IMEKO 20th TC3, 3rd TC16 and 1st TC22 International Conference
*Cultivating metrological knowledge*
27th to 30th November, 2007. Merida, Mexico

# Development of charge amplifier calibration system employing substitution method

Takashi Usuda, Akihiro Oota, Hideaki Nozato, Tamio Ishigami, Yasuhiro Nakamura, and Katsuhisa Kudo

National Metrology Institute of Japan, Advanced Industrial Science and Technology

**Abstract**

Charge amplifier is a key device for vibration metrology as well as an accelerometer itself. Reliability of vibration measurement heavily depends on the stability and frequency characteristics of charge amplifier. Especially, phase characteristic of charge amplifier becomes more important as many calibration sectors have adopted Sin-approximation method which enables calibration of accelerometer phase shift.

In this paper, development of charge amplifier calibration system both for amplitude (gain) and phase is reported. The calibration system consists of standard capacitor, inductive voltage divider, injection transformer, and sine signal generator. Because the system does not contain any active device such as voltmeter or A/D converter which requests periodic calibration, it is quite stable and reliable without any maintenance including periodical calibration. The system enables calibration uncertainty of 1.3E-3 % in gain and of 6E-5 deg. in phase shift at 160 Hz.

Key words: Piezo-electric accelerometer, charge amplifier, calibration, phase-shift, sine approximation method

## 1. Introduction

Primary calibration of accelerometer at National Metrology Institutes (NMIs) is usually provided in compliance with ISO 16063-11 (Methods for the calibration of vibration and shock transducers Part 11: Primary vibration calibration by laser interferometry)[1].

There are three methods described, Fringe-counting method, Minimum-point method, and Sine-approximation method. Sine-approximation method is eligible to evaluate both sensitivity and phase-shift (time delay between the mechanical input and the electrical output signal) while other two methods are only eligible to evaluate sensitivity (ratio of the mechanical input to the electrical output signal). Meanwhile, phase-shift of accelerometer evaluation becomes more important in industries, especially in the field of modal analysis. Thus some NMIs obtained Sine-approximation method and provide phase-shift evaluation as well as sensitivity recently [2][3].

Usually, accelerometer consists of pick-up (seismic component which has charge output: unit is Coulomb per acceleration) and charge amplifier (electrical component which has voltage output). Sine-approximation method provides phase-shift character of accelerometer output, i.e. as a combination of pick-up and charge amplifier. However, user may combine arbitral pick-up and charge amplifier on their practical use. Thus separated evaluation of pick-up and charge amplifier is expected.

Usually, frequency characteristics of charge amplifier both of gain and phase can be evaluated by employing standard capacitor, sine-generator and 2 channel wave memory as shown in Fig.1. However, wave memory should have sufficient A/D conversion resolution for accurate gain calibration and should have sufficient record length and time resolution for phase shift calibration. Especially, A/D conversion ratio (or ratio between each channel in Fig. 1 in this case) should be calibrated shortly as A/D converter is not so stable. Uncertainty evaluation is also complicated.

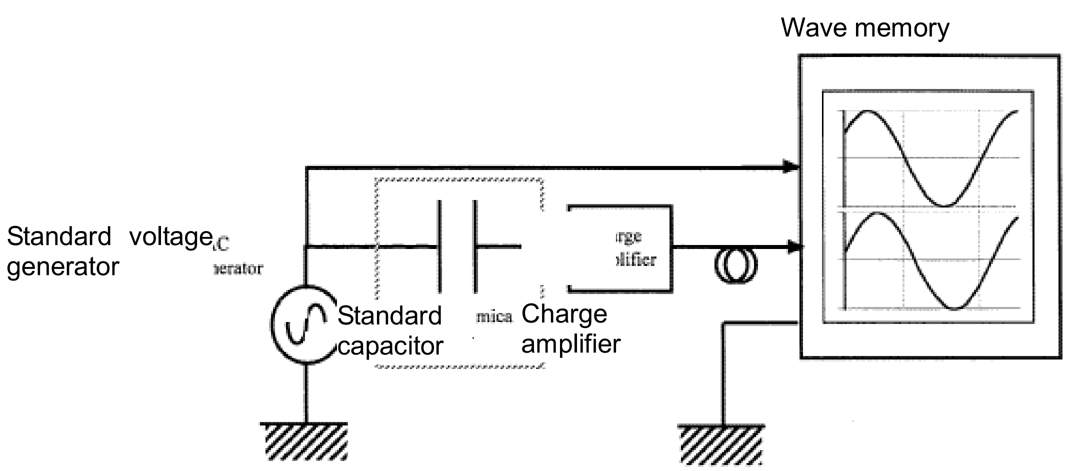


Fig. 1 Setup for gain and phase shift evaluation of charge amplifier

In this paper, we propose and demonstrate charge amplifier primary calibration system employing substitution method. The calibration system consists of standard capacitor, inductive voltage divider, injection transformer, and sine signal generator.

