A comparison of low-shock and centrifuge calibrations using piezoresistive accelerometers

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Abstract
This paper describes the degree of equivalence between low-shock and centrifuge calibrations up to 10 000 m s⁻² against three types of piezoresistive accelerometer: an undamped sputter gauge type, a damped sputter gauge type and an undamped semiconductive type. The complex sensitivity in the low-shock calibration and the DC sensitivity in the centrifuge calibration are well consistent within each expanded uncertainty in the frequency domain, together with the vibration calibration using the second-order transfer function. In addition, the preliminary uncertainty budget in the centrifuge calibration facility is also indicated, and distinctly estimated from the viewpoint of the mechanical parts and accelerometers.

Keywords: calibration, piezoresistive accelerometer, ISO 16063-17, ISO 16063-13, ISO 6487, low-shock, centrifuge

(Some figures may appear in colour only in the online journal)
types of piezoresistive accelerometer is investigated here as a collaboration between Kyowa Electric Instruments (KYOWA) and the National Metrology Institute of Japan (NMIJ).

2. Low-shock calibration facility

Figure 1 is a photograph of the low-shock calibration facility at NMIJ. The facility is equipped with two heterodyne laser interferometers based on He–Ne laser light (λ = 632.8 nm) as the length standard, in compliance with ISO 16063-13 [8]. The two heterodyne laser interferometers, which integrate the optical heads of a commercial laser Doppler vibrometer (LV-1800; Onosokki Co., Ltd), are used to monitor two different positions on the mounting plane of the accelerometer under calibration. The two laser light beams are pointed at axial-symmetrical distances from the sensitive axis of the accelerometer to measure the shock motion on the reference mounting plane. Since the difference between the acceleration measurements of these two points ranges from 0.1% to 0.8%, two heterodyne laser interferometers are required to calibrate the mean shock sensitivity of the accelerometer precisely. The dynamic momentum of a shock is generated by a rigid collision between two metallic bodies that are supported by an air bearing with an air gap of several micrometres. The devices under test are symmetrically placed at different positions on the mounting plane of the turntable (see figure 3).

The voltage ratio sensitivity of piezoresistive accelerometers can be evaluated by independently considering the characteristic of the bridge amplifier. The expanded measurement uncertainty with a coverage factor $k = 2$ is estimated as roughly 1.0%. The 32 kg aluminum turntable has a radius $r = 0.2$ m, a maximum rotational frequency of 2135 rpm, and is supported by an air bearing with an air gap of several micrometres. The devices under test are symmetrically placed at either two or four opposing positions relative to the rotational axis of the turntable (see figure 3).

Figure 4 shows a schematic of the centrifuge facility. The bridge amplifier is attached to the upper side of the turntable and rotates with it. External power is supplied to the bridge amplifier via a signal transmitter (revolving transformer). The accelerometers receive their excitation voltage from the bridge amplifier, which comprises a digitizer that transmits a digitized version of the accelerometer signal to a personal computer via the signal transmitter. The noise level of this digitized signal to a full scale is typically 0.05%. The noise level of 7264B-2000 T is 0.05 mV V$^{-1}$ peak to peak, and that of ASD-B-1KV and ASE-A-500 is 0.002 mV V$^{-1}$ when there is no input centrifuge acceleration.

This centrifuge facility gives the sensitivity $S_{ce}$ of an accelerometer as

$$S_{ce} = \frac{V}{A},$$

where $V$ is the output DC voltage from the accelerometer, and $A$ is the centrifuge DC acceleration $A = \omega^2 r$, where $\omega$ is the angular speed (a rotary encoder counts each rotation). Figure 5 shows the operational sequence used for centrifuge calibration using this facility. Firstly, the two accelerometers for the balancing purpose are set symmetrically on the turntable so that they output positive voltages. In the case of a the laser interferometer [10]. In ISO 16063-13, the shock sensitivity $S_{sh}$ is defined as the ratio of the two peak values:

$$S_{sh} = \frac{V_p}{A_p},$$

where $A_p$ is the peak value of the input acceleration applied to the accelerometer, and $V_p$ is the peak value of the accelerometer output signal. To obtain smooth waveforms, a digital fourth-order Butterworth low-pass filter with a cutoff frequency of 5 kHz is applied to both the input-acceleration and accelerometer-output waveforms.

