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ORIGINAL PAPER

Measurement Uncertainty in Vibration Calibration in Frequency Range of 5 Hz to 10 kHz

N. Garg[1,2]* and B. S. Chauhan[1,2]

[1]CSIR-National Physical Laboratory, New Delhi, India

[2]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India

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Abstract: The paper evaluates the measurement uncertainty in realizing the secondary vibration standard at CSIR-National Physical Laboratory, India, and presents a comparison of the measurement uncertainty of secondary standard with that of primary vibration standard. The relative expanded measurement uncertainty of 0.80% to 2.2% in frequency range of 5 Hz to 10 kHz is evaluated. The measurement uncertainty so calculated is verified by comparison with the results from primary vibration calibration standard of CSIR-National Physical Laboratory, New Delhi, and SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany primary calibrations. The study recommends calibrating the back-to-back accelerometer with minimal uncertainty by using a primary calibrated single-ended accelerometer mounted on the top of the back-to-back transducer.The paper serves a guiding document to the calibration laboratories, industries and other stake holders in India to understand the concept of traceability in vibration measurements and formulation of uncertainty budget as per the international standard.

Keywords: Secondary vibration calibration; Back-to-back calibration; Single-ended sensor; Back-to-back sensor

1. Introduction

The primary standard of vibration amplitude realized using laser interferometer is the most accurate and precise standard. The secondary standards are standardized in comparison with the primary standard and are usually used to provide the regular calibration services to the industry and regional laboratories. The CSIR-National Physical Laboratory, India (CSIR-NPL), being the National Measurement Institute (NMI) of India establishes, maintains and updates the national measurement standards and provides calibration facilities for different parameters [1, 2]. The Acoustics and Vibration division of CSIR-NPL, India, has the responsibility of the maintenance and up-gradation of the primary standards of sound pressure and vibration amplitude. The division is entrusted with the responsibility to establish, maintain and upgrade the national measurement standards of sound and vibration and disseminates the traceability to the industry and institutions of the country. The participation in key comparisons with other NMIs is ensured for validation of the primary standards. The secondary standards draw their traceability through the primary standards. The present paper discusses the measurement uncertainty realized in secondary vibration calibration standard of CSIR-NPL, New Delhi, for providing calibration measurement services in field of vibration metrology to the nation. The uncertainty budget of secondary vibration standard is presented, and the pivotal factors affecting the measurement uncertainty in vibration calibrations are discussed. During the laboratory assessments as per ISO 17025 and interaction with industries, it had been observed that the concept of vibration traceability, methodology and calculation of uncertainty is sometimes not clear amongst the technicians and engineers. The present paper shall be very helpful to the calibration laboratories, vibration shaker manufacturers and industries in India engaged in accelerometer calibrations and vibration measurements to undertand the fundamental concepts such as methodology and traceability, formulation of uncertainty budget as per the international standards and serve as a guide for the development of indigenous vibration transducers, shakers and calibration systems under the “Atma-

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*Corresponding author, E-mail: ngarg@nplindia.org

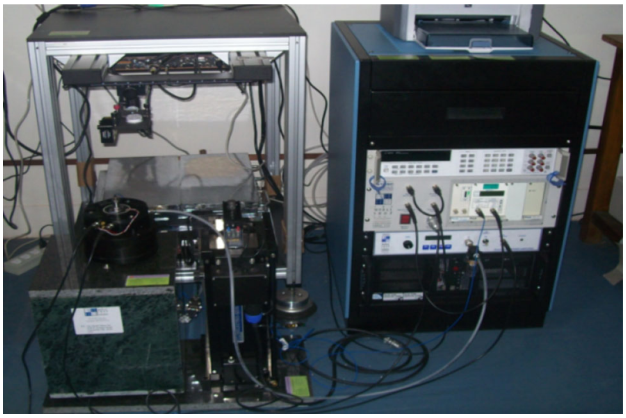


Fig. 1 Primary vibration calibration standard realized at CSIR-NPL, India, in frequency range 0.1 Hz to 20 kHz

nirbhar Bharat Abhiyan" (or Self-reliant India Mission) advocated by the government of India recently.

2. Vibration Standards and Measurement Methodology

2.1. Primary Vibration Standard

The primary vibration standard is realized using the laser interferometry technique as per ISO 16063-11 [3] and sine approximation method in the range of 0.1–20 kHz with an overall expanded uncertainty of ± 0.3% to 1.8%. CSIR-National Physical Laboratory, India, realizes the measurement frequency range using the TMS 9155D primary vibration calibration standard (0.1 Hz to 20 kHz). The details of the primary vibration standard have been already discussed in references [2, 4–6]. Figure 1 shows the primary vibration calibration standard realized at CSIR-NPL [2].

