XXI IMEKO World Congress "Measurement in Research and Industry"
August 30 – September 4, 2015, Prague, Czech Republic

A NOVEL LOW-SHOCK CALIBRATION METHOD USING DIGITAL FILTER TECHNIQUE

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Abstract – A piezoelectric accelerometer output voltage with zero shift was induced by the low-frequency response of the charge amplifier. So we designed a virtual amplifier with same input-output characteristic as the charge amplifier, and shock sensitivities of a piezoelectric accelerometer were evaluated by applying the input acceleration to the virtual amplifier. The shock sensitivities were comparable to the vibration calibration results.

Keywords: shock calibration, piezoelectric accelerometer, charge amplifier, laser interferometer, digital filter

1. INTRODUCTION

There is a strong demand by Japanese industries for shock calibration for accelerometers at acceleration levels from several hundred m/s2 to several thousand m/s2 to improve human safety levels in car crash tests and electric device drop-tests. In general, accelerometers are calibrated using a secondary shock calibration system to compare calibrations, and a high-performance piezoelectric accelerometer is used as the reference accelerometer in various secondary shock calibration systems. Thus, accurate shock calibrations by piezoelectric accelerometers are in high demand. But since a piezoelectric accelerometer is used in combination with a charge amplifier, a zero voltage drift is generated due to the high-pass characteristics of the charge amplifier in the low-frequency region [1]. Although the ISO standards 16063-13 [2] and 16063-22 [3] state that the zero shift shall be within 1%, zero shift exists as a large error component in shock calibrations with a long pulse. The aim of this study is to reduce the effect of the zero shift to achieve superior shock calibrations for piezoelectric accelerometers. To reduce the zero shift, we developed a virtual amplifier that works on a personal computer in which the virtual amplifier operates with the same input-output characteristic as a real charge amplifier [4]. This paper reports on the use of this virtual amplifier for the shock calibrations of a high-performance piezoelectric accelerometer.

2. SHOCK CALIBRATION SYSTEM

Figure 1 shows a schematic of the principles of shock calibration at the National Metrology Institute of Japan (NMIJ). The shock calibration system provides primary calibrations with laser interferometry in compliance with ISO 16063-13. This system consists of two parts; the first is a shock exciter which generates a pulsed shock with peak acceleration from 50 m/s^2 to 10,000 m/s^2. The shock is induced by a collision between two rigid bodies supported by an air bearing, and pulse widths vary between 0.5 ms and 5.0 ms. The second part is a measurement system with two PXI digitizers (5922 and 5152) and two commercial laser Doppler vibrometers. The two vibrometers monitor two different symmetric positions along the sensitive axis of an accelerometer and employs a He-Ne laser wavelength (632.8 m) as the length standard. The 5922 digitizer has a vertical resolution of 16 bits, a signal processing sampling frequency of 10 MHz, and it records Doppler signal depending on the velocity by the shock. With respect to the demodulation process from the Doppler signal to the acceleration waveform, we implemented phase unwrapping and differentiation twice through a Butterworth digital low-pass filter with a cut-off frequency of 5 kHz [5]. The accelerometer output is also passed through the Butterworth digital low-pass filter with a cut-off frequency of 5 kHz.

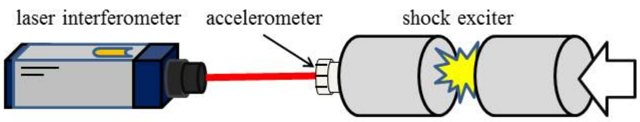

Figure 1 Principles of shock calibration.

Figures 2(a)–3(c) and 2(d)–3(f) show typical experimental waveforms for two cases with accelerations of 50 m/s^2 and 10,000 m/s^2, respectively. Here figures 2(a) and 2(d) show the acceleration measured by the He-Ne laser interferometer, and figures 2(b) and 2(e) show the voltage output from the combined piezoelectric accelerometer and charge amplifier. Figures 2(c) and 2(f) show expanded graphs around zero voltage for figures 2(b) and 2(e). Table 1 presents the setting of a Brüel & Kjaer (BK) 2635 charge amplifier in cases of 50 m/s^2 and 10,000 m/s^2. Nominal gains of 100 mV/pC and 1 mV/pC at 160 Hz are set at the gain 10 and 1k Units Volt^{-1}. Also, each cut-off frequency of high and low pass filters is 0.2 Hz and 100 kHz.