3. Centrifuge calibration facility

The centrifuge calibration facility manufactured by KYOWA comprises a turntable, a signal conditioning unit, and other mechanical parts. It can generate a maximum static centrifuge acceleration of 10 000 m s$^{-2}$ in compliance with ISO 16063-17. Recently, KYOWA developed a new centrifuge calibration facility with a removable bridge amplifier type of signal conditioner, which enables the temperature response characteristics of the bridge amplifier themselves to be inspected.

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single accelerometer, a dummy mass is used on the opposite side of the turntable for balancing purposes. After a burn-in test of several tens of seconds for zero voltage determination, the rotational speed is ramped up in 20% increments toward the specified centrifuge acceleration, after which it is ramped down in 20% decrements. Next, the accelerometers are remounted in the opposite direction to the reference surface so that they provide an (opposite) negative voltage output, and the same 20% up-and-down ramp is repeated. Finally, the hysteresis, linearity and average sensitivities of the positive and negative voltage outputs are derived.

4. Piezoresistive accelerometers under test

We prepared three types of piezoresistive accelerometer, as follows, to evaluate the consistency between the sensitivities determined by dynamic and static high acceleration calibrations.

- Undamped sputter gauge accelerometer. ASD-B-1KV, sn GF4190169 manufactured by Kyowa Electric Instruments Co., Ltd.
- Damped sputter gauge accelerometer. ASE-A-500, sn GD9300011 manufactured by Kyowa Electric Instruments Co., Ltd.
- Undamped semiconductive piezoresistive accelerometer. 7264B-2000 T, sn B69124 manufactured by Meggitt Inc.

In this comparative research, a 10 V bridge voltage is supplied by the bridge amplifier to each accelerometer. As each bridge amplifier in both the shock and centrifuge facilities is independently calibrated, the measurand to be compared is the voltage sensitivity ratio mV/V/(m s\(^{-2}\)) of accelerometers with 10 V supplied. Each of the above accelerometers covers a flat sensitivity of less than 1 kHz and is used worldwide in car crash tests. Figures 6(a)–(c) indicate the frequency response of ASD-B-1KV, ASE-A-500 and 7264B-2000 T from 20 Hz.
to 10 kHz using the NMIJ vibration calibration facility [11]. Actually, the voltage signals from the accelerometers in car crash tests are recorded by a data logger through a low-pass analog filter with a cutoff frequency of roughly 1600 Hz, in accordance with ISO 6487 standards. Thus, the static and dynamic calibrations normally become comparable in the case of flat frequency accelerometer responses of less than 1 kHz.

In order to further understand the mechanical characteristics of each accelerometer, a second-order transfer function of the resonant frequency $f_0$ and the damping factor $\delta$ is investigated as a mass spring damper model [12]. That is, the sensitivity can be written for a sinusoidal excitation with a certain frequency $f$ as follows,

$$S(f) = S_0 \left[ \left(1 - f^2/f_0^2\right)^2 + \left(2\delta f/f_0\right)^2 \right]^{-1/2}$$

and the phase shift

$$\phi(f) = \arctan \left(-\frac{2\delta f/f_0}{1 - f^2/f_0^2}\right)$$

with $S_0$ denoting the sensitivity at 0 Hz. Each mechanical characteristic of the three accelerometers is derived from an approximation between the measured frequency response and the transfer function (see table 1.) The approximation result is calculated using a solver algorithm from the EXCEL software; the 7264B-2000 T is an accelerometer with high sensitivity and a low damping factor, and the ASE-A-500 has a high damping factor that can suppress resonant effects in acceleration measurement.

Figure 7 presents the relative difference of each accelerometer based on the sensitivity at 100 Hz. The accelerometer 7264B-2000 T has stable, high-sensitivity furnishing differences lower than 0.1% up to 1 kHz measured by the vibration calibration facility.

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| Accelerometer  | $S_0$ | $f_0$ | $\delta$ |
|----------------|-------|-------|---------|
| ASD-B-1KV      | 0.0001395 | 17500 | 0.088   |
| ASE-A-500      | 0.0003428 | 10162 | 0.67    |
| 7264B-2000T    | 0.002012  | 25109 | 0.055   |

Figure 6. (a)–(c) The frequency response of ASD-B-1KV, ASE-B-500 and 7264B-2000 T from 20 Hz to 10 kHz measured by the vibration calibration facility.
5. Experimental results