2.2. Secondary Vibration Standard

The back-to-back comparison method is the widely used convenient and economical method classified as secondary vibration calibration method. This method is largely employed for calibration of accelerometers, vibration transducers, vibration analyzers and meters and accelerometer calibrators in accordance with ISO 16063-21 standard [2, 7]. The method involves the coupling of the test accelerometer directly to a double-ended reference standard accelerometer calibrated by primary method and exciting them at varied frequency and amplitude levels. It is presumed that both the device under test (DUT), i.e., the test accelerometer and the reference standard accelerometer, will experience exactly the same motion. The secondary method draws its traceability through the primary vibration calibration standard and is a vital part of the measurement traceability chain as it disseminates the traceability in vibration parameter throughout the country (Fig. 2). The secondary standard is used for providing calibration services to regional calibration and testing laboratories, automotive and avionics sector, defense sector, heavy engineering industry, Public sector undertakings, academic institutions and mining sector in the country.

The secondary vibration calibration system of CSIR-National Physical Laboratory, India, is CS18 MF system (SPEKTRA) that consists of vibration control system SRS-35, Power amplifier PA 14-80 and vibration exciter SE-10. The vibration control unit, VCU 13.5, performs the multitask of signal synthesis, acquisition, conditioning and processing through its serial interface (RS 232, USB) that communicates with a standard PC. The system uses a combination of modules, viz. two Analogue modules ANA 13.5, one controller module CPU 13.5, one DSP 13.5 module, one charge source module CAO 13.5 and one mains unit PS 13.5. The vibration control unit, VCU 13.5, and reference capacitors (Q-U-ICP 13.5) are periodically calibrated by M/s SPEKTRA, Schwingungstechnik und Akustik GmbH Dresden, Germany [8]. The reference standard accelerometers used for comparison calibration are PCB M353B17 (S. No. LW204915) of nominal sensitivity 1.0368 mV/m.s^{-2} and PCB J353B04 (S. No. 202859) of nominal sensitivity 0.9994 mV/m.s^{-2} at 80 Hz. Figure 3 a and b shows the Shaker SE-10 used in secondary vibration calibration standard.

3. Measurement Uncertainty Evaluation

The uncertainty in the sensitivity determination of the reference standard accelerometer is the major factor in secondary calibration of accelerometers. Figure 4 shows the cause-and-effect analysis diagram for analyzing the parameters affecting the accelerometer sensitivity measured using the back-to-back comparison method. The mathematical model describing the calculation of relative expanded uncertainty in the measurement of sensitivity for each applied frequency as described in ISO 16063-21 standard is as follows [7]:

$$u_{c,\mathrm{rel}}(S) = \frac{1}{S}\sqrt{\sum_i \left(\frac{\partial f}{\partial x_i}\right)^2 u_i^2(S) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_l}\frac{\partial f}{\partial x_j}u(x_i,x_j)} \tag{1}$$

$$= \sqrt{\sum_i \left(\frac{\partial f}{\partial x_i}\right)^2 u_{\mathrm{rel},i}^2(S) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_l}\frac{\partial f}{\partial x_j}u_{\mathrm{rel}}(x_i,x_j)} \tag{2}$$

