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# INVESTIGATION OF DYNAMIC CHARACTERISTICS OF CALIBRATION DEVICE FOR FATIGUE TESTING MACHINES

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**Abstract:** Fatigue testing machines are widely applied in industry. For satisfying the increasing demands for dynamic force calibration of fatigue testing machines, a series of researches and experiments on dynamic force standards and methods have been carried out by NIM. A set of calibration device, which is composed of strain-gauge force transducers/ calibration bars and a data acquisition & signal conditioning device, was developed for dynamic force calibration of fatigue testing machines. The typical dynamic force standards and methods, which were used for evaluating dynamic characteristics of the calibration device, are introduced. The experiment results are analyzed and the dynamic characteristics of the calibration device are determined. It is concluded that the calibration device has good dynamic characteristics in the low and medium frequency ranges and satisfies the dynamic force calibration requirements of fatigue testing machines.

**Keywords:** dynamic force, force transfer standard, calibration device, fatigue testing machines

## 1. INTRODUCTION

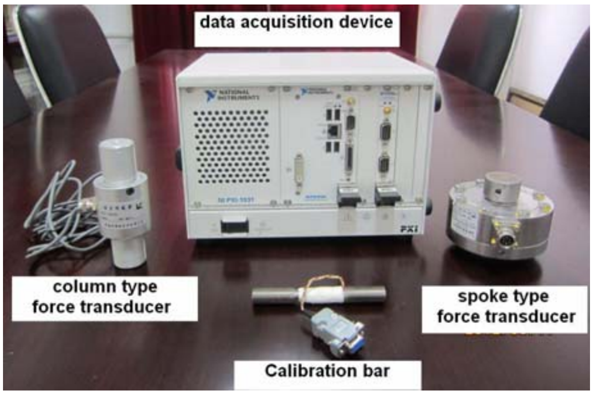
In materials science, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Fatigue will result in microscopic cracks at the surface of materials, and eventually lead to fracture of the structure. Generally, the fracture and damage suddenly occurs and leads to unpredictable accidents and disasters. In practice, mechanical characteristics of materials and components such as fatigue strength, fatigue life are tested and determined by fatigue testing machines. Therefore, fatigue testing machines are widely applied in fields of aerospace, automobile, bridge, ship, etc. and play an important role in industry.

For estimating dynamic characteristics of fatigue testing machines force transfer standard should be applied. In the past decades, due to lack of dynamic force standards in China, the dynamic characteristics of transfer standard could not be evaluated properly. As a result, transfer standard and fatigue testing machines were statically calibrated only. For satisfying the increasing demands for dynamic force calibration of fatigue testing machines, a series of researches and experiments on dynamic force standards and methods have been carried out by NIM.

Generally, the fatigue testing machines are applied under the medium force range and medium-low frequency range. Therefore strain-gauge force transducers, which have high stiffness and good dynamic characteristics under medium-low frequency range, are used as force transfer standard [1]. In previous research, dynamic characteristics of different types of force transfers were investigated [2]. As a result, spoke type (U10M type force transducers made by HBM, Germany) and column type (C3S2U type force transducers designed and made by NIM) strain gauge force transducers were applied. The former has a good linearity and symmetry of shear elastic element, can prevent from eccentric and lateral loads; the latter has compact structure, which is similar to the fatigue specimen, and can bear large force. For improving measurement accuracy, compensation techniques for zero drift and nonlinearity were used in measurement bridge circuit of force transducers. Besides, according to relative standard and regulation [3,4], strain gauged calibration bars having similar dimension and stiffness to typical fatigue specimen were designed and made in our research and experiments.

A DAQ with integrated signal conditioning for strain signal (PXI-4220 DAQ made by NI) were used as data acquisition device. The maximum sample rate of single channel is 333 kS/s. A DC amplifier is applied in the data acquisition device. Compared with AC carrier frequency amplifier, the DC amplifier has better dynamic response under medium-low frequency range. Combined with LabVIEW platform, a dynamic force acquisition and measurement system are built up.

