Primary Low-g Shock Acceleration Calibration Using Laser Interferometry

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Abstract. The current situation of low g shock is introduced with three types of shock exciters described. The measuring theory and system setup using laser interferometry is explained in accordance with ISO 16063-13 with the emphasis on key technology of signal demodulation algorithm and air-bearing shock exciter based on collision. According to calibration results, the primary shock calibration system can achieve expanded uncertainty of 1%, $k=2$, in the acceleration range from 20m/s$^2$ to 10000m/s$^2$ and pulse duration from 0.5ms to 10ms.

Keywords: Metrology; Low g shock acceleration; Shock exciter based on collision; Laser interferometry

1. Introduction
The international standard ISO 16063-13$^{[1]}$, which is calibrated by the shock primary method, specifies two types of typical shock excitation systems: the first type is the shock exciter based on rigid body collision, the peak value of shock acceleration ranges from 100~5000m/s$^2$, and the pulse width is generally less than 10ms; The second type of excitation system is based on the Hopkinson bar shock exciter, and the shock acceleration range can over $10^5$m/s$^2$, and the pulse width is generally 100μs. The shock exciter based on Hopkinson bar is mainly applied to the calibration of high-g shock acceleration. It plays an important role in aerospace and other fields. In the past 20 years, a great deal of research has been carried out in the domestic metrology field$^{[2-5]}$. The shock excitation source based on the anvil shock is mainly applied to the calibration of the shock acceleration absolute method with low g value, which is of great significance in the field of vehicle safety and personnel protection$^{[6-7]}$. The typical example is the laboratory calibration of accelerometer for vehicle shock test. Taking the shock tolerance of human head as an example, the damage index is the severity of injury to the head of human body under different magnitude shock loads, so as to provide a reference for the corresponding protection measures and safety design. The Head Shock Tolerance Curve proposed by Wayne State University$^{[8-9]}$ shows that the degree of head injury is directly related to the magnitude and width of the shock acceleration. When the peak range of shock acceleration is 3000~5000m/s$^2$ and the action time is only about 1.0ms, concussion will occur and even be fatal. It can be seen that the peak value of shock acceleration is less than 5000m/s$^2$ in the low g range. How to achieve the correct shock and accurate measurement of shock acceleration is of great significance in practical application.

The calibration technology for laser absolute method of low g shock acceleration in the field of international measurement was first studied by PTB$^{[10]}$. The peak range of shock acceleration is 50~
5000m/s², the pulse width is 0.5~10ms, and the extended uncertainty is 0.5% \((k=2)\). In the Asia Pacific Metrology planning organization, National Metrology Institute of Japan (NMIJ) has actively carried out research in this field in recent years, the peak range of shock acceleration is 200~5000m/s², the pulse width is 1.0~3.0ms, and the extended uncertainty is 1.0% \((k=2)\). PTB and NMIJ have established their own national standards for low-\(g\) shock, and China is also studying the establishment of national standards for low-\(g\) shock.

2. Measurement System

2.1. Principle of measurement

The measurement principle and basic structure of the established low-\(g\) shock standard device are basically consistent with the corresponding contents of ISO 16063-13 international standard, as shown in Figure 1. The main principle is to generate shock excitation based on the mechanical collision of rigid body. The collision shock excitation device is an example of low-\(g\) shock excitation source recommended by ISO 160663-13 international standard. The shock acceleration range is generally 100~5000m/s², and the shock pulse width is about 0.5~10ms.

After the shock hammer is shocked by the projectile body of the actuator, the hammer body moves horizontally in the air bearing for a certain distance, and then shocks the anvil body with the same diameter and length in another air bearing, thus producing a half sine square shock acceleration waveform. Because the projectile does not directly shock the anvil, the lateral motion and other possible resonance components are greatly reduced by virtue of the transition effect of the shock hammer in the air bearing and the inertial motion of the anvil in the air bearing after shock, and the waveform generated is basically free of distortion or burr. The thickness of the air film is about 15μm when the air bearing is used to support and guide the shock hammer and the anvil. In the process of collision between hammer and anvil and its forward and backward motion, there is hardly any other coupling mode except the shock force and the friction force produced by air bearing. Therefore, this kind of excitation source can produce an ideal shock acceleration waveform, which is suitable for accurate calibration of laser absolute method. The laser interferometer and the calibrated accelerometer measure the shock acceleration signal simultaneously, so as to finally determine the shock peak sensitivity \((s_{sh})\) of the accelerometer, as shown in equation (1).

