XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

METHOD OF CALIBRATING CHARGE AMPLIFIERS USING A DYNAMIC SPECTRUM ANALYZER

Seung-Hwan Nam[1,2], Yong-Bong Lee[2], Wan-Sup Cheung[2]

[1] Science of Measurement, UST, Republic of KOREA, nams@kriss.re.kr
[2] Center of Fluid and Acoustics, KRISS, Republic of KOREA

Abstract: This paper proposes a simple and salient method of calibrating the charge amplifier required for the primary and/or comparison calibration of vibration and shock transducers. The proposed method exploits the 'sine-sweep' measurement for evaluating the frequency response function (FRF) between the input and output signals using a dual-channel dynamic spectrum analyzer. The principle and theoretical model for the calibration of charge amplifiers are presented. The uncertainty evaluation models for the gain and phase shift are described. Experimental results unveil that the standard uncertainties of the gain and phase shift are less than 0.035 % and 0.05° over the frequency range of 1 Hz to 10 kHz. Compared to the previous methods, one of the salient features of the proposed method is a simple calibration setup consisting of the standard air capacitor and the spectrum analyzer.

Keywords: Charge amplifier, accelerometer, standard capacitor, vibration calibration.

1. INTRODUCTION

Primary calibration systems for vibration transducers, set up and maintained in all NMIs, can't be maintained without calibrating their charge amplifiers. The reason comes from the point that all the transfer standard or working standard accelerometers are commonly a charge output transducer. The charge output transducers have been used for the international key comparisons, i.e. CCAUV.V-K1, CCAUV.V-K2 and APMP.AUV.V-K1. Specifically, recent key comparisons CCAUV.V-K2 and APMP.AUV.V-K1 require the calibration of the phase shift of the charge amplifier in addition to its gain. This trend indicates obviously that a precision calibration of the gain and phase shift of the charge amplifier over the calibration frequency range plays a significant role in the primary calibration of linear and angular vibration transducers.

Usuda *et al.* [1] proposed the substitution method for the calibration of the charge amplifier. Their realization system consists of a standard capacitor, dual inductive voltage dividers, a injection transformer, a dual-channel sine function generator, a differential amplifier, a lock-in amplifier, and the charge amplifier under calibration. This calibration system looks quite a bulky system to maintain all of the measurement uncertainties related to all the passive devices and voltage measurement instruments. But, it seems to be the first reported system with the capacity of calibrating the gain and phase shift of the charge amplifier. Test results [1] were shown limited to the lower frequency range of 100 Hz. But, most NMIs need the more extended lower frequency limit equal to or less than 1 Hz.

On the onset of this work was examined some curiosity about what amount of the measurement uncertainties of the gain and phase shift of the frequency response function measured from the dynamic spectrum analyzer (HP 35670A) exist in the sine sweep mode. A simple electric system, the standard air capacitor (Gen Rad 1403-G, 10 pF) connected to the charge amplifier input, was configured for test. The source output port of the spectrum analyzer was connected to both the channel 1 input of the spectrum analyzer and the input terminal of the standard capacitor. The output of the charge amplifier connected was connected to the channel 2 input of the spectrum analyzer. More detailed configuration is presented in Section 3. Anyway, it was observed from repeated tests that the standard uncertainties of the modulus and phase shift of the measured frequency response functions were extremely encouraging, more specifically never greater than 0.05 % gain and 0.05° phase shift even in the automatic or fixed gain setting modes of both input channels of the spectrum analyzer. This observation was a major motivation in this work.

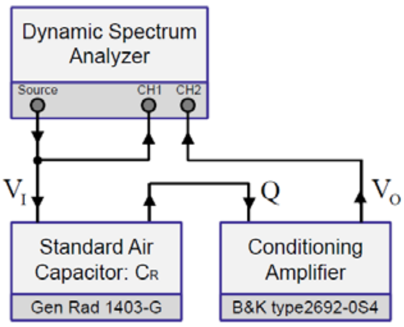
In section 2, basic ideas and theoretical models underlying behind the proposed calibration method are presented. The detailed configuration of the proposed calibration system is also described. In Section 3, the uncertainty evaluation models for the gain and phase shift of the charge amplifier under test are presented. Experimental results are demonstrated in Section 4, which illustrate the achieved uncertainty levels in this work. Finally, concluding remarks are briefly summarized.