$$U_{\mathrm{rel}}(S) = k.u_{c,\mathrm{rel}}(S) \tag{3}$$

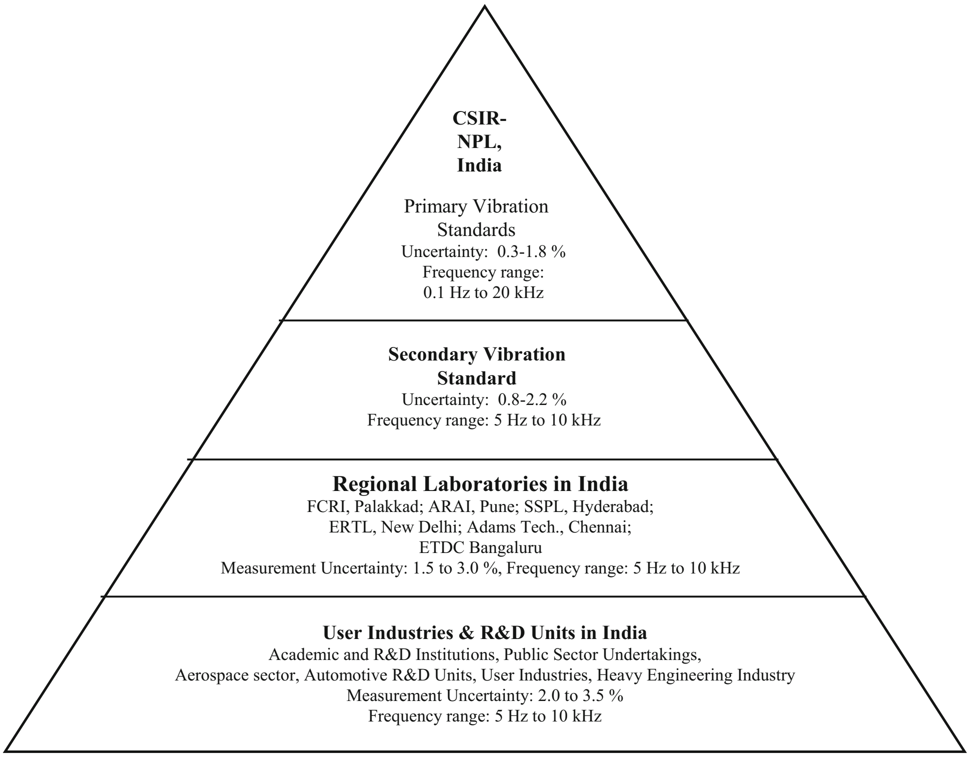


Fig. 2 Traceability chain of vibration measurements in India

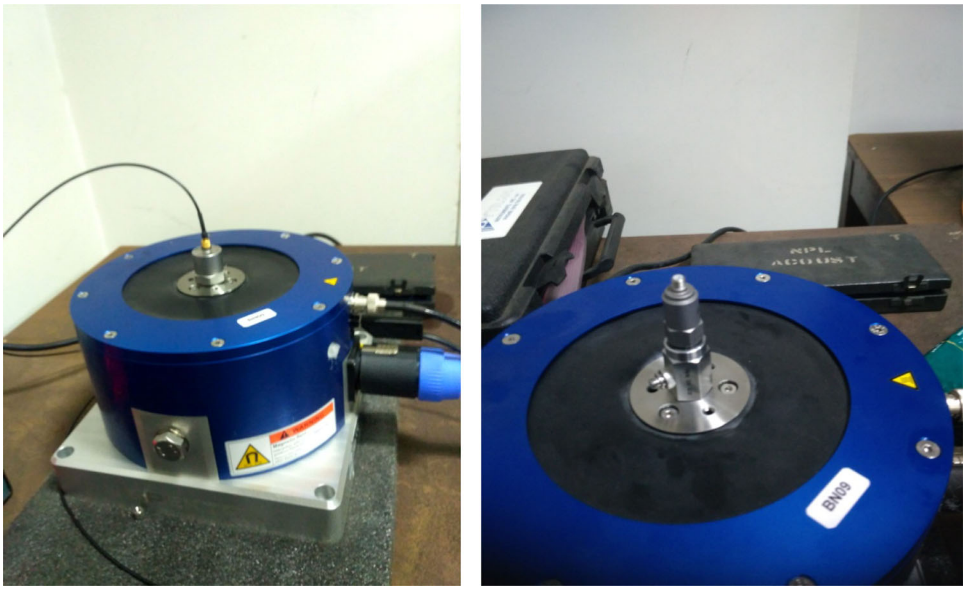


Fig. 3 **a** Shaker, SE-10, used for secondary vibration calibrations, **b** calibration of Endevco 2270 using a primary calibrated PCB J353B04 sensor mounted on top

where S is the sensitivity, $f(x_1,x_2,\ldots.., x_N)$ is the estimated sensitivity, x_l are the values of estimated parameters, $u(x_i, x_j)$ is the covariance of (x_i, x_j), U_{rel} indicates the relative expanded uncertainty, and k is the coverage factor taken as 2 for probability of approx. 95%. The various components of measurement uncertainty are analyzed for evaluating the voltage/charge sensitivity measurements as follows:

3.1. Reference Standard

The relative expanded uncertainty of 0.3% to 1.8% in range 5–20 kHz has been realized by laser interferometry technique as reported earlier [2]. The standard uncertainty of the reference accelerometer is determined through the expanded uncertainty of measurement declared in the calibration certificate. As the coverage factor (k) declared in the calibration certificate is equal to 2, then the value of the

