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BILATERAL COMPARISON IN PRIMARY VIBRATION CALIBRATION OF NPL, INDIA AND THE MODAL SHOP, USA.

Naveen Garg[1], *Tushya K. Saxena*[1] *& Mark I. Schiefer*[2]

[1]Apex Level Standards & Industrial Metrology Division, CSIR-National Physical Laboratory,
New Delhi - 110 012, India. E-mail: ngarg@mail.nplindia.ernet.in

[2]The Modal Shop Inc, Technology Development, 3149 E. Kemper Rd,
Cincinnati Ohio 45241, USA. E-mail: mschiefer@modalshop.com

Abstract: The paper presents a bilateral comparison for measurement of accelerometer sensitivity in frequency range from 0.1 Hz to 20 kHz between NPL, India and The Modal Shop, USA. Two artefacts were utilized for bilateral comparison, one PCB 353B04 sensor and another for the low frequency, PCB Q353B51 along with ICP sensor signal conditioner. The measurements were conducted in the low frequency range from 0.1 Hz to 100 Hz for the PCB Q353B51, while the PCB 353B04 sensor was used in frequency range 5 Hz to 20 kHz. The results of the bilateral comparison show an E_n value less than 0.5 for both the accelerometers. The comparison of results with PCB calibrated values shows a maximum deviation of 0.7 % at 0.1 Hz, which lies well within the measurement uncertainty stated at low frequencies.

Keywords: Measurement uncertainty, Calibration & Measurement Capabilities (CMCs).

1. INTRODUCTION

The National standard for primary vibration calibration has been established at NPL, India in the entire measurement frequency range of 0.1 Hz to 20 kHz. The system is not only helpful in establishment of strong traceability chain throughout the country, but also facilitates the calibration of seismic sensors for ground vibration studies [1]. NPLI realizes the primary vibration calibration using two systems: one of The Modal Shop, USA (TMS), Make: TMS 9155 and other using Brüel & Kjær (B&K) model 3629 calibration system established in year 2005 in frequency range 5 Hz to 5 kHz. The B&K system has been used for participation in the comparison *APMP.AUV.V.K1.2* with NIM China and KIM-LIPI, Indonesia. NPLI vibration Calibration and Measurement Capabilities, (CMCs) have been included in the Key Comparison data base (KCDB) since January, 2012 in measurement frequency range of 40 Hz to 5 kHz. Since then continuous efforts are focussed on reducing the measurement uncertainty and validation of CMCs for the low frequency range. The long-stroke shaker APS 113AB integrated in NPLI system is used for low frequency calibrations and provides a suffcient maximum stroke [2]. Good agreement exists between the results obtained using the Discrete Fourier Transform (DFT) of voltage and displacement signals and approximating the discrete time phase signal as sine function and results obtained on B&K 3629 calibration system. The results obtained with the new system compare well (<1%) with those of manufacturer's results for verification sensor [1]. In order to ascertain the validity of low frequency accelerometer calibration, an informal comparison was planned with the manufacturer, The Modal Shop, USA (TMS) to compare the performance of the system. TMS, a PCB group company has been accredited by *A2LA* in field of primary accelerometer calibration in frequency range from 0.5 Hz to 20 kHz. Both NPLI and TMS, USA utilized the same methodology and primary vibration calibration system, TMS 9155D at their respective laboratories for the comparison. The expanded measurement uncertainty (k=2, 95 % confidence interval) for determination of sensitivity in mV/ (m·s^{-2}) is enlisted in table 1.

Table 1. Expanded uncertainty (in %) stated by NPLI and TMS for bilateral comparison.

Frequency range	**Expanded uncertainty (in %)**	
	NPLI	**TMS**
5 Hz ≤ f ≤ 1 kHz	0.7	0.5
1 < f ≤ 5 kHz	0.7	0.7
5 < f ≤ 10 kHz	1.2	1.0
10 < f ≤ 15 kHz	1.5	1.2
15 < f ≤ 20 kHz	2.0	1.7

2. MEASUREMENT PROTOCOL

The bilateral comparison was informally undertaken in two steps. Initially, a PCB 353B04 (S. No. LW160454) sensor was hand carried from TMS to NPLI in November, 2012. After NPLI completed the measurements, the sensor was taken back by a TMS representative. The transducer was calibrated at TMS, USA. At the beginning and the end of the exercise, the transducer was calibrated at TMS to ascertain the reference value and monitor the stability of the transducer. The frequency range of measurement was mutually agreed to be from 5 Hz to 20 kHz. The specific aspects taken in consideration while doing measurements were [3]:

- acceleration amplitude in range 10 m/s^2 to 100 m/s^2,
- ambient temperature within (23 ± 2) ºC,
- maximum relative humidity of 75 % and
- mounting torque of accelerometer of (2.0 ± 0.1) N m.