2. FRF-BASED CALIBRATION METHOD

A singular model of the dynamic spectrum analyzer (HP 35670A) has never made us disappointed in measuring and analyzing acoustic and vibration measurement signals for longer than twenty years. It still works well for the primary angular vibration calibration system setup in KRISS [2,3].

The use of dynamic spectrum analyzer to calibrate charge amplifiers might be suspicious, as commented by Usuda *et al.* [1]. The authors [1] pointed out technical issues such as cross-channel differences of the gain and phase shift between dual input channels, limited time record length insufficient to the desired resolution of the phase shift and the complexity of evaluating their measurement uncertainties, etc. But, experimental results, which are sufficient to examine quantitatively what amount of measurement uncertainties these technical issues can contribute, are not reported yet.

As commented in Section 1, a simple electric system was configured for the calibration of charge amplifiers. Fig. 1 illustrates the measurement setup for calibrating a charge amplifier under test. As shown in Fig.1 (a), the source output V_I of the dynamic spectrum analyzer (HP 35670A) was connected to both the channel 1 input (CH1) of the spectrum analyzer and the input terminal of the standard capacitor (Gen Rad 1403-G). The capacitor output (charge) Q was connected to the input port of the charge amplifier (B&K type 2692-0S4). The output V_O of the charge amplifier was connected to the channel 2 input of the spectrum analyzer. Fig. 1 (b) shows the photo of the measurement setup.



(a) Block diagram

(b) Photo

Fig. 1 Measurement setup for calibrating the charge amplifier.

When the source voltage $V_I(f)$ of frequency f Hz is supplied, the measured voltage signals $V_1(f)$ and $V_2(f)$ from both channels of the signal analyzer are described as

$$V_1(f) = G_1(f) \cdot V_I(f) \quad (1)$$

$$V_2(f) = G_2(f) \cdot V_O(f) \quad (2)$$

The symbols $G_1(f)$ and $G_2(f)$ indicate the complex gains of the input channel 1 and 2 of the spectrum analyzer. The measured frequency response function (FRF) $H_M(f)$ between both input channels is evaluated as

$$H_M(f) = \frac{V_2(f)V_1^*(f)}{|V_1(f)|^2} = \frac{G_2(f)G_1^*(f)}{|G_1(f)|^2} \cdot \frac{V_O(f)V_I^*(f)}{|V_I(f)|^2} \quad (3)$$

In (3), the superscript * denotes the complex conjugate operator.

The output $Q(f)$ of the calibrated standard (reference) capacitor with capacitance $C_R(f)$ and the charge amplifier output with the unknown (or to be calibrated) complex gain $H_A(f)$ are defined as

$$Q(f) = C_R(f) \cdot V_I(f) \quad (4)$$

$$V_O(f) = H_A(f) \cdot Q(f) \quad (5)$$

By substituting (4) and (5) into (3) and rearranging them, the complex gain $H_A(f)$ of the charge amplifier is finally evaluated as

$$H_A(f) = \frac{1}{C_R(f)} \cdot \frac{H_M(f)}{H_C(f)} \quad (6)$$

In (6), the cross-channel frequency response function $H_C(f)$ is defined as

$$H_C(f) = \frac{G_2(f)G_1^*(f)}{|G_1(f)|^2} \quad (7)$$

The cross-channel FRF is quite readily measured by connecting the source signal to both input channels and measuring their FRFs, as shown in Fig. 2.

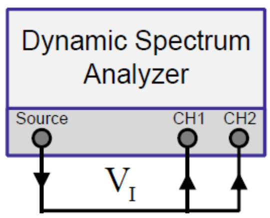


Fig. 2 Schematic setup for measuring the cross-channel FRF.