5.1. Comparison of results from low-shock and centrifuge calibrations

Figures 7–9 show the results for the low-shock and centrifuge calibrations of the three accelerometers. The specified upper limit of the accelerometer ASE-A-500 is 4903 m s$^{-2}$, whereas for the models ASD-B-1KV and 7264B-2000 T, the acceleration was measured up to 9807 m s$^{-2}$. In low-shock calibrations, it was preferable to fix the shock durations to suppress the waveform change by the frequency response of the accelerometer, and the frequency content of the shock pulse was dominant from several hundred Hz to several kHz. Nevertheless, the non-negligible linearity from 2000 m s$^{-2}$ to 10 000 m s$^{-2}$ is estimated to be roughly 1% for the accelerometer 7264B-2000 T. In contrast, the centrifuge calibration facility can evaluate the DC sensitivity of the accelerometers. If the dynamic acceleration contains abundant high-frequency components over the flat frequency response (typically less than 1 kHz) of the accelerometer, the complex sensitivity at the discrete frequencies noted in ISO 16063-13 will possibly be straightforward [13]. Because of this, the shock and complex sensitivities refer to the sensitivity of the accelerometer in the time and frequency domains, respectively. However, considering the measurement uncertainty, measured spectral region, or accelerometer specification, even the shock sensitivity of damped ASE-A-500 accelerometers with a larger phase shift is feasible for comparison, and less sensitive to shock durations of more than roughly 0.5 ms. Also, the methodology of shock sensitivity is widely accepted in the calibration certificats of accredited laboratories and in the international inter-laboratory comparisons carried out by NMIs [6].

Tables 2–4 give the numerical values that are plotted in figures 7–9. To compare the individual results of the low-shock and centrifuge calibrations, the difference with respect to a certain acceleration is calculated as

$$D = \frac{S_{ce} - S_{sh}}{S_{sh}} \times 100,$$

(5)

where $D$ is the degree of equivalence in %, $S_{ce}$ is the centrifuge sensitivity and $S_{sh}$ is the shock sensitivity. The shock sensitivity $S_{sh}$ is a reference value that consists of the Japanese national length, time and voltage standards. As the length standard, a non-stabilized He–Ne laser source with a wavelength of 632.8 nm is used. A rubidium time base and DC voltage generator calibrated by accredited Japanese laboratories are used to assure the time and voltage standards. Here, all the shock sensitivities of ASD-B-1KV and ASE-A-500 are obtained using the original shock sensitivity of the acceleration measuring chain (a combination of the accelerometer and bridge amplifier) and the gain of the bridge amplifier at 160 Hz. On the other hand, the shock sensitivities of 7264B-2000 T are given with a 10 V power supply and no gain. In the case of ASD-B-1KV and 7264B-2000 T, all the values of the low-shock, centrifuge and vibration calibrations are well consistent within a deviation of less than 0.3%. However, only the low-shock calibration of ASE-A-500 generates a constant difference of 0.9% beyond the measurement uncertainty of 0.4%. However, only the low-shock calibration of ASE-A-500 generates a constant difference of 0.9% beyond the measurement uncertainty of 0.4%, compared with centrifuge and vibration calibrations. This means that all the centrifuge and vibration calibrations are comparable in the three accelerometers. Also, a non-linear subtractive sensitivity decrease was only observed in Figure 8. (a) The relative gain based on a 100 Hz bridge amplifier for each accelerometer; (b) the phase shift of the bridge amplifier for each accelerometer.

Figure 9. The results of ASD-B-1KV in low-shock, centrifuge and vibration calibrations.
Table 2. The numerical values of ASD-B-1KV in low-shock and centrifuge calibrations.

| Acceleration  | Sensitivity | Uncertainty | Duration | Acceleration  | Sensitivity | Uncertainty | Difference |
|---------------|-------------|-------------|----------|---------------|-------------|-------------|------------|
| m s⁻²         | mV/V/(m s⁻²) | %           | ms       | m s⁻²         | mV/V/(m s⁻²) | %           | %          |
| 1947          | 0.0001399   | 0.4         | 0.59     | 1961          | 0.0001400   | 0.7         | 0.0        |
| 4008          | 0.0001400   | 0.4         | 0.54     | 3923          | 0.0001400   | 0.7         | 0.0        |
| 5861          | 0.0001398   | 0.4         | 0.52     | 5884          | 0.0001400   | 0.7         | −0.2       |
| 7950          | 0.0001400   | 0.4         | 0.51     | 7845          | 0.0001400   | 0.7         | 0.0        |
| 9524          | 0.0001399   | 0.4         | 0.51     | 9807          | 0.0001400   | 0.7         | 0.0        |

Table 3. The numerical values of ASE-A-500 in low-shock and centrifuge calibrations.