In order to reduce the influence of non-rectilinear motion, the repetitive measurements were performed for at least four symmetrical laser positions so as to analyze the random uncertainty associated. The Dual-mode charge amplifier (PCB 443B101) was calibrated using a calibrated 1 nF standard capacitor. The next step was the comparison for the low frequency measurement range. The artefact chosen for this exercise was a PCB Q353B51 (S. No. 152691) along with ICP sensor signal conditioner. The artefact was transported from TMS to M/s SSPL, Hyderabad and then hand carried to NPLI in January, 2013. The frequency range of measurement was agreed to be from 0.1 Hz to 100 Hz. The objective was to measure the modulus of complex voltage sensitivity of the accelerometer with power supply unit at different frequency and acceleration amplitude of 1 m/s^2 to 50 m/s^2. The voltage sensitivity is calculated as the ratio of amplitude of output voltage of accelerometer with power supply unit to the amplitude of acceleration at its reference surface [4]. In order to avoid the influence of non-rectilinear motion, the measurements were distributed over the respective measurement surface.

The results so obtained by the two laboratories viz., TMS and NPLI were then compared with PCB calibrated values. The low frequency transducer was sent to PCB Piezotronics, USA (PCB) for comparison. PCB reported the results in range 0.1 Hz to 3 Hz using earth's gravity [5], long stroke shaker in range 0.5 Hz to 10 Hz and high frequency shaker in range 10 Hz to 100 Hz. The rotator method used for low frequency comparison has an excellent correlation with maximum deviation of 0.05 % between rotator and long stroke shaker at 3 Hz, which is the upper end of the rotator frequency range. The E_n value is obtained from the expression:

$$E_n = \frac{S_{NPLI} - S_{TMS}}{\sqrt{U_{NPLI}^2 + U_{TMS}^2}} \qquad (1)$$

where S_{NPLI} and S_{TMS} are the sensitivity determined by NPLI and TMS in mV/ (m·s^{-2}) and U_{NPLI} and U_{TMS} are the expanded measurement uncertainty of the two laboratories.

3. RESULTS & DISCUSSION

The analysis of results for PCB353B04 sensor showed an E_n value less than 0.5 in the entire measurement frequency range of 5 Hz to 20 kHz as shown in fig 1.

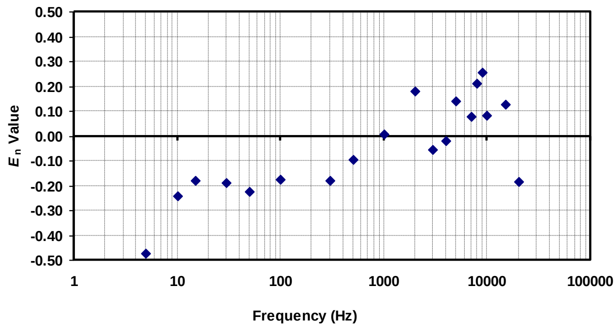

Figure 1. E_n values for the comparison in frequency range 5 Hz to 20 kHz between TMS and NPLI.

The results were then used to evaluate the weighted mean sensitivity for the two laboratories as shown in fig 2. The weighted mean ($\boldsymbol{x_{R,f}}$) with its associated combined expanded uncertainty of measurement, $\boldsymbol{U_{x(R,f)}}$ is calculated for sensitivity measured in mV/ (m·s^{-2}) as [6]:

$$x_{R,f} = \left(\frac{\sum \frac{x_i}{U_i^2}}{\sum \frac{1}{U_i^2}} \right) \qquad (2)$$

where x_i is sensitivity in mV/ (m·s^{-2}) of each laboratory and U_i is respective expanded uncertainty stated by each laboratory.

$$U^2_{x(R,f)} = \frac{1}{\sum \frac{1}{U_i^2}} \qquad (3)$$

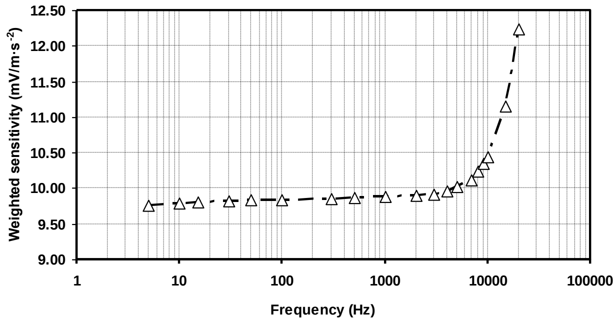

Figure 2. Weighted mean sensitivity for comparison in frequency range 5 Hz to 20 kHz for TMS and NPLI.