A set of calibration device for fatigue testing machines is composed of the force transducers/ calibration bars and the data acquisition device. Figuer1 shows the photo of the calibration device. For investigating the dynamic characteristics of the calibration device, 2~3 kinds of dynamic force standards and methods with different principles were applied. The experiment results are analysed and compared.




Figuer1 The calibration device for fatigue testing machines

## 2. DYNAMIC FORCE STANDARDS AND CALIBRATION METHODS

According to the relative standard and regulation, the calibration device should be statically calibrated by force and electrical standards firstly [3,4]. The calibration results demonstrate that the static characteristics of the calibration device satisfy the requirements of fatigue testing machine calibration [1].

According to different types of output signal, there are three types of typical dynamic force standards which generate periodical force, impact force and step force respectively [5,6]. In our research, the first 2 types of dynamic force standards were applied.

Generally periodical force (sinusoidal signal) is applied in dynamic force calibration of fatigue testing machines. Therefore, the interferometric calibration facility for dynamic force measurement developed by CIMM [7], which generates sinusoidal force excitation, was used. The photo and block diagram of the facility are shown in Figure 2. The specifications of the interferometric calibration facility are as follows: frequency range: 20 Hz ~ 1000 Hz; force range: 10 N ~ 10 kN; measuring uncertainty: 2% (amplitude), 3º(phase) （$k$=2） .

The force transducer to be calibrated is mounted on the shaker and a load mass is screwed on the top of the force transducer through an adapter. According to Newton's law, the dynamic force applied on the force transducer is expressed as follows:

$$F = m_e \cdot a_e \tag{1}$$

Where $m_e$ is the total equivalent mass, $a_e$ is the equivalent acceleration of the load mass.

The total equivalent mass $m_e$ is the sum of the load mass $m_1$, the mass of adapter between force transducer and load mass $m_2$ and the equivalent end mass of force transducer $m_3$. It is calculated as follows:

$$m_e = m_1 + m_2 + m_3 \tag{2}$$

$m_1$, $m_2$ are measured by weighting, $m_3$ is estimated by solving equations.

A heterodyne laser interferometer is used to measure acceleration of different points on upper surface of the load mass. As a result, the acceleration distribution of the load

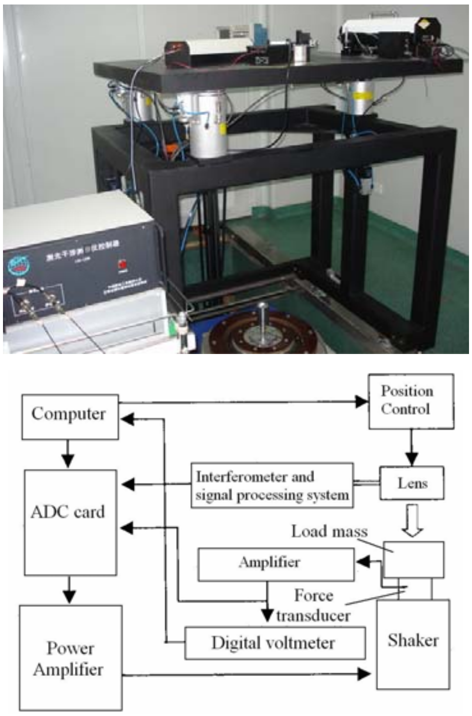



Figure 2 The interferometric calibration facility for dynamic force measurement

mass is determined. The equivalent acceleration of the load mass $a_e$ is derived from the following equation:

$$a_e = \bar{a}_0 \cdot \left( \sin \sqrt{\frac{\rho}{E} \omega_0^{\ 2}} \cdot L \right) \Big/ \left( \sqrt{\frac{\rho}{E} \omega_0^{\ 2}} \cdot L \right) \tag{3}$$

Where $\bar{a}_0$ is the average acceleration on the upper surface of the load mass; $\rho$ is the density of the load mass; $E$ is the Young's modulus of the load mass; $\omega_0$ is excitation angular frequency; L is the length of the load mass.

