Primary High Acceleration Calibration System at NIM

C Cai, Z Liu and Y Xia
National Institute of Metrology, No.18, Bei San Huan Dong Lu, Beijing, China

E-mail: caichenguang@nim.ac.cn

Abstract. Currently the maximum acceleration range of primary vibration calibration cannot meet the requirement of secondary vibration calibration and vibration testing field. In some special vibration test field, the accelerometers are required to be calibrated up to 4900 m/s$^2$ or more, but the maximum acceleration of primary vibration calibration capability is normally 100 m/s$^2$. In order to meet the high acceleration traceability requirement, a primary high acceleration calibration system has been set up in National Institute of Metrology. Two high acceleration exciters based on resonance amplification are used to produce high acceleration vibration. In order to improve the maximum acceleration of the resonator, a simple clamped-clamped beam is used, only the clamped ends are excited by a shaker to reduce the damping. The phase control method are used to track the resonant frequency. A primary vibration measuring system was set up according to ISO 16063-11. The experimental results show that the maximum acceleration of this vibration calibration system can reach more than 10000 m/s$^2$.

1. Introduction

Usually air bearing shakers are used in primary vibration calibration based on ISO 16063-11 [1]. The typical sine peak acceleration of an air bearing shaker is limited. Some high-force shakers are used in secondary vibration calibration to obtain high payload and acceleration based on ISO 16063-21 [2]. Normally the maximum acceleration of primary vibration calibration capability in middle frequency range posted on the BIPM key comparison database is 100 m/s$^2$ [3]. In practice the maximum acceleration of secondary vibration calibration can reach 800 m/s$^2$ or more [3]. Thus above 100 m/s$^2$, the secondary vibration calibration cannot be traced to primary method. Normally the amplitude linearity of the reference transducer is assumed to be good enough or checked by shock calibration.

Accelerometers are widely used in the field of vibration testing to measure the vibration of the shakers or the samples under test. Normally the maximum acceleration of an electrodynamic shaker can reach 1000 m/s$^2$, the maximum acceleration of some new electrodynamic shakers can reach 1400 m/s$^2$ or more. In some special test field, such as test of gas turbine, the accelerometers are required to be calibrated up to 5000 m/s$^2$ by vibration calibration method. So it is necessary to improve the maximum acceleration of primary vibration calibration.

At National Institute of Metrology, China, a primary high acceleration calibration system has been researched for several years, which consists of two high acceleration exciters based on resonance amplification, a resonant control system and a primary vibration measuring system. A SE-101 vibration exciter from Spektra and a clamped-clamped beam with ends excitation are used as high acceleration exciters.
Normally shakers for calibration cannot generate high acceleration more than 1000 m/s². In order to generate high acceleration, resonance amplification principle should be used. Usually a cantilever can be installed on a shaker as a resonator to amplify the vibration of the shaker. But there is rotational motion in the end of the cantilever, it is difficult to measure the rectilinear vibration of the end of the cantilever. So a clamped-clamped beam should be a good choice. There is only rectilinear motion without rotational motion at the middle of the clamped-clamped beam. For the resonator, damping is the core factor affecting the amplification effect. In order to reduce the damping of the resonator, a simple clamped-clamped beam is used as the resonator, only the clamped ends are excited by a shaker.

The resonant control system consists of two parts: phase control and amplitude control. A phase lock control method is used to track the resonant frequency. The acceleration is controlled by an amplitude control method. According to ISO 16063-11, a primary vibration measuring system is developed to measure the high acceleration produced by the resonators and resonant control system.

2. High acceleration exciters based on resonance amplification

A typical high acceleration exciter based on resonance amplification is illustrated in figure 1. A resonant beam is excited by a shaker. The resonant frequency is determined by the length between two movable clamped ends. The resonant frequency can be changed by adjusting the distance between the movable clamped ends. The base is used to fix the shaker and movable clamped ends.

![Figure 1. Schematic diagram of a resonant exciter.](image)

2.1. Resonator principle

A resonator can be described as a mechanical mass-spring-damping system (single degree of freedom underdamping system), shown in figure 2. \( m \) is the mass, \( k \) is the spring, \( c \) is the damping, \( x \) is the displacement of the resonator, and \( X \) is the displacement of excitation.