In this measurement setup, both measured signals of both channels are described as

$$V_1(f) = G_1(f) \cdot V_I(f) \quad (8)$$

$$V_2(f) = G_2(f) \cdot V_I(f) \quad (9)$$

Therefore, the cross-channel FRF $H_C(f)$ in (7) is readily obtained from the measured FRF $H_M(f)$ of the spectrum analyzer given as

$$H_M(f) = \frac{V_2(f)V_1^*(f)}{|V_1(f)|^2} = \frac{G_2(f)G_1^*(f)}{|G_1(f)|^2} = H_C(f) \quad (10)$$

This paper addresses a calibration procedure of the charge amplifier consisting of two measurement steps: (1) measuring the FRF of the charge amplifier output to the applied voltage source under the condition that a calibrated standard capacitor is connected to the input of the charge amplifier under test (refer to Fig. 1 (a)) and (2) measuring the cross-channel FRF by supplying the identical voltage source to both inputs of the spectrum analyzer (refer to Fig. 2). Of course, either of two FRF measurement steps can be first implemented and then the other second.

3. MEASUREMENT UNCERTAINTY MODELS

The measurement uncertainty of the gain and phase shift of the charge amplifier under calibration is evaluated from (6). Let the gain (or modulus) $m_A(f)$ and phase shift $\phi_A(f)$ of the complex sensitivity $H_A(f)$ of the charge amplifier, i.e.

$$H_A(f) = m_A(f)e^{j\phi_A(f)} \quad (11)$$

The modulus and phase shift components of the charge amplifier are described as

$$m_A(f) = \frac{1}{m_R(f)}\frac{m_M(f)}{m_C(f)} \quad (12)$$

$$\phi_A(f) = \phi_M(f) - \phi_C(f) - \phi_R(f) \quad (13)$$

In (12) and (13), modulus and phase shift components defined as

$$C_R(f) = m_R(f)e^{j\phi_R(f)} \quad (14)$$

$$H_M(f) = m_M(f)e^{j\phi_M(f)} \quad (15)$$

$$H_C(f) = m_C(f)e^{j\phi_C(f)} \quad (16)$$

The relative standard uncertainty of the measured modulus component of the charge amplifier is evaluated as

$$u_{r,A}(f) = \frac{u(m_A(f))}{m_A(f)} \quad (17)$$

$$= \left\{\frac{u^2(m_R(f))}{m_R^2(f)} + \frac{u^2(m_M(f))}{m_M^2(f)} + \frac{u^2(m_C(f))}{m_C^2(f)}\right\}^{1/2}$$

The function u(·) in (17) denotes the standard uncertainty which are directly measured or indirectly available from the calibration data sheet. In this work, no correlation is assumed to be between three modulus components m_M, m_C and m_R.

Similarly the standard uncertainty of the phase shift of the charge amplifier is calculated as

$$u(\phi_A(f)) = \quad (18)$$

$$\left\{u^2(\phi_M(f)) + u^2(\phi_C(f)) + u^2(\phi_R(f))\right\}^{1/2}$$

In this work, standard uncertainties $u(m_M)$, $u(m_C)$, $u(\phi_M)$, and $u(\phi_C)$ were directly measured through repeated tests. But standard uncertainties $u(m_R)$ and $u(\phi_R)$ were calculated from the calibration data sheet recorded by the electric standard laboratory in KRISS. No correlation is assumed to be between three phase shift components ϕ_M, ϕ_C and ϕ_R.

4. EXPERIMETAL RESULTS

Before starting experiment, the mainly used input range of the charge amplifier was evaluated. In the primary angular vibration calibration over 1 Hz ~ 1 kHz, the charge output peak range of the working standard accelerometer under calibration was found to be 0.4 pC ~ 4 pC. Thus, a level of 1 pC was chosen in this work. Since the nominal capacitance of the standard air capacitor has 10 pF (calibrated one = 10.001825 pF at 1 kHz), the source voltage of the spectrum analyzer was chosen to be 100 mV-rms such that the 1 pC-rms charge output was supplied to the charge amplifier. Because the sensitivity of the charge amplifier for the primary calibration is set to be 1 V/pC, the input voltage range of the spectrum analyzer was manually selected to be closest to 1 V-rms.