The output signal of the transducer and the acceleration on upper surface of the load mass are measured simultaneously. The dynamic sensitivity of the force transducer is determined as follows:

$$S = \frac{U}{F} = \frac{U}{(m_1 + m_2 + m_3) \cdot \bar{a}_0 \cdot \left( \sin \sqrt{\frac{\rho}{E} \omega_0^{\ 2}} \cdot L \right) / \left( \sqrt{\frac{\rho}{E} \omega_0^{\ 2}} \cdot L \right)} \tag{4}$$

where $U$ is the output signal of the force transducer; $F$ is the applied dynamic force calculated from equation (1) ~ (3).

Additionally, 2 sets of the fall hammer type dynamic force calibration equipments developed by NIM [8], were used for investigating dynamic characteristics of the calibration device. The first fall hammer type dynamic force calibration equipment in NIM (shown in Figure 3(a)) consists of anvil, frame, hammer, lifting and releasing mechanism, reference dynamic force transducer and standard accelerometer. The equipment adopts integer structure with a good rigidity and high frequency response. The standard accelerometer is mounted on the hammer, the force transducer to be calibrated is put on the anvil and covered by a felt pad. The impact force generated by the falling hammer is applied to the force transducer and traced to mass and acceleration. The output signals of the accelerometer and the force transducer are acquired simultaneously. The dynamic force error $\delta$ is calculated by using comparison method as follows:

$$\delta = \frac{F_{mea} - F_{ref}}{F_{ref}} \qquad (5)$$

Where $F_{mea}$ is the peak value of output signal of force transducer to be calibrated and $F_{ref}$ is the peak value of impact force generated by calibration equipment. The specifications of the equipment are as follows: force measuring range: 500 N ~ 1 MN; force rising time ≥ 0.3 ms; expanded uncertainty: 3 % ( $k$=3).

（a） (b)

Figure 3 2 sets of the fall hammer type dynamic force calibration equipments

The new fall hammer type dynamic force calibration equipment in NIM (shown in Figure 3(b)) applies a laser-Doppler- interferometer to measure acceleration. The interferometer, which is mounted on top of the equipment, acquires the signals of mechanical vibration or transient motion process of the hammer. There are two hammers with different mass for different dynamic force range. The comparison experiments were carried out using interferometer and accelerometer to measure dynamic force respectively. The consistency of the two methods is better than 1%. Its specifications are as follows: force measuring range: 500 N ~ 200 kN; force rising time ≥ 0.3 ms; expanded uncertainty: 2 %( $k$=3).

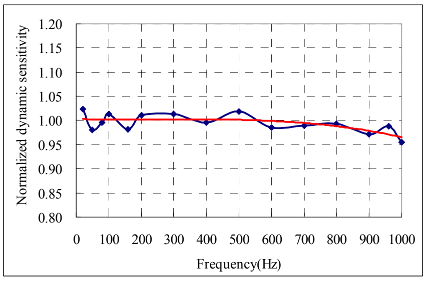
Besides, the natural frequency of the calibration device was estimated by following method[2]. The force transducer was hung up and hit by a heavy stiff hammer. As a result, a free oscillation was generated and its waveform was recorded. Frequency spectrum was analyzed and the natural frequency was determined.

## 3. EXPERIMENT RESULTS OF DYNAMC CHARACTERISTICS OF THE CALIBRATION DEVICE FOR FATIGUE TESTING MACHINES

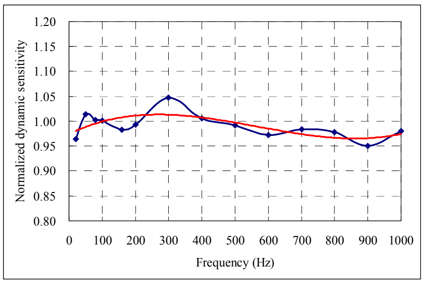
Generally, the dynamic characteristics of force standards are investigated in frequency domain or time domain. The working frequency band corresponding to specified error limit is used as a main dynamic characteristic of fatigue testing machines. Therefore, the dynamic characteristics of calibration device are expressed and determined in frequency domain.

