The Dynamic Performance Study of Six-Dimensional Dynamic Force Generator

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Abstract: A six-dimensional dynamic force generating device is developed based on the dynamic performance calibration requirement of a six-dimensional force test platform based on the exciter force generating unit. The finite element software is used to perform modal analysis on the dynamic force generating device to obtain the natural frequency response of the device. Based on the finite element analysis results, the second-order transfer function at the sixth-order natural frequency point of the device is obtained, and the amplitude-phase frequency characteristic curve is obtained. Combined with the characteristic parameters of the exciter, the relationship curve between the excitation frequency and the excitation force under the influence of the natural frequency of the device is obtained. The comprehensive of finite element method and calculation results show that the designed dynamic force generating device can meet the requirements of use. According to the analysis results, it is found that the excitation capability can be maintained at a low frequency state to achieve high amplitude fixed frequency excitation, and low amplitude fixed frequency excitation is realized at a high frequency state.

1. Introduction

With the rapid development of high-precision test instruments, the methods of static force measurement have become more and more perfect, and the measurement accuracy is also constantly improving. For dynamic forces, dynamic force measurement is different from static, and is often used in a "Static calibration to measure dynamic forces" approach. When dynamically calibrating a force sensor, the important thing to address is how to get the standard dynamic force required for dynamic calibration. Dynamic force generating devices are primarily used to generate standard dynamic forces for dynamic calibration of test devices [1]. According to the standard dynamic force generating device output force signal form, the standard force generating devices commonly used at home and abroad can be divided into steady-state sinusoidal excitation type force source.

The research of the German PTB National Laboratory is mainly based on the steady-state sinusoidal[2]. Professor Y. Fujii of Japan has been involved in the above three research directions, while domestic research is mostly stepped. The PTB National Laboratory of Germany[3] has developed a dynamic calibration device for the PTB steady-state sinusoidal force sensor. It is a typical steady-state sinusoidal excitation force source with an exciter as the actuator. By changing the frequency and load quality of the sinusoidal signal, the dynamic force output of the variable force value
and frequency can be realized. Japan's Yusaku Fujii [4] uses a hammer to strike a mass connected to the spring to generate a sinusoidal force source for the force sensor to be calibrated. Wang Hongyan et al. [5] developed a trapezoidal pulse force generating device based on a proportional electromagnet. By inputting a certain excitation signal to a proportional electromagnet, the dynamic force required for calibration can be obtained. Wang Weijun [6] proposed a shock wave step force generating device. By connecting the air source to the outside, the air pressure difference from the high pressure section to the low pressure section forms a very ideal pressure step before and after the shock wave, acting on the force sensor installed at the end of the low pressure section, so that the force sensor is subjected to the positive step force. Wang Qingming et al. [7] designed and manufactured the drop hammer-pre-stressed rod type minus step force signal generating device, which uses the drop hammer impact load method to generate minus step force. Japan's Yusaku Fujii [8] produced a positive step force source that shears the wire which hangs heavy objects.

In summary, from the dynamic calibration source generation form and the dynamic calibration requirements of a six-dimensional force test platform, a six-dimensional dynamic force generation device based on the exciter is designed.

2. Overall structure of six-dimensional dynamic force generating device
The electric exciter is connected to a specific signal generator, in addition to generating a fixed amplitude sinusoidal force with adjustable frequency, it can also generate various complex dynamic force signals related to time. The generation of dynamic force is different from pulsation mechanism, and the electromagnetic induction force can be realized under the condition of no displacement. Therefore, the experimental device uses an exciter as an excitation unit, and the structural design can apply the excitation force to the excited object, so that the excited object obtains a certain amount and magnitude of vibration, so vibration and strength testing of the objects can be done. It also can calibrate vibration test instruments and sensors. The overall structure of the designed six-dimensional force generating device is shown in Figure 1.

3. Modal analysis
The essence of modal analysis is to solve eigenvectors (mode shapes) and eigenvalues (frequencies) of motion equations with finite degrees of freedom and without external loads and dampers, so as to avoid resonance caused by equal external excitation frequencies and natural frequencies of the system itself. As shown in Figure 2, after the constraint is added to the bottom end of the experimental device, the first 6 natural frequencies and natural modes of the device itself are calculated by finite element analysis. Since the 6th-order natural mode has the greatest influence on the experiment, it is important
to consider the 6th-order natural frequency affecting the Z direction of 126.9 Hz.

