A 250kN Sinusoidal Force Calibration Device Based on Laser Interferometric Acceleration Measurement

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Abstract. In view of the current situation that the range of the existing sinusoidal force calibration device can not fully meet the requirements of dynamic force calibration, this paper provided an introduction on the development of a (2.5~250) kN sinusoidal force calibration device. For the purpose of expanding the calibration range and reducing the measurement uncertainty of the sinusoidal force, the device is expected to help bridge the gap in the dynamic force traceability system in China and set up the benchmark for high-precision sinusoidal force standards.

1. Introduction
Dynamic force has been widely applied in various industries such as aerospace, military science, safety protection, transportation, vehicle manufacturing, construction, bridge and material testing, etc., as well as in every aspect of daily social life. Sinusoidal force, as one of the dynamic force (consisting of pulse force, step force, sinusoidal force and random force), its typical application fields include:
- fatigue test for materials, packaged equipment and components;
- traceability of standard dynamic dynamometer;
- aircraft power feedback control;
- weapon system dynamic test;
- quality control of product production process;
- vehicle manufacturing, bridge construction, drilling platform erection and construction, seismic simulation, driving/flight instructor simulator, and many other aspects.

The accuracy of the above test results relies on and is guaranteed by the measurement and calibration of the dynamic sinusoidal force. For the time-being, domestic sinusoidal force calibration devices are not capable of achieving dynamic calibration in the amplitude range of over 10kN. As a result, the majority of the domestic force measuring systems with a range of over 10kN are stuck in the status of “dynamic application with static calibration”. [1] The inconsistency
between calibration status and application status significantly increases the uncertainty of application. In this regard, Changcheng Institute of Metrology & Measurement (CIMM) has developed a 250kN sinusoidal force calibration device. The device is capable of tracing the dynamic sinusoidal force value back to the three elementary quantities of the international system of units (SI system), namely mass, length and time, via the primary calibration method based on the standard mass block and acceleration, laying a foundation for establishment of the dynamic force measurement system.

2. Status quo of domestic and international research
See Table 1. for the overview of sinusoidal force calibration capability at home and abroad.

| Institute                | Country | Frequency range | Upper limit of amplitude value | Remarks          |
|-------------------------|---------|-----------------|--------------------------------|------------------|
| PTB                     | Germany | 10Hz~2kHz       | 400N                           | Laser interferometry |
|                         |         | 10Hz~3kHz       | 800N                           | Laser interferometry |
|                         |         | 10Hz~2kHz       | 10kN                           | Laser interferometry |
|                         |         | (0~00) Hz       | 100kN                          | Comparison method |
|                         |         | (0~200) Hz      | 20kN                           | Comparison method |
| CEM                     | Spain   | 10Hz~2kHz       | 10kN                           | Laser interferometry |
| AVIC Institute 304      | China   | 10Hz~2kHz       | 10kN                           | Laser interferometry |
| Zhejiang Institute of   | China   | 20Hz~2kHz       | 40kN                           | Accelerometer method |
| Metrology               |         |                 |                                |                   |
| Heilongjiang Huaan Metering company | China | (0~50) Hz       | 50kN                           | Accelerometer method |

In terms of small and medium-range sinusoidal force calibration, several domestic and overseas institutes including Die Physikalisch-Technische Bundesanstalt (PTB) in Germany, Centro Esptal de Metrologia (CEM) in Spain, Aviation Institute 304 and Zhejiang Institute of Metrology have all engaged in the research of sinusoidal force calibration and have built the corresponding calibration devices. The principle, structure and indicators of these calibration devices are essentially the same, which is to use electromagnetic vibrating table as the excitation source, install dynamic force transducer and standard mass block on the excitation source in turn, and support the moving ring or mass block of the vibrating table by air bearing in order to reduce the transverse movement of mass block[2]; The upper limit of force value range can reach 10kN with a frequency range of 10Hz~2000Hz. PTB's calibration device consists of three units with different ranges, where the calibration frequency of the unit with the upper amplitude limit of 800N can be extended to 3kHz. The calibration device of Zhejiang Institute of Metrology employs the electromagnetic vibrating table with rated thrust of 60kN as the excitation source, and the upper limit of its sinusoidal force amplitude can reach 40kN, [3,4].