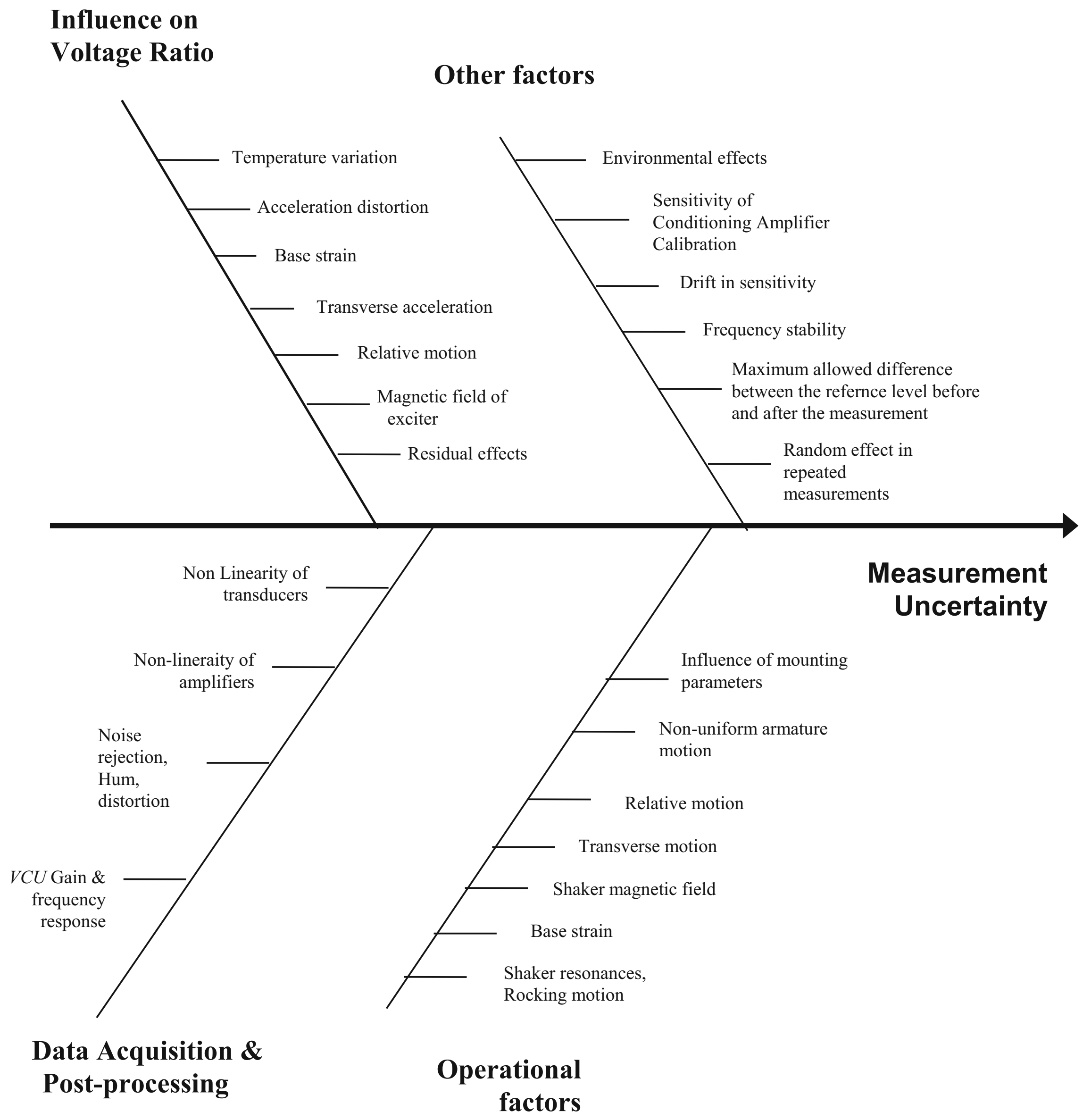


Fig. 4 Cause-and-effect analysis diagram for factors affecting measurement uncertainty in secondary vibration calibration

expanded uncertainty is divided by 2 to obtain the standard uncertainty of the reference accelerometer.

3.2. Drift in Sensitivity

The yearly drift in the sensitivity of reference standard is also to be accounted for. This value is estimated based on yearly measurements for the reference standard as maximum 0.15% in the range 5–10 kHz. The uncertainty value of 0.087% is evaluated assuming a rectangular distribution.

3.3. Relative Motion

The natural frequencies and modes of the mounting system, i.e., shaker and transducer assembly, will contribute to the relative motion between the DUT and reference. A CAD model was developed in CATIA (version: V5) and ANSYS software (version 12) as shown in Fig. 5 for the shaker–transducer coupled mechanical system for analyzing the resonance modes when shaker–transducer coupled assembly is excited at varied excitation levels ranging from 1 to 10 m/s^2. The observed eigen modes (1st eigen mode;