\[ s_{sh} = \frac{u_p}{a_p} \]  

\(u_p\) is the peak voltage of the output signal of the calibrated accelerometer, \(a_p\) is the peak value of the shock acceleration measured by the laser interferometry. In fact, the time-domain waveform of the shock acceleration produced by the shock excitation system is a half sine square acceleration waveform:

\[ a_{\text{sh}}(t) = a_{\text{sh,max}} \sin \left( \frac{\pi t}{T_{\text{sh}}} \right), 0 \leq t \leq T_{\text{sh}} \]  

Figure 1. System block diagram of low-\(g\) shock standard device
$T_{\text{sin}}$ is the duration of shock pulse width, and $a_{\text{sin,max}}$ is the peak value of shock acceleration. The expression of the corresponding shock velocity waveform can be obtained by integrating the formula (2) as follows:

$$v_{\text{sin}}(t) = a_{\text{sin,max}} \left[ \frac{t}{2} - \frac{T_{\text{sin}}}{4\pi} \sin \left( \frac{2\pi t}{T_{\text{sin}}} \right) \right]$$

(3)

Typical ideal shock acceleration waveform and velocity waveform are shown in Figure 2.

Figure 2. Acceleration and velocity waveforms generated by collision excitation system

2.2. Shock excitation device

As the energy supply part of the whole system, the energy directly determines the peak value and pulse width of the acceleration wave. The shock acceleration range is generally 20–10000m/s$^2$, and the pulse width is about 0.5–10ms. The exciter adopts two types of power, the electromagnetic exciter and the air exciter. The advantages of electromagnetic exciter are good controllability and repeatability. According to the test result, the repeatability of the shock velocity produced by the electromagnetic exciter is better than 1%. Due to the limited voltage of the electromagnetic exciter, the shock energy provided by the electromagnetic exciter is limited, which leads to the limited range of the peak value of the acceleration. The air exciter can make up for this deficiency. The energy of compressed air is higher, and when the air pressure rise, it can provide more energy. Air exciter can meet the requirements of producing higher peak acceleration.

In order to produce an ideal shock acceleration wave, we need to ensure that the hammer collide anvil freely, and the relative deviation of their center lines should be less than ±0.2mm. In order to avoid the adverse influence of other mechanical structures on the moving part (such as mechanical resonance and other interference motion), the high-precision air bearing is used to support the hammer and anvil, which can not only reduce the friction, but also isolate from other parts, and ensure that the anvil is subjected to symmetrical force, so as to prevent rotation or non-axial movement.

The hammer and anvil are installed in the air bearing. The air bearings are installed in the sleeve. In order to ensure the air can intake of the air bearing, the air inlet and outlet are designed at the inner of the sleeve.

The machining of hammer and anvil, the matching degree with air bearing and the precision of installation are directly related to the acceleration waveform results. The diameter of hammer and anvil are both 30mm, and the length is 200mm, analyze the resonant frequency of anvil, The first-order resonant frequency is about 12 kHz, The resonant frequency determines the range of the pulse width. According to the international standard calculation, we want to produce the pulse with is 0.5mm, the first-order resonant frequency should be more than 12.5kHz. In addition, because the main energy component of the pulse is distributed in the low frequency, the energy component over 8kHz is less. it can produce a good acceleration waveform.

Figure 3. Measurement result of axial resonant frequency of anvil
2.3. Signal processing

Discrete time series of laser orthogonal signals output by Michelson laser interferometer improved by orthogonal zero difference \( \{u_1(t_i)\} \) and \( \{u_2(t_i)\} \). The phase modulation value sequence can be solved \( \{\varphi_{\text{Mod}}(t_i)\} \):

\[
\varphi_{\text{Mod}}(t_i) = \arctan \frac{u_1(t_i)}{u_2(t_i)} + n\pi, n = 0, 1, 2, \cdots
\]

Discrete time series values of displacements \( \{s_{D}(t_i)\} \):

\[
s_{D}(t_i) = \frac{2}{4\pi} \varphi_{\text{Mod}}(t_i)
\]

Where, \( \lambda \) is the wavelength of He-Ne laser. The subscript \( D \) indicates that the value is interfered by high frequency noise. Using the digital low-pass filtering algorithm and the parameters used to suppress high frequency noise, the displacement sequence value \( \{s_{D}(t_i)\} \) is filtered to get the smooth displacement sequence value represented by \( \{s(t_i)\} \). For the half sine square impulse waveform generated by the collision excitation device, the filter adopts the fourth-order recursive Butterworth low-pass filter with monotonic amplitude response, and the cut-off frequency is \( 5/T \) (\( T \) is the pulse duration). It is worth noting that, due to the additional phase delay caused by the filtering process, it is necessary to reverse the displacement sequence values and then use the same filter to reverse the filtering process again, so as to compensate the phase delay caused by the previous forward filtering.