Because the system does not contain any active device such as voltmeter or A/D converter which requests periodic calibration, it is quite stable and reliable without any maintenance including periodical calibration.

## 2. Principle of the calibration

To evaluate electrical gain (or attenuation) of an artifact, substitution method has been applied from the past. Fig. 2 shows an example for charge amplifier calibration setup, which consists of voltage source, voltmeter and attenuator. The attenuator is inserted to the input of charge amplifier. The voltmeter can observe voltage source output and charge amplifier output alternatively. When the two outputs from voltage source and charge amplifier show the same level, the attenuation inverse ratio is the amplifier gain. With this method, voltage source and voltmeter do not need calibration if the attenuator has been calibrated. Moreover, attenuator does not require periodic calibration, as it is a static and stable device.

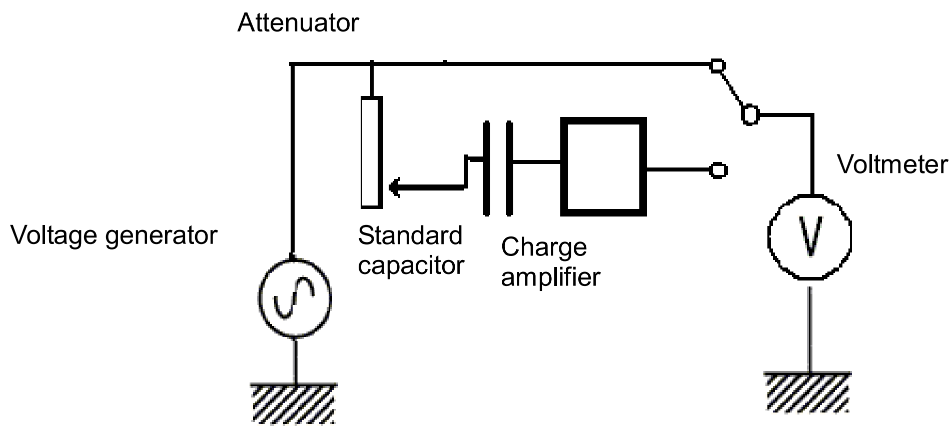


Fig. 2 Gain calibration setup by substitution method

Needless to say, the method above cannot be applied for phase-shift calibration. However, it can be calibrated if impedance can be changed. Based on this methodology, we developed a charge amplifier calibration system employing substitution method.

Fig. 3 shows a schematic diagram of the system. Main component of the system consists of 2 inductive voltage dividers (IVD1, IVD2), injection transformer, 2 channel sine generator, standard capacitor, differential amplifier and lock-in amplifier.