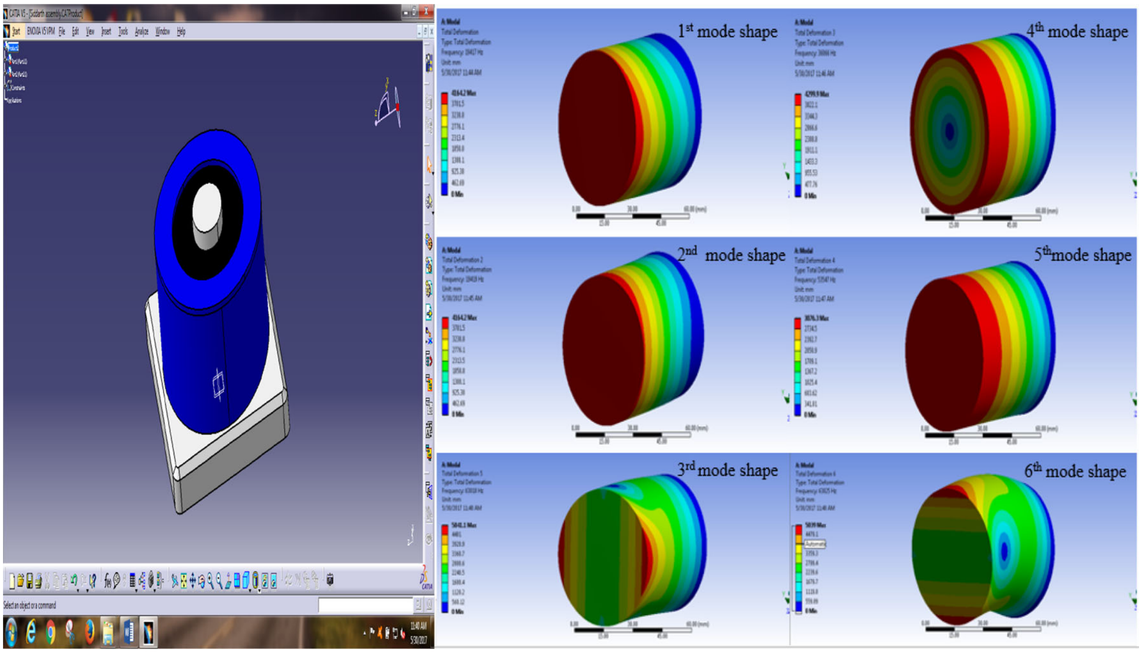


Fig. 5 CAD modal and FEM analysis of base-armature coupled mechanical system of Shaker SE-10 of secondary vibration standard

19.417 kHz) were higher than the measurement frequency range, which shows that the resonance modes of the electro-dynamic shaker SE-10 have least effect on sensitivity determination in the measurement frequency range. The relative error due to relative motion is considered as 0.05% in range 5–10 kHz, whereby the uncertainty contribution is 0.029% assuming rectangular distribution.

3.4. VCU Gain and Frequency Response

The vibration control unit (VCU) has been calibrated by M/s SPEKTRA using a Precision multimeter, Agilent 3458 A and precision attenuator, SPEKTRA ATS-15. The measurement uncertainty stated for voltage and charge measurements with analogue inputs is 0.21% up to 1 kHz and 0.12% in range of 1–10 kHz. The measurement uncertainty in the entire frequency range of the generator voltage is specified as 0.20%. Thus, the uncertainty contribution due to vibration control unit (VCU) gain and frequency response has been evaluated to be 0.23% in frequency range 5–1 kHz, and 0.29% in frequency range 1–5 kHz. However, in range 5–10 kHz, the uncertainty contribution is calculated to be 0.46% accounting for the contribution of data latency, analogue input (AI) gain amplitude accuracy and deviations in voltage in comparison with a standard AC voltage source.

3.5. Transverse Motion

The error due to transverse motion can be thus simply calculated as recommended in ISO 16063-21 assuming the transverse sensitivity of reference transducer and device under test and maximum transverse motion of the dynamic shaker in range 5–10 kHz. The transverse sensitivity of shaker–transducer assembly was measured using a triaxial sensor (B&K 4321, S.No. 993500). The study revealed that transverse sensitivity as a percentage of axial sensitivity varied from 1 to 9%, which is well below the limit recommended by ISO 16063-21 standard. Thus, assuming the transverse sensitivity of reference standard (PCB M353B17 and J353B04) as 5% and that of DUT as 5%, the uncertainty contribution assuming special distribution as recommended in ISO 16063-21 is evaluated as 0.17% in frequency range of 5–10 kHz.

3.6. Magnetic Field

The shaker magnetic field has a higher influence on the sensitivity of transducer at low frequencies [9]. An uncertainty of 0.0003% at 160 Hz is calculated considering a rectangular distribution.

3.7. Base Strain

The maximum error is measured as 0.08% in frequency range of 1–10 kHz [9]. Thus, an uncertainty of 0.046% assuming rectangular distribution is calculated.

3.8. Conditioning Amplifier

The relative expanded uncertainty in the sensitivity or gain of conditioning amplifier assuming normal distribution has been evaluated as 0.2% in range 5–10 kHz [10].

