state, the low-order natural frequencies and mode shapes of the wheel disk assembly basically remain unchanged, but some high-order natural frequencies and mode shapes change slightly.

(2) From the amplitude-frequency curves of the measured points obtained from the experiment, it can be seen that in the frequency range of 0-3000Hz, when there is a bolt loosening at the installation side leading to the change of pre-tightening force state, the measured point's axial and bending acceleration amplitude-frequency curve has no obvious change; but in the frequency band of 3000-6400Hz, the change of pre-tightening force state caused by a bolt loosening has certain influence on the vibration amplitude-frequency characteristics. Especially in the frequency band above 5000Hz, with the change of pre-tightening force state, the frequency response curve of axial acceleration shifts obviously, and the peak response of bending acceleration frequency response curve increases. That is to say, when the preload state changes, the axial and bending dynamic stiffness of the wheel disk assembly will be reduced to a certain extent in the high frequency band.

(3) The change of pre-tightening force state is sensitive to the phase-frequency curve of the vibration of the wheel disk assembly.

Therefore, the pre-tightening force state of the installation side can be identified by comparing the changes of higher natural frequencies and higher frequency response curves. In addition, the vibration phase can be used as a detection index to identify the change of pre-tightening force state.

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