The measurement results at high frequency showed an E_n values less than 0.3 which is quite appreciable at high frequencies. Both NPLI and TMS utilized homodyne interferometer for displacement measurements.

The low frequency measurement were analysed and an E_n value less than 0.5 was observed in the entire measurement frequency range. This was quite appreciable particularly in ultra low frequency range (0.1 < f ≤ 0.5 Hz) whereby an expanded uncertainty of 1.4 % is stated by NPLI.

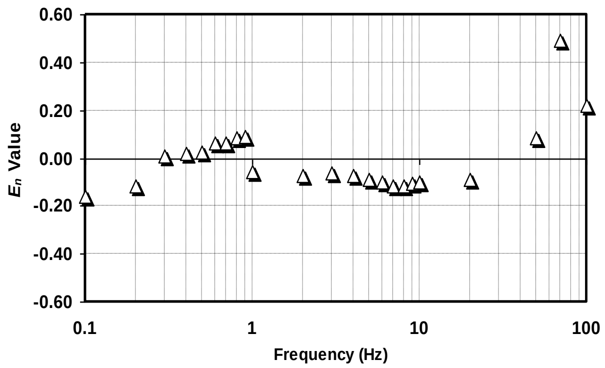

Figure 3. E_n value for the comparison in frequency range 0.1 Hz to 100 Hz between TMS and NPLI.

Table 2. Expanded uncertainty (in %) stated by NPLI and TMS for bilateral comparison.

Frequency range	Expanded uncertainty (in %)	
	NPLI	TMS
$0.1 < f \leq 0.5$ Hz	1.40	0.90
$0.5 < f \leq 5$ Hz	0.75	0.70
$5 < f \leq 100$ Hz	0.50	0.50

The expanded measurement uncertainty (k=2, 95 % confidence interval) for determination of sensitivity in mV/(m·s^{-2}) in frequency range 0.1 Hz to 100 Hz using low frequency shaker is enlisted in table 2. The maximum E_n value of 0.49 observed at 70 Hz is attributed to the similar measurement uncertainty of 0.5 % stated by two laboratories although the deviation in NPLI reported sensitivity w.r.t TMS is observed as 0.34 %.

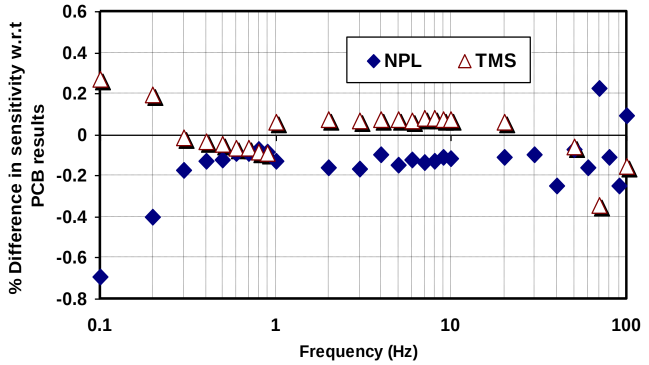

Figure 4. Relative difference of NPLI and TMS calibration results compared with PCB results

The results were then compared with PCB values as shown in fig. 4. TMS results were very close to PCB values in the frequency range 1 Hz to 10 Hz, with maximum deviation of 0.08 %. The deviations excluding this frequency range is less than 0.30 %. NPL results differ from PCB values maximum by 0.30 % in frequency range 0.3 Hz to 100 Hz. The deviation at 0.1 Hz was observed to be 0.7 % and at 0.2 Hz was 0.4 %. The weighted mean sensitivity was also calculated using equations (2) & (3). The weighted mean values were compared with PCB values. The percentage difference between the weighted mean sensitivity and the PCB value was 0.61 % at 0.1 Hz, 0.34 % at 0.2 Hz.