Table 1 Relative measurement uncertainty (in %) in accelerometer sensitivity determination in frequency range 5 Hz to 10 kHz

Description of influencing component to uncertainty in measurement	100 & 160 Hz	$5 \le f < 100$ Hz	$160 < f \le 1$ kHz	1 kHz $< f \le 5$ kHz	5 kHz $< f <$ 10 kHz	10 kHz
Calibration of reference transducer	0.15	0.30	0.40	0.50	0.75	0.80
Drift in sensitivity	0.087	0.087	0.087	0.087	0.087	0.087
Influence of temperature variation	0.21	0.21	0.21	0.21	0.21	0.21
Relative motion	0.029	0.029	0.029	0.029	0.029	0.046
VCU gain and frequency response	0.17	0.23	0.23	0.29	0.46	0.46
Transverse motion	0.17	0.17	0.17	0.17	0.17	0.17
Magnetic field	0.0003	0.003	0.0003	0.0001	0.0001	0.0001
Base strain	0.029	0.029	0.029	0.046	0.046	0.046
Sensitivity of conditioning amplifier	0.10	0.10	0.10	0.10	0.10	0.10
Influence of mounting parameters	0.029	0.029	0.029	0.06	0.06	0.06
Influence on voltage ratio from acceleration distortion	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
Vibration frequency measurement	0.06	0.06	0.06	0.06	0.06	0.06
Residual effects on sensitivity measurement	0.06	0.115	0.115	0.115	0.115	0.173
Random uncertainty	0.05	0.14	0.19	0.29	0.36	0.39
Expanded uncertainty ($k = 2$)	0.80	1.04	1.20	1.50	2.00	2.20

3.9. Influence of Mounting Parameters

The error induced due to the influence of mounting parameters on the transducer to be calibrated is measured as 0.05% up to 1 kHz and 0.1% at higher frequencies above 1 kHz. Thus, the uncertainty contribution assuming rectangular distribution is 0.029% up to 1 kHz and 0.06% above 1 kHz.

3.10. Other Uncertainty Components

The uncertainty contribution due to the influence of voltage ratio from acceleration distortion is taken as 0.0014% as recommended in ISO 16063-21 standard. The error induced due to harmonics was calculated as $e_d = ½\ d_a^2$, wherein d_a is the distortion factor [2]. The error due to distortion is thus calculated as 0.00125% for a maximum

Table 2 Relative measurement uncertainty (in %) in acceleration parameter (modulus) in frequency range 5 Hz to 10 kHz

Description of influencing component to uncertainty in measurement	100 & 160 Hz	$5 \le f < 100$ Hz	$160 < f \le 1$ kHz	1 kHz $< f \le 5$ kHz	5 kHz $< f <$ 10 kHz	10 kHz
Calibration of reference transducer	0.15	0.30	0.40	0.50	0.75	0.80
Drift in sensitivity	0.087	0.087	0.087	0.087	0.087	0.087
Influence of temperature variation	0.21	0.21	0.21	0.21	0.21	0.21
Relative motion	0.029	0.029	0.029	0.029	0.029	0.046
VCU gain and frequency response	0.17	0.23	0.23	0.29	0.46	0.46
Transverse motion	0.17	0.17	0.17	0.17	0.17	0.17
Magnetic field	0.0003	0.003	0.0003	0.0001	0.0001	0.0001
Base strain	0.029	0.029	0.029	0.046	0.046	0.046
Sensitivity of conditioning amplifier	0.10	0.10	0.10	0.10	0.10	0.10
Influence of mounting parameters	0.029	0.029	0.029	0.06	0.06	0.06
Influence on voltage ratio from acceleration distortion	0.0014	0.0014	0.0014	0.0014	0.0014	0.0014
Vibration frequency measurement	0.06	0.06	0.06	0.06	0.06	0.06
Residual effects on sensitivity measurement	0.06	0.115	0.115	0.115	0.115	0.173
Random uncertainty	0.08	0.14	0.19	0.25	0.28	0.31
Expanded uncertainty ($k = 2$)	0.80	1.04	1.15	1.40	2.00	2.10

distortion of 5% measured during the calibration. The uncertainty contribution due to vibration frequency measurement is estimated as 0.06% assuming the rectangular distribution. The effect of some of the parameters like hum, noise, drift, filtering effect, temperature sensitivity, etc., has been accounted by the residual effects. Table 1 presents the relative expanded uncertainty in the calibration results. The expanded uncertainty can thus be reasonably reported to be 0.8% to 2.2% in the range of 5–10 kHz in accordance with the *Guide to the Expression of Uncertainty in Measurement* [11]. Similarly, the expanded uncertainty in acceleration measurements was evaluated to be 0.8% to 2.1% in the range of 5–10 kHz as shown in Table 2.

4. Validation of Measurement Uncertainty

The secondary calibrations were validated by comparison with the primary calibrations done by laser interferometer from CSIR-NPL, India, primary vibration calibration standard and M/s SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany Primary calibrations. The sensors used for comparison were a single-ended PCB J353B04 and Endevco 2270 sensor.