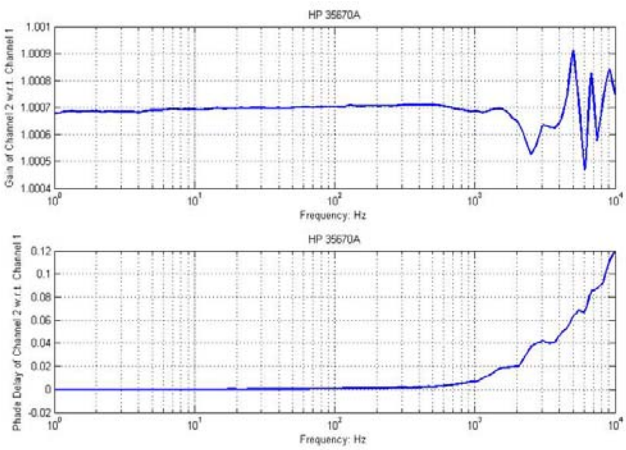


Fig. 3 Averaged cross-channel frequency response function of twenty measurement results.

Fig. 3 shows the averaged cross-channel frequency response function of the twenty measurement results obtained by the spectrum analyzer (HP 35670A). In this cross-channel FRF measurement, the source output voltage was manually set to be 1 V-rms. Below 2 kHz, the cross-channel gain difference was found to be 1.00066 ~ 1.00072 and the phase difference to be equal to and less than 0.02°. Specifically, the cross channel difference over 2 kHz was shown to be 1.00048 ~ 1.00092 in gain and 0.02° ~ 0.12° in phase. These results may indicate that the measured cross-channel FRF should be compensated in calibrating the charge amplifier. Fig. 4 shows the evaluated standard uncertainties of the gain and phase shift of the cross-channel FRF from twenty test results. The relative standard uncertainty of the gain was observed to be 0.003 % ~ 0.017 % from 1 Hz to 10 kHz and the standard uncertainty of the phase difference to be 0.0002° ~ 0.017°.

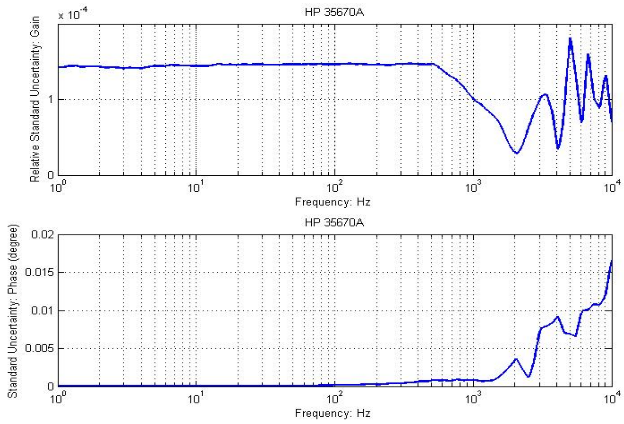


Fig. 4. Standard uncertainties of the modulus and phase shift of the cross-channel FRF evaluated from the twenty test results.

Fig. 5 shows the measured FRF $H_M(f)$ averaged from twenty test results obtained under the condition that the 0.1 V-rms source voltage was applied to the standard capacitor. It is obvious that a large variation in the gain and phase shift of the charge amplifier (B&K 2692-OS4) exists from 1 Hz to 10 kHz. More specifically, it was 0.05 % ~ 0.27 % in the gain and -11.4° ~ 5° in the phase. They may come from the high-pass and/or low-pass filters of the charge amplifier under calibration. Of course, their effects on the calibration of charge output vibration pickups can be minimized by compensating the calibrated gain and phase shift of the charge amplifier.

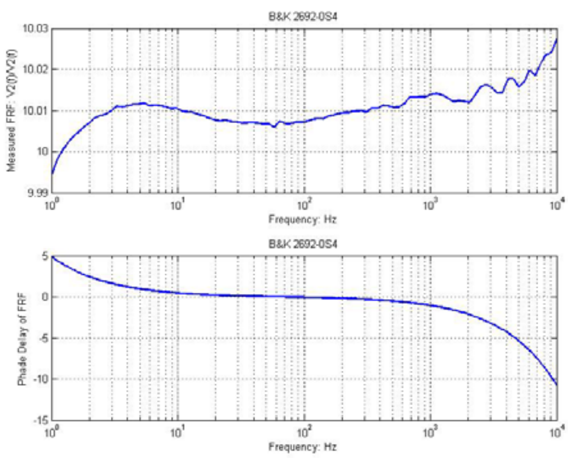


Fig. 5 Measured frequency response function of the charge amplifier averaged from twenty test results.