In terms of medium and high-range sinusoidal force calibration, German PTB has carried out measurement and calibration using the comparison method of electro-hydraulic servo excitation. The comparison method-based calibration device by PTB consists of two sets of electro-hydraulic servo excitation systems with different ranges, namely 100kN (0~100Hz) and 20kN (0~200Hz).
The physical device and system composition are shown in Figure 1 and Figure 2 respectively. The two sets of devices adopt the working mode of placing up and pushing down, where the actuator is installed on the moving beam. The 100Hz device employs the double-column frame while the 200Hz device utilizes the three-column frame structure. Both devices are primarily used for calibration of the sinusoidal force based on the comparison method. In addition, PTB has attempted to use a 915kg mass block for the preliminary study of the absolute method calibration, as shown in Figure 1, left. [5]

![Figure 1. PTB's Electrohydraulic Servo Sinusoidal Force Calibration Device](image)

![Figure 2. System Composition of PTB's Electrohydraulic Servo Sinusoidal Force Calibration Device](image)

Domestically, Heilongjiang Huaan Metering company has carried out research on sinusoidal force calibration with a range of over 10kN, and established a set of sinusoidal force calibration device excited by electrohydraulic servo excitation source. The device, with a measuring range of 50kN and a frequency of 0–60Hz, is similar to the structure of PTB's device, employing a double-column frame structure with the actuator placing on and pushing down. In addition to sinusoidal wave, the device can also reproduce triangular wave, rectangular wave, etc. By working with laser interferometer or acceleration transducer, the device is capable of calibrating sinusoidal force using the absolute method or relative method. [6]

### 3. System composition of 250kN sinusoidal force calibration device

The system composition of 250kN sinusoidal force calibration device is shown in Figure 3. The excitation source is installed on a dedicated base with a transverse vibration suppression mechanism.
to reduce the adverse effect of transverse vibration on the calibration of axial sinusoidal force. Meanwhile, an air spring is installed under the dedicated base to reduce the vibration transmitted to the foundation and the periphery. Through the adapter, the standard mass block is rigidly connected with the calibrated transducer and the reference dynamic force transducer installed at the end of the actuator output rod. The moving beam is driven by the ballscrew and can move up and down along the four directional columns, thus enabling to lift and lower the standard mass block by the mass block suspension to adjust the size of the calibration testing space. The upper end of the moving beam is also equipped with a gravity compensation mechanism, which can offset the additional gravity exerted on the calibrated transducer due to installation of the standard mass block if necessary. Moving the beam enables to lock and fix the beam on the four directional columns through four locking cylinders. In the meantime, remove the standard mass block and install a special adapter plate to achieve the comparison method-based sinusoidal force calibration. The laser interferometer and two-dimensional position adjustment mechanism are placed on the vibration isolation platform. In order to reduce the impact of vibration on measurement, the excitation source and laser interference measurement system are installed on different foundations respectively, and various vibration isolation and noise reduction measures shall be taken in the meantime. The computer controls the vibration of the excitation source through the vibration controller. The laser interferometer signal is first mixed and filtered, and then input into the data acquisition system. The output signal of the force transducer is amplified and then transmitted into the data acquisition system.

![System Composition of Sinusoidal Force Calibration Device](image)

**Figure 3.** System Composition of Sinusoidal Force Calibration Device
3.1. Excitation source

The excitation source of the device adopts the servo control-based hydraulic excitation source, and mainly consists of servo valve, hydraulic source, control device and actuator. The frequency range of vibration generated by the sinusoidal force source is 1Hz ~ 250Hz, and the amplitude range of sinusoidal force is 2.5kN~250kN. The electrohydraulic servo valve serves the core of the excitation source. For the high-frequency servo valve, the flow attenuation is very noticeable. In order to meet the flow requirements at high frequency, the excitation source adopts the design method of double valves in parallel.