The Endevco 2270 sensor was calibrated by using a primary calibrated single-ended accelerometer (PCB J353B04 sensor) mounted on its top, and by mounting it directly on the reference standard accelerometer (PCB M353B17 in the present case). It was observed that calibrations done using a single-ended accelerometer compared well with that of the primary calibrations results (using a Laser interferometer) especially at higher frequencies (> 6.3 kHz) with a maximum deviation of 1.21%. However, the calibrations done with mounting the BTB sensor onto the reference standard accelerometer had the maximal deviation of 1.63% at 10 kHz with respect to primary calibrations of back-to-back sensor. These observations were thus consistent with previous studies [12, 13] that suggest that back-to-back sensors are somewhat mass sensitive especially above 7 kHz and the sensitivity is a function of the mass mounted on its top surface. Therefore, in order to obtain an accurate calibration, the back-to-back accelerometer must be calibrated with a mass on its top surface or by using a calibrated single-ended accelerometer mounted on top of the back-to-back accelerometer [12].

Figure 6 shows the comparison of secondary calibration results with that of CSIR-NPL primary calibration results. It can be observed that the maximum difference of 1.23% at 10 kHz for PCB J353B04 sensor and that of 1.21% for Endevco 2270 sensor at 8 kHz are observed, which lies within the domains of uncertainty calculated. Figure 7 shows the comparison of secondary calibration results with that of CSIR-NPL primary calibration results. Similarly, when comparing the results with SPEKTRA primary calibration results, the difference of 1.30% is observed at 8 kHz for PCB J353B04 sensor and that of 1.10% for Endevco 2270 sensor at 8 kHz is observed, which lies within the domains of uncertainty calculated.

The En values were also calculated in both cases for the two transducers considering CSIR-NPL primary vibration standard results as reference in first case and that of M/s SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany Primary calibration results as reference in the second case. The expanded measurement uncertainty of CSIR-NPL primary vibration standard is calculated as 0.3 to 1.5% [2], while that of M/s SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany, was 0.3 to 0.5% in range 5–10 kHz. The maximum En value calculated in the first case considering CSIR-NPL

Fig. 6 Difference in sensitivity (in %) between the secondary system and CSIR-National Physical Laboratory Primary Calibrations for sensors, PCB J353B04 and Endevco 2270

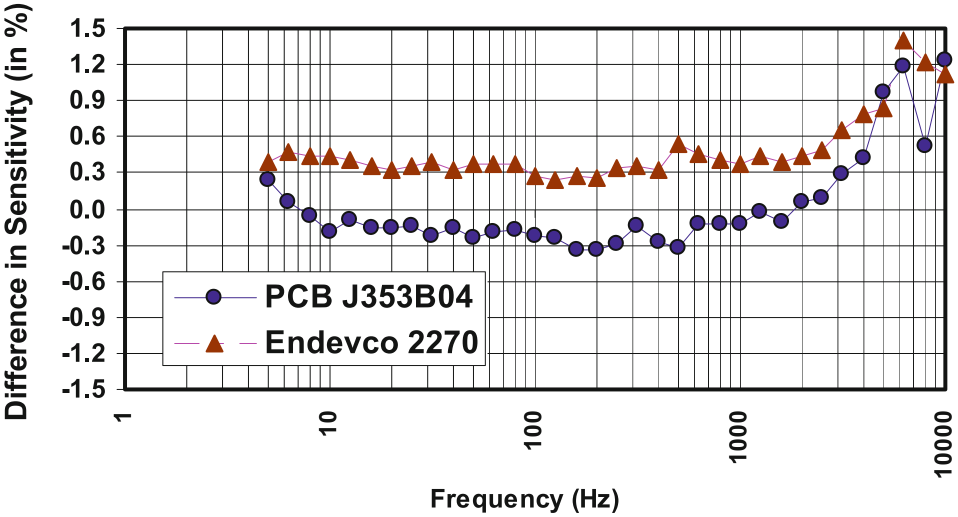


Fig. 7 Difference in sensitivity (in %) between the secondary system and M/s SPEKTRA primary calibrations for sensors, PCB J353B04 and Endevco 2270