In our experiments using the interferometric calibration facility, load mass of 7.621 kg and 2.203 kg were applied to determine the equivalent end mass of force transducer $m_3$. Corresponding to different load mass, the dynamic sensitivities of the force transducer were calculated respectively using equation (4) at identical reference frequency. The equivalent end mass of force transducer $m_3$ was calculated through solving equations (4).

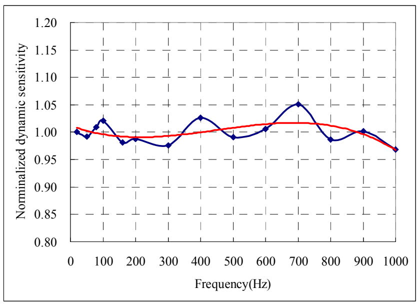
Because the capacity of our calibration device is dozens of kilonewton, the load mass of 41.511 kg was used for realizing large forces. The dynamic sensitivity of force transducer was calculated using equation (4) at different frequencies from 10 Hz to 1000 Hz. The dynamic sensitivities were normalized to its static sensitivities which were determined by force standard machines. The normalized dynamic sensitivities (presented by the trend line) were derived from discrete measuring points and shown in Figure 4. The large dynamic force errors at few frequencies were caused by the lateral movement of the system. The results demonstrate that the normalized dynamic sensitivities of the calibration device were within ±1% in the frequency range of 500 Hz, within ±3% in the frequency range of 1000 Hz.




(a) Spoke type force transducer




(b) Column type force transducer




(c) Calibration bar

Figure 4 The normalized dynamic sensitivity of calibration device

Table 1 The experiment results in fall hammer type dynamic force calibration equipments

| Spoke type force transducer | | | Column type force transducer | | | Calibration bar | | |
|---|---|---|---|---|---|---|---|---|
| Reference force (N) | Indicated force (N) | Dynamic force error (%) | Reference force (N) | Indicated force (N) | Dynamic force error (%) | Reference force (N) | Indicated force (N) | Dynamic force error (%) |
| 4945 | 4994 | 1.00% | 4444 | 4420 | -0.54% | 4830 | 4785 | -0.93% |
| 7301 | 7329 | 0.39% | 8115 | 8038 | -0.95% | 7230 | 7206 | -0.33% |
| 7703 | 7854 | 1.96% | 10840 | 10807 | -0.30% | 9685 | 9598 | -0.90% |
| 9181 | 9381 | 2.18% | 11905 | 11846 | -0.50% | 10985 | 11035 | 0.46% |
| 10861 | 10969 | 0.99% | 14825 | 14717 | -0.73% | 13000 | 13111 | 0.85% |

The calibration device was calibrated by NIM fall hammer type dynamic force calibration equipments. The hammer fell from different heights to generate impact forces with different peak values. The peak values of reference impact force and output signals of the calibration device were acquired simultaneously. The dynamic force errors are determined by equation (5), and the experiment results are shown in Table 1.

Table 2 The experiment results of the natural frequency

| Number of experiment | The natural frequency (Hz) | | |
|---|---|---|---|
| | Spoke type force transducer | Column type force transducer | calibration bar |
| 1 | 9400 | 12840 | 2980 |
| 2 | 9380 | 12840 | 3020 |
| 3 | 9340 | 12900 | 3020 |
| 4 | 9160 | 12880 | 3000 |
| 5 | 9260 | 12860 | 2980 |
| Average | 9308 | 12864 | 3000 |

In addition, the natural frequency of the calibration device was determined through frequency spectrum analysis by hitting transducer method. The experiment results are shown in Table 2.