Fig. 6 shows the standard uncertainties of the gain and phase shift evaluated from the twenty measured FRFs, i.e. the A-type measurement uncertainties of the gain and phase given in Fig. 5. The relative standard uncertainty of the gain was found to be 0.019 % ~ 0.032 % over 1 Hz ~ 10 kHz and the standard uncertainty of the phase shift to be 0.001° ~ 0.04°.

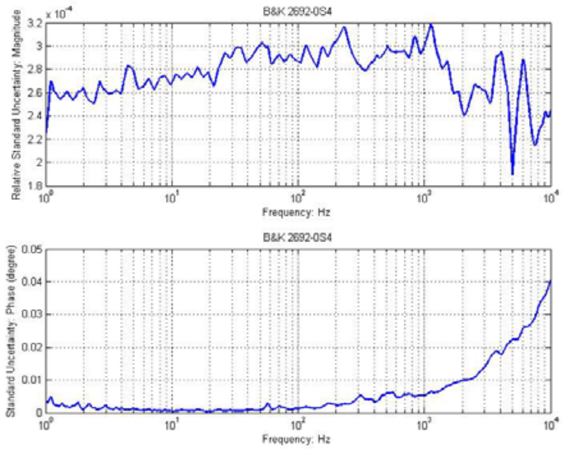


Fig. 6 Standard uncertainties of the gain and phase shift evaluated from twenty measured FRFs.

The standard air capacitor was calibrated only at 1 kHz due to the international traceability of the capacitance measurement in KRISS. Its calibrated capacitance was 10.001825 pF with the expanded uncertainty of 20 ppm (or 0.002 %) (coverage factor k = 2). Its tangent loss was tuned to be equal to or less than 10^{-6} during calibration such that the imaginary part of the complex capacitance $C_R(f)$ was ignored in this work. Moreover, the calibrated capacitance at 1 kHz was assumed to be constant over 1 Hz ~ 10 kHz. Resultantly, the relative standard uncertainty of the standard capacitor was regarded to be 0.001 %, more specifically, $u(m_R)/ m_R$ = 0.001 % and $u(\phi_R) = 0$.

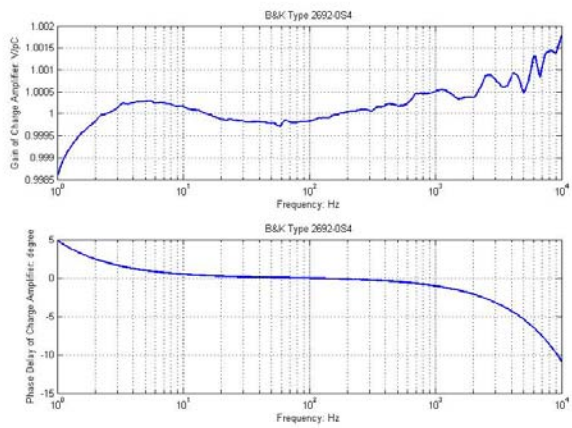


Fig.7 Calibrated gain and phase shift of the charge amplifier (B&K type 2692-0S4).

Fig. 7 illustrates the complex frequency response of the calibrated charge amplifier, which was calculated as in (6) from three measurement data (the calibration sheet of the standard capacitor, the cross-channel FRF and the measured FRF between the input voltage to the capacitor and the output of the charge amplifier. Since the sensitivity setting of the charge amplifier during calibration was 1 V/pC, an ideal value must be unit gain and zero phase shift. But, the measured complex sensitivity of the charge amplifier was observed to be far from the ideal value. Actually, the inverse of the measured complex sensitivity shown in Fig. 7 is multiplied to the measured output of the charge amplifier in calibrating a charge output vibration transducer under calibration.