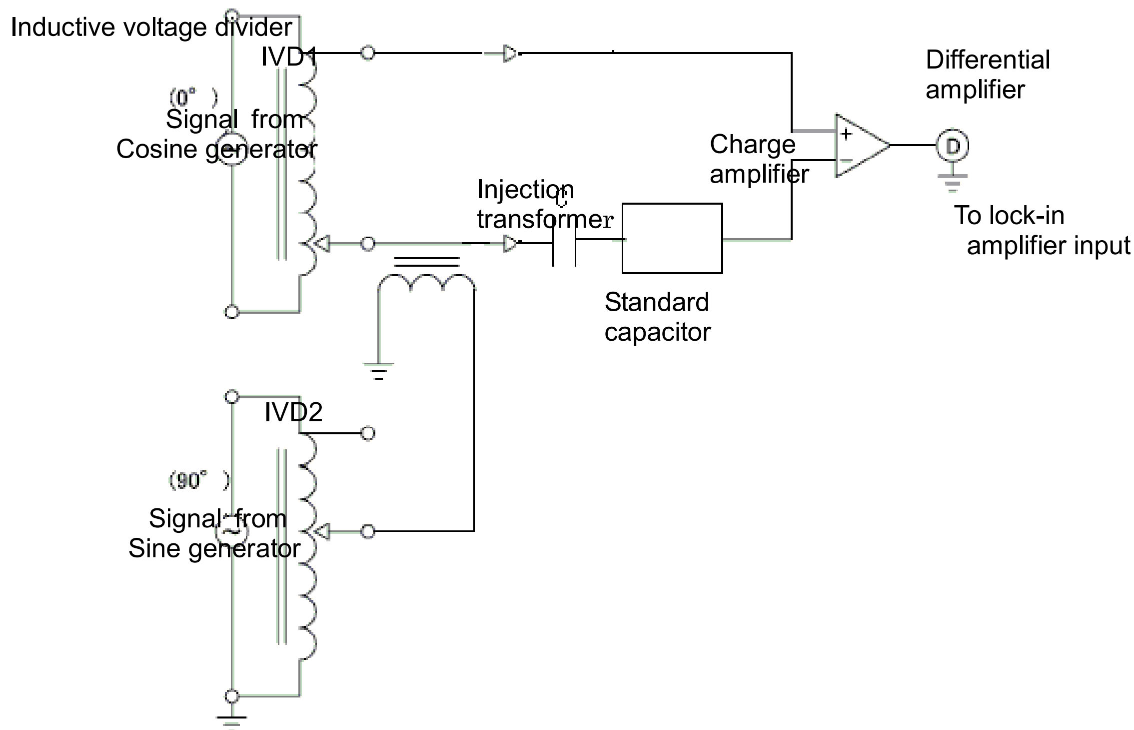


Fig. 3 Schematic diagram of charge amplifier calibration system employing substitution method

90 degree phase shifted voltage signals ( $\hat{V}_{in}\cos 2\pi ft$ , $\hat{V}_{in}\sin 2\pi ft$ ) from sine generator are induced to the primaries of IVD1 and IVD2. Here $\hat{V}_{in}$ is amplitude, $f$ is frequency and $t$ is time. Divided voltage outputs from IVD1 and IVD2 are then synthesized by the injection transformer and introduced to the standard capacitor. Fig. 4 shows relations of phase of each output voltage from IDV1, IDV2 and injection transformer.

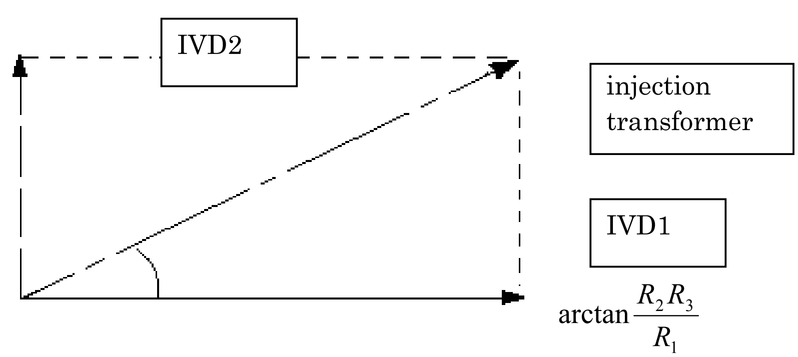


Fig. 4 Phase of each output voltage from IDV1, IDV2 and injection transformer.

The output phase of injection transformer can be changed according to the ratio between output voltage from IDV1, IDV2. The induced voltage to the standard capacitor $V_{Cin}(t)$ can be described as

$$V_{Cin}(t) = \sqrt{R_1{}^2 + (R_2 R_3)^2}\,\hat{V}_{in} \cos\left(2\pi ft - \arctan\frac{R_2 R_3}{R_1}\right) \tag{1}$$

where $R_1$ and $R_2$ are transformer ratios of VD1 and VD2 respectively. $R_3$ is transformer ratio of the injection transformer.

Output voltage from charge amplifier $V_{Cout}(t)$ can be described as

$$V_{Cout}(t) = A_{CA} C \sqrt{R_1{}^2 + (R_2 R_3)^2}\,\hat{V}_{in} \cos\left(2\pi ft - \arctan\frac{R_2 R_3}{R_1} + \phi_{CA}\right) \tag{2}$$

where $C$ is capacity of standard capacitor, $A_{CA}$ and $\phi_{CA}$ are gain and phase-shift of charge amplifier respectively.