| Acceleration  | Sensitivity | Uncertainty | Duration | Acceleration  | Sensitivity | Uncertainty | Difference |
|---------------|-------------|-------------|----------|---------------|-------------|-------------|------------|
| m s⁻²         | mV/V/(m s⁻²) | %           | ms       | m s⁻²         | mV/V/(m s⁻²) | %           | %          |
| 994           | 0.0003399   | 0.4         | 0.64     | 981           | 0.0003429   | 0.8         | −0.9       |
| 2057          | 0.0003399   | 0.4         | 0.55     | 1961          | 0.0003429   | 0.8         | −0.9       |
| 2986          | 0.0003397   | 0.4         | 0.52     | 2942          | 0.0003429   | 0.8         | −0.9       |
| 4056          | 0.0003398   | 0.4         | 0.50     | 3923          | 0.0003429   | 0.8         | −0.9       |
| 5086          | 0.0003397   | 0.4         | 0.48     | 4903          | 0.0003429   | 0.8         | −0.9       |

Table 4. The numerical values of 7264B-2000 T in low-shock and centrifuge calibrations.

| Acceleration  | Sensitivity | Uncertainty | Duration | Acceleration  | Sensitivity | Uncertainty | Difference |
|---------------|-------------|-------------|----------|---------------|-------------|-------------|------------|
| m s⁻²         | mV/V/(m s⁻²) | %           | ms       | m s⁻²         | mV/V/(m s⁻²) | %           | %          |
| 2028          | 0.0020111   | 0.4         | 0.55     | 1961          | 0.002006    | 0.7         | 0.2        |
| 2996          | 0.002009    | 0.4         | 0.54     | 3993          | 0.002006    | 0.7         | 0.0        |
| 3984          | 0.002007    | 0.4         | 0.53     | 5884          | 0.002005    | 0.7         | 0.0        |
| 5087          | 0.002008    | 0.4         | 0.51     | 7845          | 0.002004    | 0.7         | −0.1       |
| 6063          | 0.002006    | 0.4         | 0.51     | 9807          | 0.002003    | 0.7         | −0.6       |

Table 5. The preliminary uncertainty budget of three accelerometers in centrifuge calibration.

| Uncertainty components | Comments                                                                 | ASD     | ASE     | 7264B   |
|------------------------|---------------------------------------------------------------------------|---------|---------|---------|
| Factor of centrifuge acceleration | Attachment of accelerometer; rotation radius uncertainty; rotation frequency uncertainty | $8.0 \times 10^{-4}$ | $1.0 \times 10^{-3}$ | $8.0 \times 10^{-4}$ |
| Measurement of accelerometer output | Repeatability of measurement; accuracy of voltage standard | $8.0 \times 10^{-4}$ | $7.0 \times 10^{-4}$ | $1.1 \times 10^{-3}$ |
| Hum and noise | Accuracy of bridge voltage; accuracy of voltage standard; stability in rotation | $2.0 \times 10^{-4}$ | $2.0 \times 10^{-4}$ | $2.0 \times 10^{-4}$ |
| Excitation voltage | Sensitivity of accelerometer; zero voltage of accelerometer; temperature effect of bridge amplifier | $1.0 \times 10^{-4}$ | $1.0 \times 10^{-4}$ | $1.0 \times 10^{-4}$ |
| Temperature effect | Sensitivity of accelerometer; zero voltage of accelerometer; temperature effect of bridge amplifier | $3.1 \times 10^{-3}$ | $3.4 \times 10^{-3}$ | $3.1 \times 10^{-3}$ |
| Factor of bridge amplifier | Linearity of bridge amplifier; difference between plus and minus gains | $3.0 \times 10^{-4}$ | $3.0 \times 10^{-4}$ | $3.0 \times 10^{-4}$ |
| Comb. Std. uncertainty in % | | 0.33 | 0.36 | 0.34 |
| Expanded uncertainty ($k = 2$) in % | | 0.66 | 0.73 | 0.68 |
| Stated expanded uncertainty in % | | 0.70 | 0.8 | 0.7 |
5.2. Uncertainty budget of centrifuge calibration

The uncertainty budget of the three accelerometers in centrifuge calibration is under investigation, but has been preliminarily estimated in table 5. The centrifuge calibration facility can achieve a small and stable uncertainty. However, the dominant uncertainty component is the temperature effect, which is given as a change in the sensitivity or zero voltage of the accelerometers. Owing to the heat generation from the drive motor in rotational operation, the temperature of the accelerometers increases by 1.5 °C during centrifuge calibration. Currently, although the assured expanded uncertainty is subject to the temperature effect of accelerometers, some improvements in the centrifuge calibration facility are being investigated with the view of suppressing temperature increase in the future.
6. Discussions