Besides, PXI-4220 DAQ was calibrated by FLUKE 5700A precision meter calibrator, which is traced to NIM electrical standard. The calibration was carried out in accordance with BS7935-2:2004[9]. Sinusoidal voltage signals with RMS value of 14.2 mV、10.6 mV、7.07 mV、3.54 mV were used as standard signals respectively. The calibration results show that the relative errors of the RMS value indicated by PXI-4220 DAQ were within ±0.2% in the frequency range of 500 Hz, within ±0.5% in the frequency range of 1000 Hz.

## 4. CONCLUSION AND DISCUSSION

According to relative standard and verification regulation, the calibration device for dynamic force of fatigue testing machines should be comply with following requirements: the variance of the frequency response is within ±0.1 dB in working frequencies or the natural frequency is not less than 15 times of maximum working frequency of fatigue testing machines [4,10]. Generally, the working frequency of most fatigue testing machines is within 500 Hz. From the results of a series of experiments based on different dynamic force standards, the calibration device has good dynamic characteristics in the low and medium frequency ranges and satisfies the dynamic force calibration requirements of fatigue testing machines. It can be found from the experiment results that the natural frequency of strain gauged calibration bar is smaller than that of force transducer. Therefore the calibration bar is only used for calibrating fatigue testing machines with frequency below 100 Hz. In addition, force transducer with good linearity and stability is suitable to use as transfer standard.

The calibration device was applied to estimate and correct the dynamic force error for uniaxial fatigue testing machines [11]. The dynamic force error results from the so called inertial force, which bears a relation to the amplitude of motion, the frequency, the equivalent mass and stiffness of system.

Actually, some other factors in dynamic force measurement, such as the installing and fixing conditions of force transducer or the damping of the system, also have influence on the dynamic force calibration results [12]. Therefore, not only the dynamic characteristics of the calibration devices should be calibrated and analyzed, but also the relative influence factors on inertial force should be taken into account. Besides, the transfer standard and the fixture having similar mass and stiffness to typical fatigue specimen are proposed to apply.

## 5. REFERENCES


[1] Hu gang, "The research and establishment of calibration device for dynamic force calibration of fatigue testing machines", China metrology, no.10, pp. 86-88, 2011.

[2] Zhang Wei, Zhang Yue, Zhang Zhimin, "Dynamic Characteristic of Strain Gauge Force Transducer and Dynamic Force Measurement System Based on LabVIEW", Dissertation, National Institute of Metrology, Beijing, 2010.

[3] ISO 4965:1979, Axial load fatigue testing machines – Dynamic force calibration - Strain gauge technique, 1979.

[4] Chinese verification regulation, JJG556-2011, Axial load fatigue testing machines, 2011

[5] Yusaku Fujii, "Dynamic calibration methods for force transducers", in proceedings of IMEKO XVIII World

Congress and IV Brazilian Congress of Metrology，pp. 758-760, 2006.
[6] He wen, “Domestic and foreign investigation of dynamic force standards”, Journal of Mechanical & Electrical Engineering, no.2, pp. 47-49, 1999.
[7] Li Zhang, “Investigation of Interferometric Methods in Sinusoidal Force Calibration”, Acta Metrologica Sinica, Vol. 26, No.4, pp. 337-342, 2005.
[8] Meng feng, Zhang zhimin, Zhang yue and Zhang wei, “Dynamic force calibration at NIM”, in proceedings of APMF 2011, pp.116-122, 2011
[9] BS 7935-2: 2004, Constant amplitude dynamic force calibration – Part 2: calibration of the calibration device instrumentation to be used for the dynamic calibration of non-resonant uniaxial dynamic testing system—Method, 2004
[10] Chinese standard, JB/T 5488-1991, High-frequency fatigue testing machines, 1991
[11] Hu gang, Yang zong ying, “Estimation and correction of dynamic force error for uniaxial fatigue testing machines”, in proceedings of APMF 2011, pp.75-81, 2011
[12] Hessling J.P., “Dynamic calibration of uni-axial material testing machines”, Mechanical systems and signal processing 22, pp. 451-466, 2008