ISO 16063-13 for primary shock calibration defines the shock sensitivity of an accelerometer as two peak ratios between the input acceleration and the accelerometer output, as shown in Equation (1).

$$S_V = \frac{V_P}{A_P} \tag{1}$$

where:

S_V is the shock sensitivity,

A_p is the peak value of the acceleration input to the accelerometer,

V_p is the peak value of the accelerometer output.

However, V_p includes the frequency response effect of not only the piezoelectric accelerometer but also the charge amplifier. Thus, by eliminating the effect of the charge amplifier, the charge sensitivity of the piezoelectric accelerometer can be calibrated.

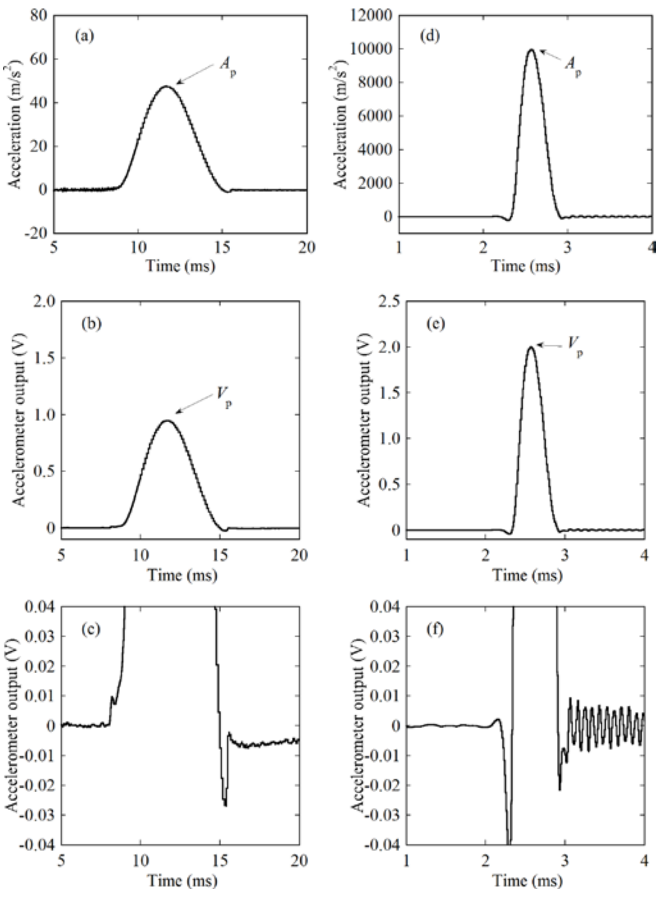

Figure 2 Waveform examples of the acceleration and accelerometer outputs.

Table 1 Settings of BK 2635 in shock calibration.

	BK 2635	
Acceleration	50 m/s^2	10,000 m/s^2
Gain	10 Units / Volt	1 k Units / Volt
High pass filter	0.2 Hz	0.2 Hz
Low pass filter	100 kHz	100 kHz

3. VIRTUAL AMPLIFIER

Figure 3 shows the frequency response with the gain of 10 Units Volt^{-1} on a Brüel & Kjaer (BK) 2635 charge amplifier which has high-pass characteristics in the low-frequency region. Due to the effect of these high-pass characteristics, the charge amplifier output voltage with zero shift results in a zero voltage drift, which results in a large error component in the shock calibration. To reduce the effect of the zero shift, we developed a virtual amplifier by designing an impulse infinite response digital filter [4]. The virtual amplifier is composed of three 2nd order transfer functions at the sampling frequency of 1 MHz, and operates with the same input-output characteristics as the charge amplifier in personal computer software. A 2nd order transfer function $H(z)$ of IIR filter in the *z* domain can be represented as