![Figure 2. Single degree of freedom underdamping system.](image)

Motion equation of the resonator is:

\[
mx + cx + kx = -m\dot{X}
\]  

The normalized frequency characteristic function of the resonator is:

\[
\frac{x(j\omega)}{X(j\omega)} = \frac{1}{m(\omega^2 + j\omega + \frac{c}{m})} = \frac{1}{(\omega^2)^2 + 2\xi\omega_0\omega + \omega_0^2}
\]
In the formula, $\xi$, the equivalent damping ratio coefficient of the resonator, $\xi = c / (2\sqrt{k/m})$, $\omega_n$ is the natural frequency of the resonator, $\omega_n = \sqrt{k/m}$. The frequency characteristic curve of a resonator is shown in figure 3. At the natural frequency of the resonator, the magnification of the resonator is $A(\omega_n) = 1/(2\xi)$, the phase shift of the resonator is $\varphi(\omega_n) = -90^\circ$. The smaller the equivalent damping ratio coefficient is, the greater the amplitude gain of the resonator.

![Amplitude frequency characteristic curve](image1)
![Phase frequency characteristic curve](image2)

**Figure 3.** The frequency characteristic curve of a resonator

### 2.2. Improvement of the resonator

According to the analysis above, reducing damping is the key to increasing magnification. A shaker is connected to the middle of the resonator illustrated in figure 1. Mechanical and electromagnetic damping of the shaker will affect the magnification of the resonator. So the direct idea is to remove the shaker from the middle of the resonant beam, only the clamped ends are excited by a shaker. The schematic diagram and the actual implement of the improved resonator is shown in figure 4. In order to cover a certain range of frequency range, several resonant beams with different materials and thickness are designed and machined.

![Schematic diagram](image3)

**Figure 4.** The schematic diagram and the actual implement of the improved resonator.

### 3. Resonant control system

The resonant control system is illustrated in figure 5. The resonant control system consists of two parts: phase control and amplitude control. Firstly a phase lock control part is used to track the resonant frequency, then the acceleration is adjusted by a amplitude control part.
4. Experimental results
An accelerometer (model: PCB 301A12) was selected to be calibrated using the primary high acceleration calibration system according to ISO 16063-11. The measure results are shown in table 1. According to figure 3, the resonator is equivalent to a good bandpass filter. Although a normal electrodynamic shaker is used to excite the resonator, the distortion and transverse motion are controlled well, the measurement uncertainties from the exciter are limited.

| Resonant frequency (Hz) | Acceleration (m/s²) | Sensitivity magnitude (mV/m/s²) | Sensitivity phase shift (°) |
|------------------------|---------------------|-------------------------------|--------------------------|
| 19.7                   | 50.0                | 0.04633                       | 0.54                     |
| 30.5                   | 139.8               | 0.04691                       | 0.01                     |
| 50.8                   | 461.2               | 0.04697                       | -0.39                    |
| 97.6                   | 1320.7              | 0.04667                       | -0.18                    |
| 625.0                  | 2930.2              | 0.04673                       | 0.19                     |
| 937.5                  | 11853.0             | 0.04671                       | 0.32                     |
| 1015.3                 | 4301.3              | 0.04675                       | 0.31                     |
| 1171.9                 | 2227.0              | 0.04647                       | 0.30                     |
| 1679.7                 | 2464.8              | 0.04649                       | 0.53                     |

5. Conclusion
A primary high acceleration calibration system has been set up in National Institute of Metrology, China, which consists of two high acceleration exciters based on resonance amplification, a resonant control system and a primary vibration measuring system. In order to reduce the damping and increase the magnification, the resonator is improved by moving the exciting position from the middle to the clamped ends of resonant beam. Although a normal electrodynamic shaker is used to excite the resonator, the distortion and transverse motion are controlled well. The experimental results show that the maximum acceleration of this calibration system can reach more than 10000 m/s².

Acknowledgments
This work has been supported by National Key R&D Program of China (2017YFF0205003) and AQSIQ science and technology project project (2015QK223).

References
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