4. Dynamic performance study

4.1. Analysis of amplitude and phase frequency characteristics

The dynamic force generator device accords with the typical 2-order mechanical system, the differential equation of motion for a single degree of freedom damping system is as follows:

\[ m\ddot{x} + c\dot{x} + kx = F \]  

Therefore, based on the results of finite element analysis, the 2-order system transfer function at the 6-order natural frequency point of the experimental device is established:

\[ G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \]  

Among, \( m \) is quality, \( c \) is damping, \( k \) is stiffness, \( F \) is an incentive, \( x \) is the displacement response. Undamped natural frequency \( \omega_n = \sqrt{k/m} \), Damping ratio is \( \zeta = c/2\sqrt{km} \). Natural frequency is \( \omega_n = \sqrt{1-\zeta^2}\omega_n \). According to the MATLAB program, the Bode diagram of the experimental device can be fitted, as shown in Figure 3.

According to the amplitude-phase frequency characteristic curve, it can be seen that the device is prone to Z-direction resonance at the sixth-order natural frequency. The upper beam of the dynamic force generating device is a monolithic structure, and the upper beam stiffness \( K \) is further analyzed according to the finite element is 9.43×10^6 N/m.

\[ F = Kx \]
\[ L(\omega) = 20 \log \left( \frac{A_1}{A_2} \right) \]  

(4)

Among \( F \) is the external force source, \( K \) is the upper beam stiffness, \( x \) is the displacement, \( A_1 \) is the effective displacement, \( A_2 \) is the displacement under different force values, \( A_1 \) is also the \( x \) in (3). The effective displacement of the upper beam is specified to be 0.2mm. When the external force source force value is between 10N and 500N, the frequency is in the range of 5Hz to 200Hz. The effective frequency band is calculated according to formula (2.3) and formula (2.4), as shown in Figure 4.

According to the relationship between the force value and the frequency, a preliminary conclusion can be drawn. When the external force is less than 370N, the excitation experiment can be performed in the full frequency band (0Hz to 200Hz). When the force value is more than 370N, in order not to damage the experimental device, the excitation experiment should be performed in the safe frequency band. Based on this, it can provide some theoretical basis for the experimental operators, and also play a certain protective role on the experimental equipment.

### 4.2. Analysis of excitation capacity characteristics

The six-dimensional dynamic force generating device uses an exciter as a force source for dynamic calibration experiments. According to the external force source requirements set forth above, it can be seen that the dynamic force excitation frequency band is wide and the force value range is wide too. Therefore, in order to be more suitable for dynamic calibration experiments, the excitation force source will be analyzed for the excitation capability characteristics. It is generally believed that the excitation capacity increases simultaneously with the increase of the excitation amplitude at the same excitation frequency. In addition, in dynamic calibration experiments, it is also important to determine the relationship between excitation force and frequency.

![Excitation amplitude at 5 Hz](image)

It can be seen from Figure 5 that, under the same frequency, the excitation capacity increases with the increase of the excitation amplitude. Based on this, the theoretical basis for the dynamic experiment of the excitation force can be provided. Next, 5Hz, 50Hz and 100Hz are selected for the excitation test, and the experimental data shown in Fig. 6 is obtained by multiple experiments.
Figure 6 Excitation amplitude at different frequencies

It can be seen from Figure 6 that the relationship between the excitation frequency and the excitation amplitude is obvious. When the excitation frequency is low, the excitation amplitude is high, and when the excitation frequency is high, the excitation amplitude is correspondingly low. According to the above analysis, it can be concluded that the overall characteristics of the exciter's excitation capability is that high-amplitude fixed-frequency excitation force value can be achieved in the low-frequency input state, while low-amplitude fixed-frequency excitation force value can only be realized in the high-frequency input state. Therefore, in the background of wide excitation frequency and wide range of force values, dynamic calibration experiments can be carried out with reference to the characteristics of excitation capability.

5. Conclusion
In this paper, the six-dimensional dynamic force generating device is modeled by Pro/E software, and the modal analysis of the six-dimensional dynamic force generating device is solved by ANSYS Workbench finite element software, and the modal shape of the six-dimensional dynamic force generating device is obtained. From the analysis of the amplitude-phase frequency characteristic curve, it is concluded that the excitation experiment should be performed in the safe frequency band to prevent the device from generating resonance. In addition, according to the analysis of the excitation capacity, it is found that the overall characteristic is that high-amplitude fixed-frequency excitation can be realized in the low-frequency state, and low-amplitude fixed-frequency excitation can only be realized in the high-frequency state. In summary, the initially concluded is that the dynamic force experimental device can generate six-dimensional dynamic force and meet the test requirements.

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