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}} \tag{2}$$

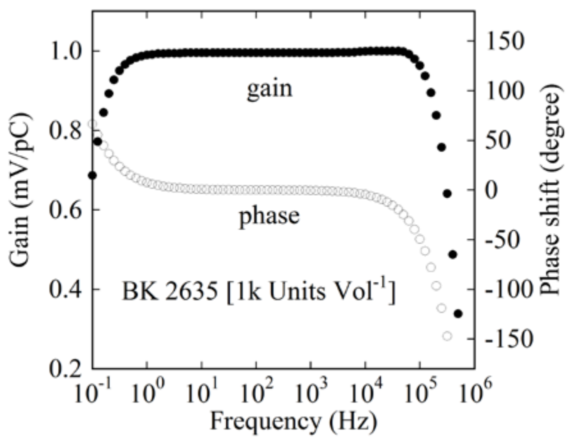

Figure 3 Frequency responses with gain of 1k Units Volt^{-1} on BK 2635 charge amplifier.

Equation (3) presents 2nd order transfer function of low frequency region in case of the gain of 1k Units Volt^{-1}. Here, each filter coefficient was determined at pre-warping of 500 kHz.

$$H(z)_{\mathrm{gain1k}} = \frac{0.999999582724830 - 1.999999193011158 z^{-1} + 0.999999610286332 z^{-2}}{1 - 1.999999193011087 z^{-1} + 0.999999193011234 z^{-2}} \tag{3}$$

Equations (4) and (5) are two 2nd order transfer functions of high frequency region.

$G_1(z)_{\mathrm{gain1k}} =$

$$\frac{0.998144254777175 + 1.996288509554351z^{-1} + 0.998144254777175z^{-2}}{1 + 2z^{-1} + z^{-2}} \tag{4}$$

$$G_2(z)_{\text{gain1k}} = \frac{-0.003204040885953 - 0.006408081771903z^{-1} - 0.003204040885950z^{-2}}{1 + 1.999999999999996z^{-1} + 0.999999999999996z^{-2}} \tag{5}$$

Figure 4 shows a comparison of each output from charge and virtual amplifiers by using rectangular signals with two heights of 2 V and a capacitance of 1000 pF, and we see that the output of the virtual amplifier agrees with that of the charge amplifier.

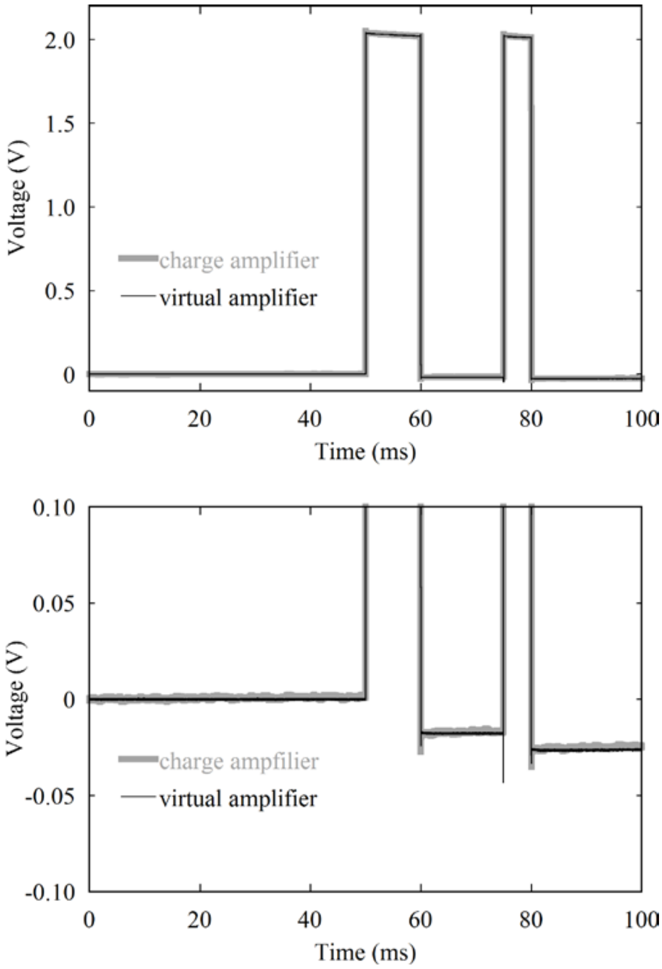

Figure 4 Comparison results between the charge and virtual amplifiers with gain of 1k Units Volt^{-1}.