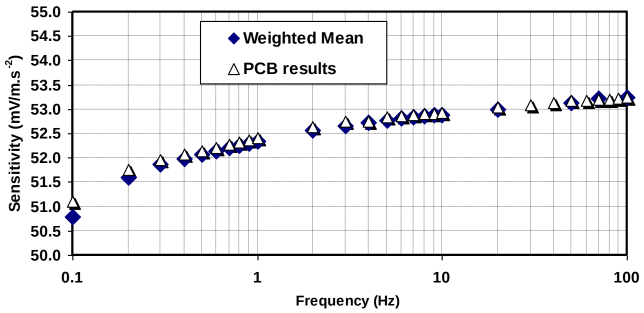

Figure 5. Weighted mean sensitivity for NPLI and TMS in comparison with the PCB sensitivity values in frequency range 0.1 Hz to 100 Hz.

The difference was less than 0.15 % in the frequency range 0.3 Hz to 100 Hz as shown in fig 5. The calibration of accelerometers in low frequency range below 100 Hz is a special challenge. Thus, use of an high quality air-bearing, long-stroke vibration exciter, mounted on a heavy rigid base which is well isolated from ambient vibration is mandatory [7]. The harmonic distortion was observed to drop from 11.5 % at 0.1 Hz to 1.04 % at 100 Hz as shown in fig 6, whereby a maximum random uncertainty of 0.31 % at 0.1 Hz was observed. However, the sine approximation method and DFT methods are less susceptible by distortion as they are frequency-selective methods [8]. The measurement accuracy associated with voltage output of accelerometer at lower frequencies is however a limiting factor in measurement uncertainty. Veldman [9] work pertaining to calibration of *DAQ* devices by implementing AC voltage measurement techniques with proven traceability to DC voltage in conjunction with use of least squares linear fit approach show a measurement accuracy better than 0.01 % over a wide frequency range. At low frequency, because of the large displacement, shaker transverse motion is extremely small, in comparison with the peak to peak displacement. As a result, the influence of transverse motion on the sensor under test (*SUT*) output is negligible. Above 10 Hz however, the influence of transverse motion can become significant, especially if the shaker payload is not centered on the armature.

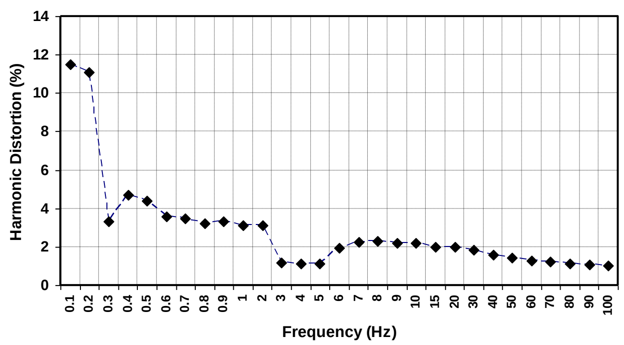

Figure 6. Harmonic distortion in low frequency measurements in range 0.1 Hz to 100 Hz.

Transverse motion limits are required by ISO 16063-11 [10] to be less than 1% for frequencies below 10 Hz, less than 10% for frequencies below 1000 Hz and less than 20% for frequencies below 10 kHz. The measurement of transverse motion for the medium frequency range (on PCB 396C11 shaker) has been observed to lie well within the transverse limits recommended by the *ISO 16063-11* standard [10,11].

4. CONCLUSIONS

The paper presented an informal comparison carried out between NPL, India and The Modal Shop, USA. The results for low frequency have been compared with PCB results for the same transducer calibrated at PCB, Piezotronics. The maximum deviation of 0.7 % at 0.1 Hz supports the uncertainties of measurement estimated by the participants within the comparison frequency range.

This comparison was planned to be a preliminary exercise before finally registering for participation in an International Key Comparison exercise. The measurement results have inculcated a confidence in methodology and instrumentation used in realizing the primary vibration calibration standard by laser interferometery and also provided an opportunity to reduce measurement uncertainties in ultra low frequency range of 0.1 Hz to 0.5 Hz. Participation in future Key Comparison exercises with NMIs shall give an opportunity to investigate the extent of deviations particularly at low frequencies from the Key Comparison Reference Value (KCRV) for validation of NPLI CMCs in the low frequency range as well.

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5. REFEERNCES

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