Comparison results between PTB and CIMM on the force transducer calibration under sinusoidal loading

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Abstract. Sinusoidal force is a typical kind of dynamic force applied widely in practice, and the sinusoidal force calibration systems are set up in Physikalisch-Technische Bundesanstalt (PTB) and Changcheng Institute of Metrology & Measurement (CIMM) respectively. To examine and compare the measurement methods for force transducer calibration, a comparison on sinusoidal force calibration is taken between PTB and CIMM. The experiment results show that the absolute value of the normalized error En between both sides is always less than 1, in the frequency range from 20Hz to 2000Hz, by using mass blocks A (nominal 1kg) and B (nominal 2kg). While the large deviation corresponding to the mass block C (nominal 4kg) at frequencies higher than 1000Hz may be contributed to some rocking effect at high frequency.

1. Introduction

Sinusoidal force measurement is one of the primary methods for the calibration of dynamic force, whereby the force is determined according to Newton’s Law, i.e. mass times acceleration. The traceability is thereby realized by the acceleration measurement based on a laser vibrometer and the mass measurement. The comparison between Physikalisch-Technische Bundesanstalt (PTB) and Changcheng Institute of Metrology & Measurement (CIMM) aims to compare the measurement of sinusoidal force in the frequency range from 20 Hz to 2000 Hz. Moreover, the measurement methods for force transducer calibration are to be examined and compared.

In the comparison, the charge sensitivity of a piezoelectric force transducer at different frequencies and force amplitudes are to be measured. The charge sensitivity is calculated as the ratio of the amplitude of the transducer output charge to the amplitude of the force acted on it. A calibrated charge amplifier is used to measure the output charge of the force transducers.

For the dynamic calibration of the force transducer, acceleration is measured by laser vibrometers in accordance with ISO 16063-11[1]. Before dynamic calibration, the force transducer is statically calibrated according to ISO 376[2]: the piezoelectric force transducer is reloaded from zero every time for different force level. And some method in the field of key comparison of vibration[3][4] is adopted in the comparison.

2. Conditions of the comparison experiments

The temperature is 23°C ±2°C (actual values should be stated within tolerances of ±0.3°C). Relative humidity is below 75%. The vibration frequency of sinusoidal forces is from 20 Hz to 2000 Hz, and the peak value of the achieved force is from 25 N to 1000 N.

3. Methodologies of measurement
According to Newton’s law, the dynamic force acting on the force transducer is traceable to mass and acceleration by \( F(t) = ma(t) \), where \( m \) is the total mass acting on the sensing element of the force transducer and \( a(t) \) is the time-dependent acceleration of the corresponding mass.

The calibration system setup from PTB and Cimm are shown in Fig. 1, which are set up according to the same principle. The sinusoidal excitation was realized by a shaker which can be used with force peak up to 10 kN and frequencies of 10 Hz to 2 kHz. The force transducer to be calibrated is mounted on an electro-dynamic shaker, and a mass block is screwed on the top of the force transducer. The displacements are applied at the bottom of the force transducer, with sinusoidal acceleration feedback control. Laser vibrometers are used for acceleration measurement and they are mounted on an active controlled vibration isolator. In PTB, the beam of the laser vibrometer is guided via a 45° mirror down to the surface of the loading mass, mounted on top of the force transducer. The active damping table is mounted directly below the vibrometer. The big advantage in using a scanning vibrometer is the more detailed measurement of the acceleration. The acceleration distribution measured on top of a loading mass is not always a uniform distribution. Due to rocking modes of the top mass which might originate from the kind of coupling to the force transducer or the shaker, the acceleration can vary over the surface. In this comparison, five points were chosen uniformly on the top of mass blocks, to measure the acceleration.

To improve the calibration accuracy of dynamic force, attention must be paid to several factors: (a) Determining spatial-dependent acceleration on mass block; (b) Measuring the end mass of the force transducer; (c) Generating good excitation. Detail studies can be found in [7-9].

![Fig. 1. Setup of dynamic force calibration system in PTB (a) and in Cimm (b).](image)

### 4. Results of measurement

#### 4.1 Results from PTB.

The calibrated sensitivity curve obtained from PTB is shown in Fig. 3 (a), and the corresponding uncertainty at different frequency is indicated with error bar.

![Fig. 2. The sensitivity curves of 9331B obtained from PTB (a) and Cimm (b).](image)

![Fig. 3. The normalized error En between PTB and Cimm](image)

#### 4.2 Results from Cimm.

The calibrated sensitivity curve obtained from Cimm is shown in Fig. 2 (b), and the corresponding uncertainty at different frequency is indicated with error bar.
In this comparison, the acceleration of the mass blocks is measured with the laser vibrometers at five separate points (one point is at the center, and four points is uniform distributed around the center point with 90 degree interval between each other, at the distance from the center point about half the radius of the mass block) on the top of a mass block. The average acceleration over the five points is taken account to decide the acceleration on the mass block top.