3.2. Test bench

The test bench of the calibration device mainly consists of actuator, standard mass block, frame, table, gravity compensation mechanism, and the adaption tooling components for comparison method calibration. The actuator is the core component of the test bench. Together with the adapter, calibrated transducer and standard mass block, it determines the mechanical frequency response of the vibration system. The actuator mainly consists of cylinder block, end cover, piston rod, hydrostatic bearing, sealing assembly, displacement transducer, etc. In order to increase the dynamic characteristics of the servo hydraulic exciter, improve the anti-overturning ability of piston rod, and reduce the friction between piston rod and end cover, the piston rod is supported by clearance hydrostatic bearing, through which the piston rod can run at high speed under high lateral load.

3.3. Control system

The electrohydraulic excitation source tends to generate considerable waveform distortion due to a combination of multiple factors such as the pressure fluctuation of the oil pump, the resonance caused by the oil compressibility, the friction between the piston and the cylinder block, the friction of hydraulic seals, the high-order harmonic caused by local vibration, the non-linearity of the servo valve, etc. When using laser absolute calibration, the transducer sensitivity calibration formula is based on the ideal sinusoidal vibration of the motion borne by the transducer, that is, the vibration of the vibrating table is the ideal sinusoidal vibration. But in reality, any vibrating table inevitably contains harmonic distortion and noise. The sensitivity calculation method must contain the systematic error caused by the method error. The size of this method error is related to the motion distortion of the working face to the excitation source. Therefore, reducing waveform distortion is one of the technical barriers in control of calibration device.

The control system of the calibration device is divided into inner loop servo control and outer loop vibration control, as shown in Figure 4. The inner loop servo control serves the foundation for the control system of the calibration device as well as for the calibration device to complete other complex control functions. It plays the role of signal acquisition, amplification, current/voltage conversion, feedback correction, etc. The outer ring vibration control on the other hand is the top-level control component of the calibration device and the core of the calibration device control system. It is used to enable the functions of calibration system model parameter identification, complex control loading, transfer function iterative control, etc.[7]. During calibration, the controller adjusts the standard sinusoidal drive signal to the DA output through adaptive control, and transmits the signal to the power amplifier and vibrating table. In practice, the waveform tends to be distorted due to various complex reasons. The device utilizes the adaptive harmonic control algorithm to detect the high-order harmonic of the acceleration signal through identification of the system structure. With the estimated nonlinear characteristics of the system and the harmonic control algorithm, the specific harmonic signal input to the system via the phase shifter is offset with the original harmonic to suppress the high-order harmonic, thus, the distortion of sinusoidal wave can be reduced below a certain range to improve the acceleration waveform.
4. Measurement

4.1. Acceleration measurement
The acceleration distribution on the surface of the mass can be measured by the laser interference measurement system. Considering the influence of uneven acceleration distribution on the sinusoidal force calibration, the average value of acceleration can be taken as the acceleration value of the top surface of the mass block by measuring the acceleration at the center of the mass block and four outer edge corners. The distribution of measuring points is shown in Figure 1, where Point 1 is the midpoint, and the other 4 points are evenly distributed on the circumference with a radius of R/2. For the standard mass block with large volume and mass, only the acceleration of 5 points is selected to describe the overall acceleration distribution of the mass block, which might be not sufficient in some cases. Therefore, if necessary, the number of measuring points shall be increased. During the actual calibration of dynamic force transducer, only the acceleration at a certain point on the top surface of the standard mass block is often measured, while that of other positions is calculated by finite element simulation or analytical method[2]. After multiplying the measured acceleration by the total vibration equivalent mass, the amplitude and phase of sinusoidal wave can be obtained by discrete Fourier transform (DFT) method or sine fitting method.
4.2. Measurement of transducer end mass

The dynamic force $F$ exerted on the force transducer is the sum of the dynamic force generated by the mass of the standard mass block, $m_1$, the mass of the connecting piece between the mass block and the transducer, $m_2$, and the end mass of the force transducer, $m_e$, i.e. $F = (m_1 + m_2 + m_e) \cdot a$. Where, the mass of the standard mass block and connecting piece is easy to measure, however, the end mass of the force transducer on the other hand is difficult to measure accurately.