Operator adjusts $R_1$ and $R_2$ so that the charge amplifier output amplitude becomes $\hat{V}_{in}$, and charge amplifier output phase-shift becomes zero. This shall be confirmed by differential amplifier and lock-in amplifier as it indicates differences of amplitude and phase between charge amplifier output and original signal ($\hat{V}_{in} \cos 2\pi ft$). Under this condition, gain and phase-shift can be expressed as follows

$$A_{CA} = \left(C\sqrt{R_1{}^2 + (R_2 R_3)^2}\right)^{-1} \tag{3}$$

and

$$\phi_{CA} = \arctan\frac{R_2 R_3}{R_1} \tag{4}$$

.

As shown in equations (3) and (4), we can obtain gain and phase only by employing the transformer ratios of IVD1, IVD2 and the fixed transformer ratio of injection transformer. We should note that this method has following advantages compared to the conventional method shown in Fig. 1.

- Output voltage fluctuation from sine generator does not affect the calibration results.
- Most of all key components are static devices such as inductance and capacitor and have good long term stability. Thus short term calibration is not requested.
- Other active devices such as differential amplifier and lock-in amplifier can be checked autonomously without any reference artifact.

### 3. Prototype of the system

The resolution of inductive voltage divider is 1 ppm. The ratio of injection transformer is 1/100. A 100 pF standard air capacitor is employed. Two channel sine-wave generator produces sine and cosine signals over the calibration frequency range. The inductive devices (voltage divider and injection transformer) can be applied from some tenth Hz to 10 kHz. Thus the system can cover the most of all commercial charge amplifier operation range (e.g. 20 Hz to 10 kHz). Synchronous signal to the lock-in amplifier is induced from sine-wave generator. Fig. 5 shows the prototype of the system.