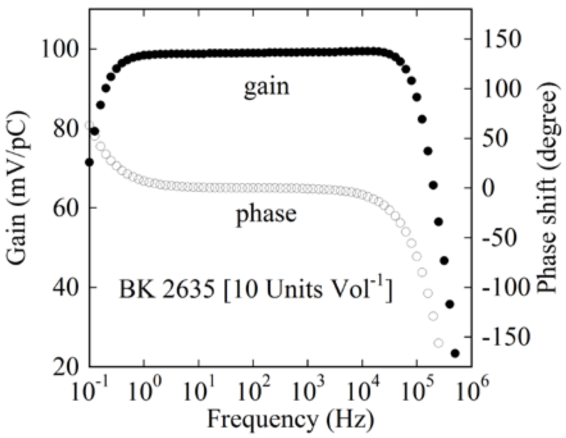

Figure 5 Frequency responses with gain of 10 Units Volt^{-1} on BK 2635 charge amplifier.

Figure 5 shows the frequency response with the gain of 10 Units Volt^{-1}. The nominal gain is one hundred times compared to the gain of 1k Units Volt^{-1}. Figure 6 presents a comparison of each output from the charge and virtual amplifiers by using two rectangular signals with height of 0.05 V and a capacitance of 1000 pF. This comparison result also indicates the validity of the virtual amplifier. Equation (6) presents 2nd order transfer function of low frequency region in case of the gain of 10 Units Volt^{-1}.

$$H(z)_{\text{gain10}} = \frac{0.999999610954179 - 1.999999340990764z^{-1} + 0.999999730036607z^{-2}}{1 - 1.999999340990740z^{-1} + 0.999999340990810z^{-2}} \tag{6}$$

Equations (7) and (8) are two 2nd order transfer functions of high frequency region.

$$G_1(z)_{\text{gain10}} = \frac{99.33139070224530 + 198.66278140449060z^{-1} + 99.33139070224530z^{-2}}{1 + 2z^{-1} + z^{-2}} \tag{7}$$

$$G_2(z)_{\text{gain10}} = \frac{-0.275792044176878 - 0.551584088352545z^{-1} - 0.275792044175668z^{-2}}{1 + 1.999999999999980z^{-1} + 0.999999999999980z^{-2}} \tag{8}$$

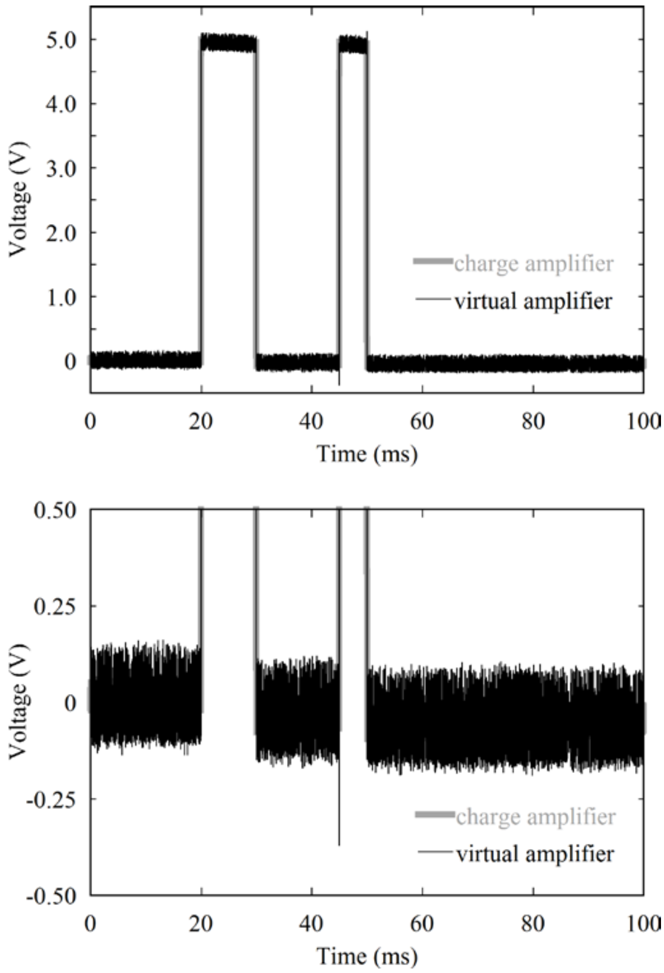

Figure 6 Comparison results between the charge and virtual amplifiers with gain of 10 Units Volt^{-1}.