The end mass of the calibrated transducer can be calculated by installing standard mass blocks with different mass and using the linear relationship.

\[
\begin{align*}
(m + M_1)a_1 &= U_1S \\
(m + M_2)a_2 &= U_2S
\end{align*}
\]

Transform the above formula to obtain:

\[
m = \frac{M_1a_2U_1 - M_2a_2U_1}{a_2U_1 - a_1U_2}
\]

where:

- $m$ - The end mass of the calibrated dynamic force transducer;
- $M_1$, $M_2$ - The mass of the standard mass block installed and connected during the 1st and 2nd calibration;
- $a_1$, $a_2$ - Acceleration during the 1st and 2nd calibration;
- $U_1$, $U_2$ - Voltage output value of dynamic force transducer during the 1st and 2nd calibration;
- $S$ - Sensitivity coefficient of dynamic force transducer.

In the actual calibration, the acceleration values of the two loads can be controlled to make them essentially consistent, for instance $a = 5g$, $M_2 = 2M_1$. Because $M_1$ and $M_2$ are loads with larger mass, the sensitivity of the dynamic force transducer under the condition of two calibration configurations is approximately the same, which is represented by $S$, [8].

The dynamic forces on the force transducer during the two calibrations are:

\[
F_1 = (M_1 + m_e) a = U_1S, \\
F_2 = (M_2 + m_e) a = U_2S
\]

According to Equations (3) and (4), the sensor end mass $m_e$ is

\[
m_e = \frac{M_1U_2 - M_2U_1}{U_1 - U_2}
\]

4.3. Testing instances

Using the above measurement methods for acceleration and mass, a U10M strain type dynamic force tester manufactured by HBM was tested. The measuring range of the tester is 500kN, the static error of force value is -0.1%, and the natural frequency is 6.1 kHz. Taking the given acceleration of 5g and the test frequency of 200Hz as an example, the amplitude of the calibration device is about 100kN. See Table 2 for the test data. The amplitude difference of sinusoidal force at other measuring points is shown in Figure 6.
Table 2. Instances of Transducer Calibration Data by Sinusoidal Absolute Method

| Force transducer | Sinusoidal force amplitude/kN | 103.91 |
|------------------|--------------------------------|--------|
|                  | Position 1                     | 49.05  |
| Sinusoidal force calibration device | Position 2                     | 49.07  |
|                  | Position 3                     | 49.03  |
|                  | Position 4                     | 48.72  |
|                  | Position 5                     | 48.79  |
|                  | Equivalent acceleration        | 48.93  |
| Reference vibration mass/kg | Standard mass block            | 2000.09|
|                  | Connecting piece               | 87.22  |
|                  | Transducer end mass            | 45.87  |
|                  | Total reference vibration mass | 2133.18|
| Test results     | Amplitude relative error/%     | -0.45  |

![Figure 6. Sinusoidal Force Amplitude Difference](image)

5. Summary
- The excitation source adopts the design mode of double servo valves in parallel for oil supply to ensure the large flow demand of the system in case of high-frequency vibration.
- The test bench employs an actuator with hydrostatic bearing support, which can improve the anti-overturning ability of the piston rod, reduce the friction between the piston rod and the end cover, and increase the dynamic characteristics of the servo hydraulic exciter.
- The control system utilizes the adaptive harmonic control algorithm. Through identification of the system structure, the high-order harmonic of the acceleration signal is detected, and the
specific harmonic signal is input to the system via the phase shifter to offset the original harmonic, thus to improve the acceleration waveform.

- The test results indicate that the accuracy of the sinusoidal force amplitude reproduced by the calibration device is better than 1.5%. Further verification is needed to compare the sinusoidal force values at home and abroad. In addition, it is necessary to carry out further study on the non-uniformity of acceleration distribution along and perpendicular to the force application axis as well as the optimization and improvement of acceleration measurement methods.

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