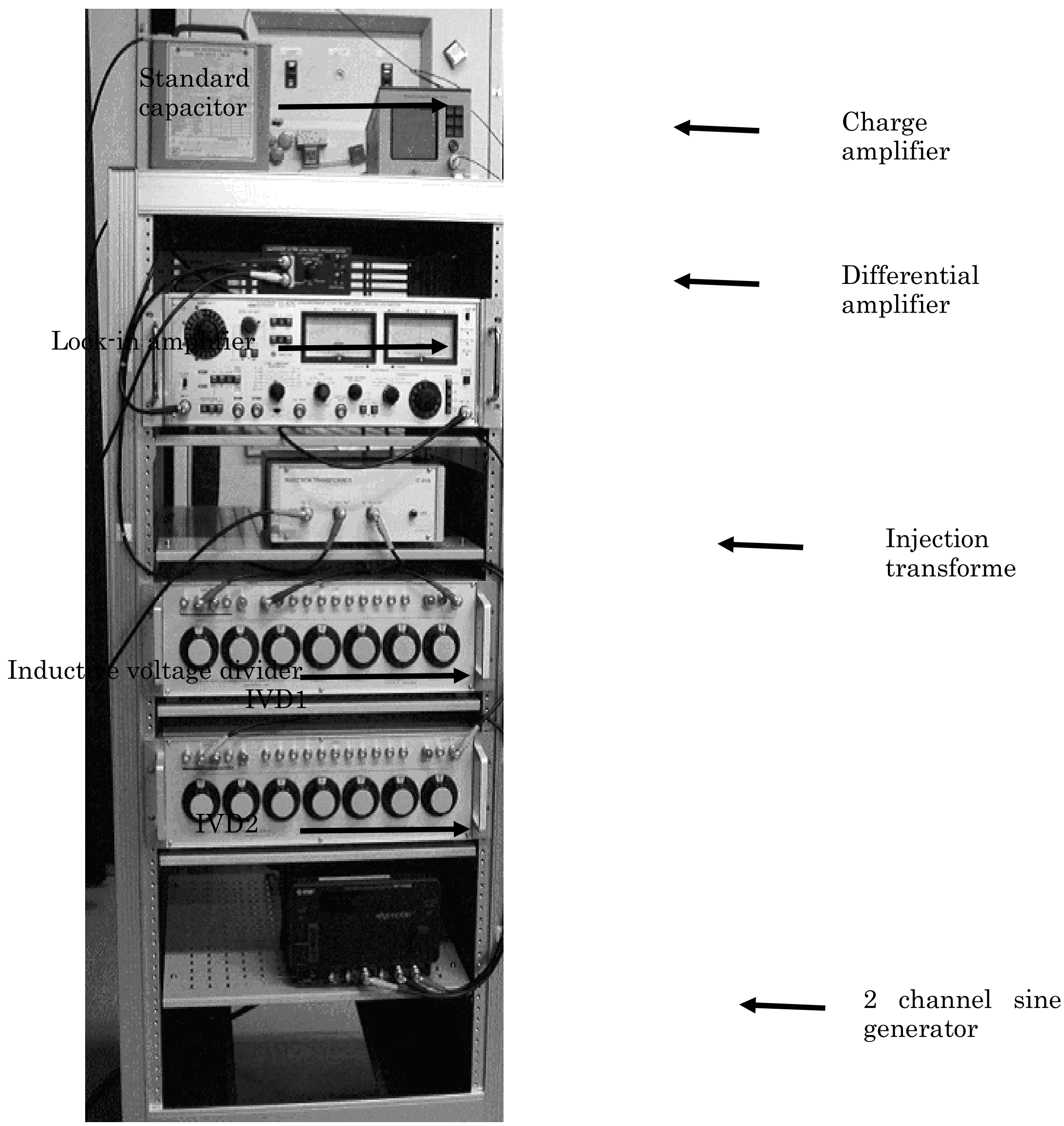


Fig. 5 Outlook of the system

## 4. Experimental result and uncertainty

Charge amplifier type 2525 of Brüel & Kjær is evaluated. Fig. 6 shows gain and Fig. 7 shows phase-shift obtained by the system. Gain and phase-shift are successfully evaluated.