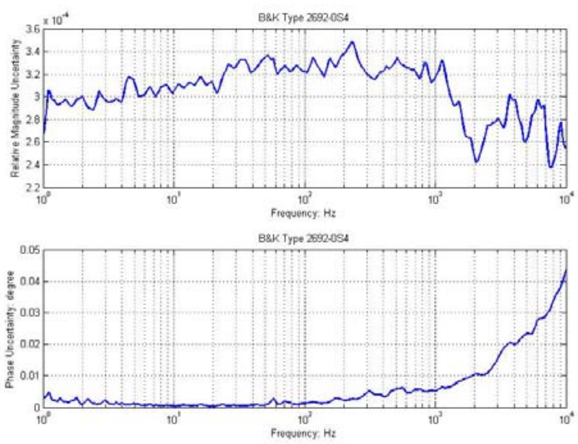


Fig.8 Standard uncertainties of the modulus and phase shift of the calibrated charge amplifier (B&K type 2692-0S4).

As introduced in Section3, the standard uncertainties of the modulus and phase shift of the complex sensitivity of the calibrated charge amplifier (shown in Fig. 7) were calculated according to (17) and (18). Fig. 8 illustrates those of the calibrated charge amplifier. The relative standard uncertainty of the modulus was shown to be 0.024 % ~ 0.035 % over 1 Hz ~ 10 kHz and the standard uncertainty of the phase shift to be 0.001° ~ 0.044° in the same frequency range. These uncertainty results are comparably small in comparison to the typical uncertainty levels of accelerometer calibration (i.e. 0.1 % in modulus and 0.1° in phase shift).

5. CONCLUDING REMARKS

This paper proposes a simple and salient method of calibrating the charge amplifier required for the primary and/or comparison calibration of vibration and shock transducers. The proposed method exploits the ‘sine-sweep’ measurement for evaluating the frequency response function (FRF) between the input and output signals using a dual-channel dynamic spectrum analyzer. The principle and theoretical model for the calibration of charge amplifiers are presented. The uncertainty evaluation models for the gain and phase shift are described. Experimental results unveil that the standard uncertainties of the gain and phase shift are less than 0.035 % and 0.05° over the frequency range of 1 Hz to 10 kHz. Compared to the previous methods, one of the salient features of the proposed method is a simple calibration setup consisting of the standard air capacitor and the spectrum analyzer.

It should be noted that the capacitance of the standard air capacitor was calibrated only at 1 kHz and that the calibrated value and its uncertainty were assumed to be constant over the frequency range of interest in this paper. Really, an internationally linked traceability of the electric impedance including the capacitance is not yet established in the low frequency of equal to or less than 40 Hz. Moreover, that of AC voltage is also under the similar situation. Further advance in calibrating vibration pickups even below 10 Hz could delay without establishing the international traceability in calibration and measurement of AC voltage and electric impedance quantities.

The proposed method of calibrating the charge amplifier using the spectrum analyzer is expected to be realizable in precision digital voltage measurement systems, i.e. data acquisition systems with the high bit resolution of 16 to 24 bits and the high sampling rate of 1 MHz to 20 MHz. By exploiting them, further attempts in KRISS have been started to improve and extend the calibration and measurement capability of the modulus and phase shift of the charge amplifier better than results presented in this paper.

ACKNOWLEDGEMENT

This work was supported by the KRISS project, “Establishment of National Physical Measurement Standards and Improvement of Calibration Measurement Capability.”

REFERENCES

[1]T. Usuda, A. Oota, H. Nozato, and T. Ishigami, Y. Nakamura, and K. Kudo, “Development of charge amplifier calibration system employing substitution method,” *IMEKO 20th TC3, 3rd TC16 and 1st TC22 International Congress*, Merida, Mexcico, 2007.

[2] Wan-Sup Cheung and Cheol-Ung Chung, “Angle prism-based laser interferometer for high prision measurement of angular vibration,” *TC22, IMEKO XVIII World Congress*, Rio de Janeiro, Brasil, 2006.

[3] Wan-Sup Cheung and Torben Licht, “Progress in development of calibration systems for angular vibration pickups,” *TC22, IMEKO XIX World Congress*, Lisbon, Portugal, 2009.