4. CALIBRATION WITH VIRTUAL AMPLIFER

Figure 7 shows the procedure for calculating the charge sensitivity of a piezoelectric accelerometer. Here, the three transfer functions of the piezoelectric accelerometer for both the charge and virtual amplifiers are $K(s)$, $H(s)$ and $H^*(s)$. The measured acceleration is input into the virtual amplifier to obtain the peak output, B_p, from the virtual amplifier. If the frequency response of a piezoelectric accelerometer is almost constant in the frequency component of a shock, the charge sensitivity of the piezoelectric accelerometer can be evaluated by dividing the two peak outputs (V_p and B_p) between the charge and virtual amplifiers, as in Equation (9).

$$S_q = \frac{V_P}{B_P} \quad (9)$$

where:

S_q is the charge sensitivity for the shock sensitivity,

V_p is the peak value of the charge amplifier output,

B_p is the peak value of the virtual amplifier output.

Figure 8 indicates the calibration result of a piezoelectric accelerometer (Meggitt 2270, back-to-back type) based on the above-mentioned calibration procedure using the virtual amplifier. Normally, the charge sensitivity decreases in the low-acceleration region due to the zero shift. However, we obtained a flat calibration result for the charge sensitivities by the advantage of using the virtual amplifier. Also, the charge sensitivities in the shock calibration are comparable to those in the vibration calibration.

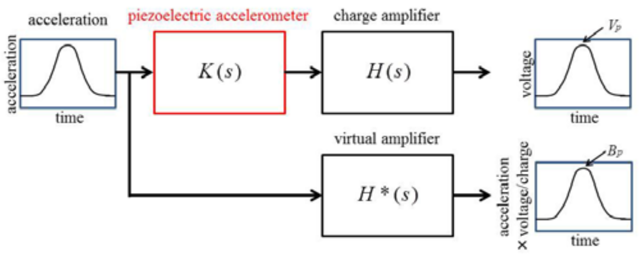

Figure 7 Calibration procedure for a piezoelectric accelerometer using the virtual amplifier.

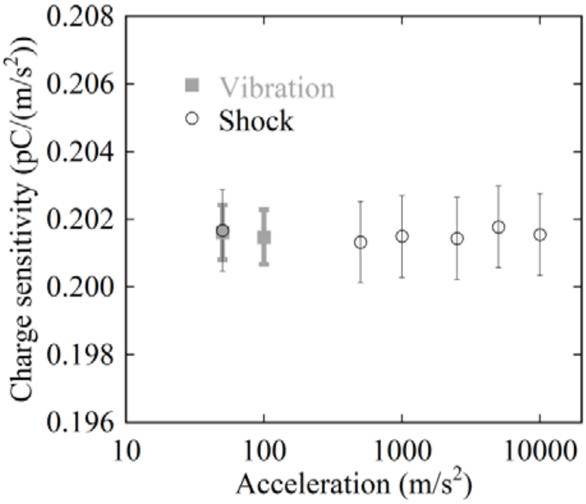

Figure 8 Calibration results for a piezoelectric accelerometer.

5. CONCLUSIONS

By constructing a calibration procedure that uses a virtual amplifier for the shock calibration of piezoelectric accelerometers, we obtained superior calibration results for the charge sensitivities in the acceleration range of 50 m/s^2 to 10,000 m/s^2 with pulse widths in the order of milliseconds. We investigated the charge sensitivities of a high-performance piezoelectric accelerometer (Meggitt 2270) by implementing this calibration procedure, and achieved flat charge sensitivities in the acceleration range. In addition, a BK 2635 charge amplifier was used as the virtual amplifier, which has superior input-output characteristics as compared with a charge amplifier.

ACKNOWLEDGMENTS

This manuscript was supported by an international collaboration between PTB (the working groups “Realization of acceleration” and “Impact Dynamics”) and NMIJ (Vibration and Hardness Section). This work was based on the JSPS (Japan Society for the Promotion of Science) International Program for Young Researcher Overseas Visits.

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