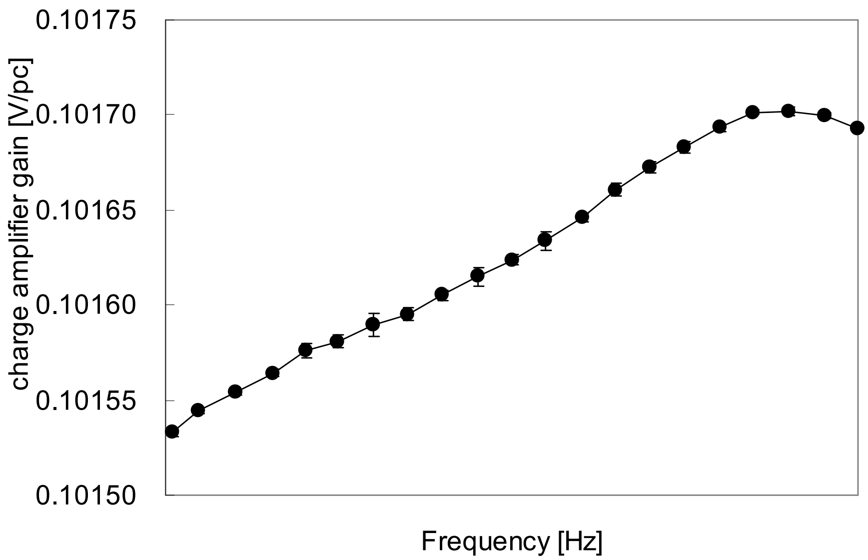


Fig. 6 Gain characteristic of charge amplifier obtained by the system

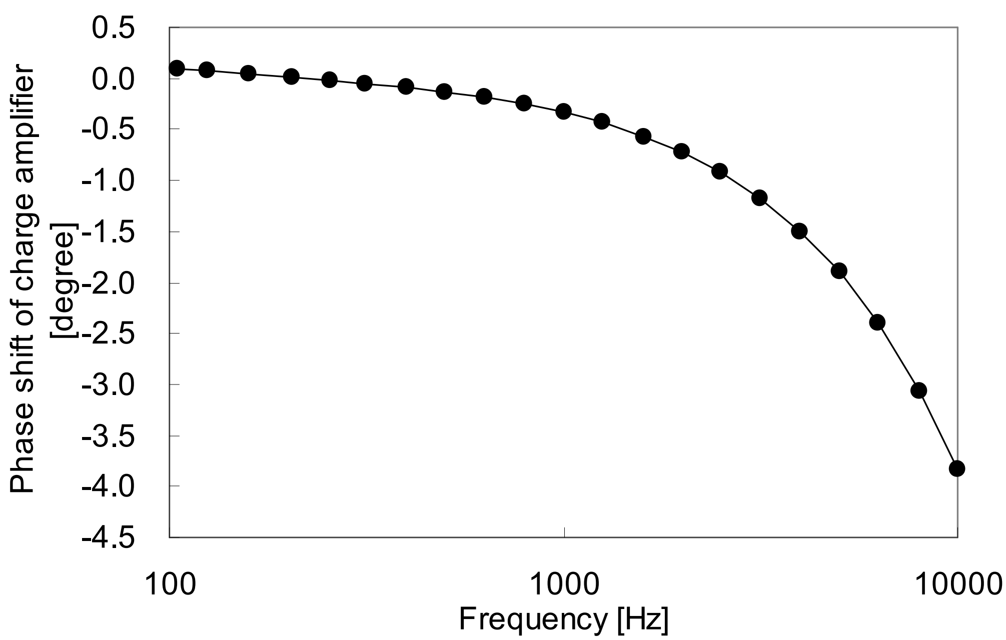


Fig. 7 Phase characteristic of charge amplifier obtained by the system

According to equation (3), uncertainty of gain can be described as

$$\left[\frac{u(A_{CA})}{A_{CA}}\right]^2 = \left[\frac{u(C)}{C}\right]^2 + \left[\frac{R_1}{R_1^{\ 2}+(R_2R_3)^2}\right]^2 u^2(R_1) + \left[\frac{R_2R_3^{\ 2}}{R_1^{\ 2}+(R_2R_3)^2}\right]^2 u^2(R_2) + \left[\frac{R_2^{\ 2}R_3}{R_1^{\ 2}+(R_2R_3)^2}\right]^2 u^2(R_3) \tag{5}$$

Here, $u(C)$ is standard capacitance uncertainty which is given as B type uncertainty. $u(R_1)$ and $u(R_2)$ are uncertainty of IVD1 and IVD2. They include its intrinsic uncertainty (B type) and setting error (A type). $u(R_3)$ is uncertainty of injection transformer ratio which is given as B type uncertainty.

According to equation (4), uncertainty of phase-shift can be described as

$$u(\phi_{CA}) = \pm\left\{\left[\frac{\partial\phi_{CA}}{\partial R_1}\right]^2 u^2(R_1) + \left[\frac{\partial\phi_{CA}}{\partial R_2}\right]^2 u^2(R_2) + \left[\frac{\partial\phi_{CA}}{\partial R_3}\right]^2 u^2(R_3)\right\}^{1/2} \tag{6}$$

Employing proposition

$$\frac{\partial(\arctan x)}{\partial x} = \frac{1}{1+x^2},$$

equation (6) can be described as

$$u(\phi_{CA}) = \pm\left\{\left[\frac{R_2R_3}{R_1^{\ 2}+(R_2R_3)^2}\right]^2 u^2(R_1) + \left[\frac{R_1R_3}{R_1^{\ 2}+(R_2R_3)^2}\right]^2 u^2(R_2) + \left[\frac{R_1R_2}{R_1^{\ 2}+(R_2R_3)^2}\right]^2 u^2(R_3)\right\}^{1/2} \tag{7}$$

We evaluated each uncertainty sources as

$u(C)$: 6E-4 %, $u(R_1)$: 3E-4 %, $u(R_2)$: 2E-7 %, and $u(R_3)$: 4E-2 % at 160 Hz.

Accordingly, we obtained charge amplifier calibration uncertainty of 1.3E-3 % in gain and 6E-5 degree in phase shift ($k$=2) at 160 Hz.

Those uncertainty levels are small enough compare with typical uncertainty of accelerometer calibration (e.g. 0.1 % level in sensitivity and 0.1 degree level in phase-shift).

## 5. Conclusion

Charge amplifier primary calibration system employing substitution method is proposed and demonstrated. The system consists of 2 inductive voltage dividers, injection transformer, 2 channel sine generator, standard capacitor, differential amplifier and lock-in amplifier. The system enables calibration both of gain and phase-shift directly. Estimated uncertainty is small enough compare with overall uncertainty of accelerometer calibration. The system is quite stable as the key devices are static one. It does not request periodic calibration. We are planning to develop the working model so that users may evaluate own charge amplifier by themselves.

## Acknowledgements

This work was supported by NEDO (New Energy and Industrial Technology Development Organization) under "Technology Development for an e-trace System" program.

## References

[1] ISO 16063-11:1999 Methods for the calibration of vibration and shock transducers -- Part 11: Primary vibration calibration by laser interferometry.

[2] I. Veldman,H-J. von Martens, Final report on supplementary comparison SADCMET.AUV.V-S1, Metrologia, 2004, 41, Tech. Suppl., 09001.

[3] T. Usuda, M. Dobosz, T. Kurosawa, The methods for the calibration of vibration pick-ups by laser interferometry: part III. Phase-lag evaluation, Meas. Sci. Technol. 9 (1998) 1672–1677.