4.3 Comparison results from PTB and CILMM. The normalized error En is shown in Fig. 3, for the mass blocks A(nominal 1kg) and B(nominal 2kg) used, the absolute value of the normalized error En is always less than 1, while the absolute value of the normalized error En for the mass block C(nominal 4kg) is larger the 1 at frequencies higher the 1000Hz. Therefore, the comparison is satisfied except for the results of the mass block C at high frequency. The large deviation corresponding to the mass block C may be contributed to some rocking effect at high frequency.

5. The uncertainty

5.1 The principle of measurement. The force acting on the force transducer is equal to the sum of the inertia forces of the mass block, the connector and the end mass of the transducer:

\[ F = (m_1 + m_2 + m_e) \cdot \ddot{a}_0 \cdot k_0 \]  

(1)

Where \( m_1 \) is the mass value of the mass block; \( m_2 \) is the mass value of the connector; \( m_e \) is the mass value of the transducer end mass; \( \ddot{a}_0 \) is the average acceleration on the top of the mass block (m/s²); \( k_0 \) is the modifying factor of the acceleration.

5.2 The relative expanded uncertainty \( U_{rel}(S) \) of the sensitivity measurement. The sensitivity of the force transducer is:

\[ S = U / F = U / ((m_1 + m_2 + m_e) \cdot \ddot{a}_0 \cdot k_0) \]

(2)

where: \( U \) — the output voltage of the force transducer.

\[ u_{rel}^2(S) = (c_1^2 u^2(m_1) + (c_1^2 u^2(m_2)) + (c_1^2 u^2(m_3)) + (c_1^2 u^2(a)) + (c_1^2 u^2(U)) + u_1^2(\ddot{S})) \]

(3)

where: \( u_{rel}^2(S) \) — the A-type uncertainty of the sensitivity measurement.

\[ u_{rel}^2(S) = \left( \frac{u_r(S)}{S} \right)^2 = u_{1,rel}^2 + u_{2,rel}^2 + u_{3,rel}^2 + u_{4,rel}^2 + u_{5,rel}^2 + u_{6,rel}^2 + u_{A,rel}^2(\ddot{S}) \]

(4)

Where:

\[ u_{1,rel} = \frac{\partial S}{\partial m_1} \frac{u(m_1)}{S} = \frac{-u(m_1)}{m_1 + m_2 + m_e}, \quad u_{2,rel} = \frac{\partial S}{\partial m_2} \frac{u(m_2)}{S} = \frac{-u(m_2)}{m_1 + m_2 + m_e}, \]

\[ u_{3,rel} = \frac{\partial S}{\partial m_e} \frac{u(m_e)}{S} = \frac{-u(m_e)}{m_1 + m_2 + m_e}, \quad u_{4,rel} = \frac{\partial S}{\partial a} \frac{u(a)}{S} = \frac{-u(\ddot{a})}{\ddot{a}_0}, \]

\[ u_{5,rel} = \frac{\partial S}{\partial k_0} \frac{u(k_0)}{S} = \frac{-u(k_0)}{k_0}, \quad u_{6,rel} = \frac{\partial S}{\partial U} \frac{u(U)}{S} = \frac{u(U)}{U}, \quad u_{A,rel}(\ddot{S}) = \frac{u_A(\ddot{S})}{S} \]

The corresponding uncertainty components are: \( u_{1,rel} = 2.8 \times 10^{-6} \), \( u_{2,rel} = 8.4 \times 10^{-3} \), \( u_{3,rel} = 0.1 \% \), \( u_{5,rel} = 0.3 \% \), \( u_{6,rel} = 0.05 \% \) respectively, and the uncertainty component of the repeatability corresponding to 10 times of metering, is:

\[ u_{A,rel}(\ddot{S}) = 2\% \sqrt{10} = 0.63\% \]

(5)

Therefore, the combined standard uncertainty is:

\[ u_{c,rel}(S) = \sqrt{u_{1,rel}^2 + u_{2,rel}^2 + u_{3,rel}^2 + u_{4,rel}^2 + u_{5,rel}^2 + u_{6,rel}^2 + (0.63\%)^2} = 0.71\% \]

(6)

and the expanded uncertainty is:

\[ U_{rel} = 0.71\% \times 2 = 1.42\% \]

(7)
6. Analysis of measurement

The frequency dependent sensitivity of the same force transducer (Kistler 9331B) is obtained on the sinusoidal force calibration systems from PTB and CIMM respectively, by using the same amplifier (Kistler 5015) and the same set of mass blocks. The comparisons between PTB and CIMM show a good agreement at frequencies from 20Hz up to 2000Hz for the mass blocks A (nominal 1kg) and B (nominal 2kg). While the large deviation corresponding to the mass block C (nominal 4kg) at frequencies higher than 1000Hz may be contributed to some rocking effect at high frequency.

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