The discrete time series of velocity can be obtained by differential equation (5) in time domain \( \{v_{D}(t_i)\} \):

\[
v_{D}(t_i) = \frac{1}{2\Delta t}[s(t_i) - s(t_{i-1})]
\]

The velocity sequence value expressed in \( \{v(t_i)\} \) can be obtained by using the same filtering method as the displacement sequence value, and the velocity sequence value \( \{v_{D}(t_i)\} \) is filtered twice in the positive and negative directions. The discrete time series value of acceleration \( \{a(t_i)\} \) can be obtained by differential equation (6):

\[
a(t_i) = \frac{1}{2\Delta t}[v(t_i) - v(t_{i-1})]
\]

From the calculated acceleration input value sequence, the maximum value is found as the peak value of acceleration.

3. Experiment

The standard piezoelectric acceleration sensor (model: Endevco 2270, No:10315) is calibrated with primary method on the low-g collision shock acceleration calibration device of the Changcheng Institute of Metrology and Measurement according to the requirements of ISO 16063-13: Primary shock calibration using laser interferometry. The peak of shock acceleration is about 20~10000 m/s\(^2\). The measurement part adopts laser vibrometer.

Table 1 shows the result of 10 times repeated calibration of the sensitivity when the acceleration is about 5070 m/s\(^2\) and the pulse width is 0.73 ms. According to the calculation, the standard deviation of measurement repeatability is 4.8×10\(^{-5}\) mV/(m·s\(^{-2}\)), it shows the good repeatability.

| Table 1. The result of repeatability |
|-----------------------------------|
| m/s\(^2\) | ms | mV/(m·s\(^{-2}\)) |
|-------|----|-----------------|
| 1 | 5072 | 0.73 | 0.2067 |
| 2 | 5077 | 0.72 | 0.2066 |
Refer to ISO16063-13:2001 and Table 1, the expanded uncertainty of sensitivity calibration is 0.5% (k=2), and the uncertainty component table is shown in Table 2.

**Table 2. The component of uncertainty**

| Impact category | Sources of standard uncertainty components | Relative standard uncertainty component |
|----------------|--------------------------------------------|---------------------------------------|
| 1              | Relative standard uncertainty introduced by sampling interval | $u_1=1.0 \times 10^{-6}$ |
| 2              | Reference shock acceleration               | $u_2=2.0 \times 10^{-6}$ |
| 3              | Relative standard uncertainty introduced by laser wavelength instability | $u_3=6.9 \times 10^{-5}$ |
| 4              | Relative standard uncertainty caused by phase measurement error | $u_4=1.1 \times 10^{-3}$ |
| 5              | Relative standard uncertainty of peak acceleration measurement introduced by data processing method | $u_5=1.0 \times 10^{-3}$ |
| 6              | The influence of zero acceleration on standard uncertainty | $u_6=1.0 \times 10^{-3}$ |
| 7              | The influence of anvil on resonant frequency | $u_7=4.2 \times 10^{-4}$ |
| 8              | The influence of transverse motion          | $u_8=1.0 \times 10^{-4}$ |
| 9              | The influence of the relative motion of the impact exciter and the laser measuring part | $u_9=5.0 \times 10^{-4}$ |
| 10             | The influence of repeated error of shock acceleration amplitude excitation | $u_{10}=1.5 \times 10^{-3}$ |
|                | Combined standard uncertainty              | $u_c=2.43 \times 10^{-3}$ |
|                | Relative uncertainty (k=2)                 | $U_{rel}=2 \times u_c=4.86 \times 10^{-3}$ |

4. Conclusion

We have put forward a mechanical shock excitation system with low-g and wide pulse width based on collusion, and reached on the realization method of the low-g primary calibration. The low-g shock standard device based on rigid body collision for shock acceleration calibration was investigated and established within a half-sine squared acceleration wave shape range from 20m/s² to 10000m/s² and a
pulse width time from 0.5~10ms. It can meet the requirement of wide pulse width and high accuracy in the field of shock measurement.

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