6.1. Dependence of shock sensitivity on damping factor

In order to investigate the dependence of shock sensitivity on the damping factor, the actual shock duration is calculated using a difference equation based on equations (3) and (4). Then, a known input waveform of 100 peak value is prepared with a pulse width of 0.6 ms, corresponding to a shock duration of 0.47 ms, which is a time width between two points at 10% peak acceleration in the shock pulse [14]. Figure 12 presents three kinds of waveforms: one is an input waveform (grey line) and the other two output waveforms are based on a resonance frequency of 10 kHz with damping factor of 0.05 (black line) and 1.0 (black dashed line). The output waveform with a resonance frequency of 10 kHz and a damping factor of 0.05 has a slightly increased peak value with a negligible time delay due to the low-damped characteristic. Another waveform is generated with a time delay of several tens µs by the high damping factor, but the resonant perturbation after the shock pulse is not observed.

Figure 13 indicates the dependence of shock sensitivity on the resonance frequency and damping factor in the case of a pulse width of 0.6 ms. Since the estimated damping factor of ASE-A-500 is the largest and closest to 0.707 of the presented damping factors in table 1, then little or no resonance is excited by external forces. The approximation of figure 6(b) is carried out against the sensitivity, and a damping factor of 0.67 is obtained, as shown in table 1. In this case, with the damping factor of 0.67, a constant time delay of several tens µs by the high damping factor, but the resonant perturbation after the shock pulse is not observed.

Figure 15. The results of ASD-B-1KV in low-shock, centrifuge and vibration calibrations.

Figure 16. The results of ASE-A-500 in low-shock, centrifuge and vibration calibrations.

Figure 17. The results of 7264B-2000 T in low-shock, centrifuge and vibration calibrations.
where $\angle$ stands for an argument and the dead time $L$ corresponds to 3.72 ms.

Meanwhile, the 0.707 damping factor acts as a threshold, which decreases the shock sensitivity. In figures 9 and 11, ASD-B-1KV and 7264B-2000 T, with a low damping factor of less than 0.1, show comparable sensitivity regarding vibration, shock and centrifuge calibrations. In contrast, the difference between two sensitivities in the shock and centrifuge calibrations of ASE-B-500 can be explained by the high damping factor. Figure 14 presents the frequency response of the three accelerometers based on the spring damper model, as indicated in table 1, and the frequency components (dotted line) of a shock pulse with a pulse width of 0.6 ms. Since the sensitivity of the accelerometer ASE-B-500 does not increase in the high-frequency range, as shown in figure 6(b), and decreases from several kHz, it is estimated that the shock sensitivity also drops to a lower value.

6.2. Approach to centrifuge calibration from complex sensitivity in low-shock calibration

In order to compare the shock sensitivity with the complex sensitivity precisely, both the time and frequency domains should be analysed using the same shock pulse. Up to now, some similar research has been attempted to determine the complex sensitivity at each discrete frequency using the fast Fourier transform [13, 15]. For this purpose, a rectangular window from 2.0 ms to 7.0 ms is applied to a shock pulse (see figure 2). Normally, the low-shock calibration facility records the measurement data at 10 ms, in which the trigger is given at 3.0 ms by the rising edge of the voltage output signal from the accelerometer.

Table 6 presents a results comparison of the shock and complex sensitivities, using each shock pulse at a peak acceleration of around 4000 m s$^{-2}$ for three kinds of accelerometers. Since the basic frequency becomes 200 Hz by a window length of 5.0 ms, complex sensitivities from 200 Hz to 600 Hz are obtained. The average complex sensitivity is given by the three accelerometers based on the spring damper model, as indicated in table 1, and the three types of accelerometer from the viewpoint of the frequency domain, the frequency response of each of the three accelerometers is investigated. Using this, the dependence of the shock sensitivity on the damping factor is calculated. Furthermore, assessment of the consistency of complex sensitivity in low-shock calibration has also been confirmed compared to the centrifuge and vibration calibrations in the frequency domain. These results support the technical validity of static calibration as required by ISO 6487. For future experimental comparisons of different types of sensor between dynamic and static calibrations, a large and diverse set of data must be investigated from the viewpoint of both the time and frequency domains.

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