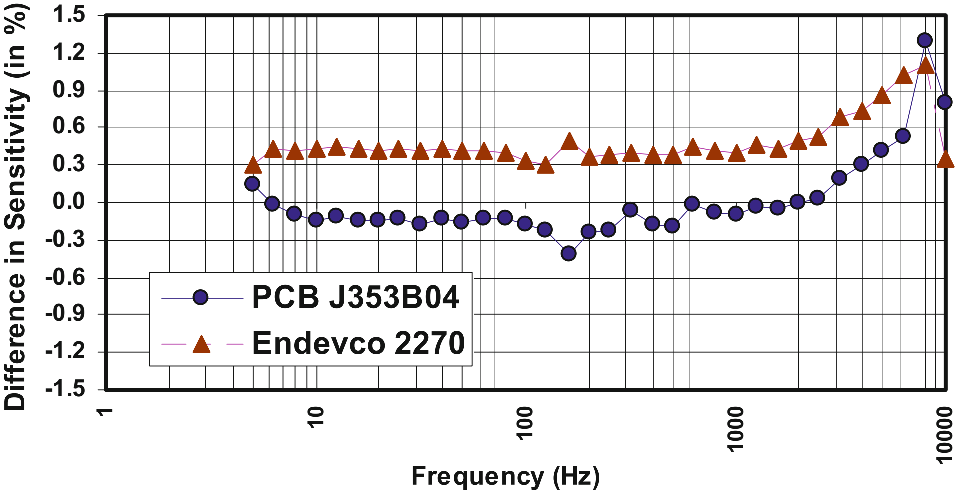
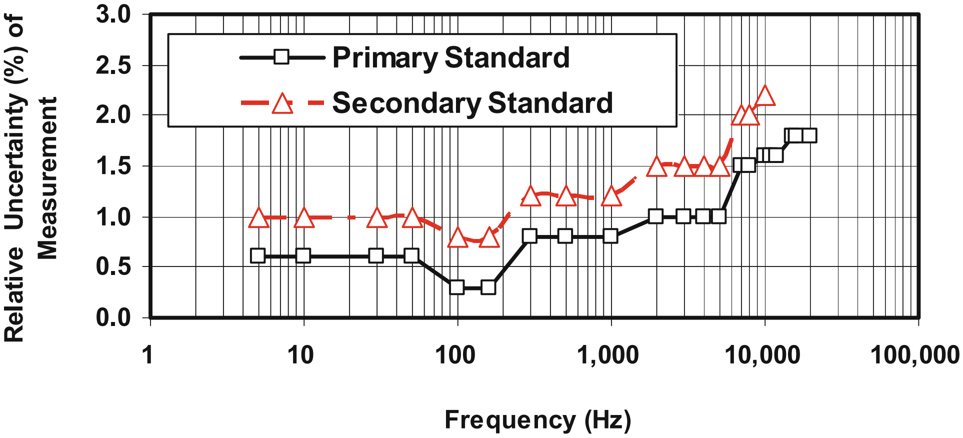


Fig. 8 Relative uncertainty of measurement (in %) for primary and secondary vibration standard



primary standard as reference was calculated to be 0.6 at 5 kHz for PCB J353B04 sensor and 0.6 at 6.3 kHz for Endevco 2270 sensor. The maximum En value calculated in the second case was calculated to be 0.6 at 8 kHz for PCB J353B04 sensor and 0.5 at 5 kHz for Endevco 2270 sensor. Thus, the $|En| \leq 1$ signifies the satisfactory performance of the secondary vibration calibrations [14].

These studies thus validate the measurement uncertainty of 0.80 to 2.20% ($k = 2$, 95% confidence level) so evaluated in 5–10 kHz range for secondary calibrations. Also, it is evident that calibrating the Endevco 2270 accelerometer with minimal uncertainty can be accomplished by using a primary calibrated single-ended accelerometer mounted on the top. Figure 8 thus shows the comparison of relative expanded measurement uncertainty evaluated for the primary [2] and secondary vibration calibrations at CSIR-NPL, New Delhi. Future studies shall be focused on calculation of measurement uncertainty using various methods [15] and validation of vibration calibration in range of 0.1–40 Hz for strengthening the measurement traceability chain in sound and vibration measurements in India [16–18]. It is envisaged that the participation in international key comparisons [19, 20] with other NMIs in low frequency and high frequency range shall be indispensable for inclusion of CMCs [21] in the entire measurement frequency range and shall benefit all the regional laboratories, industries, automotive and avionics sector, Public sector undertakings and other stake holders in India.

5. Conclusions

This paper has presented the details of secondary vibration calibration standard realized at CSIR-National Physical Laboratory, New Delhi, in the frequency range of 5–10 kHz as per the ISO 16063-21 standard. The system is in-house traceable to the national standards of vibration amplitude and is utilized for calibration of single-ended and back-to-back accelerometers, vibration meters and accelerometer calibrators, thus disseminating the traceability for vibration measurements throughout the country. The validation study recommends calibrating the back-to-back accelerometer with minimal uncertainty by using a single-ended accelerometer calibrated by primary method mounted on the top of the back-to-back transducer. The industrial sector particularly the Automotive and Public Sector Undertakings in India draw their traceability though the secondary vibration standard as secondary calibrations is more widely done as compared to the primary ones. The relative expanded measurement uncertainty of 0.80 to 2.20% is estimated in 5–10 kHz range for the calibration of single-ended and back-to-back accelerometers. The measurement uncertainty so evaluated is validated in comparison with CSIR-NPL, Primary Standard and SPEKTRA Schwingungstechnik und Akustik GmbH Dresden, Germany Primary calibrations, whereby a $|En| \leq 1$ is observed in each case. CSIR-NPL, India, Calibration and Measurement Capabilities (CMCs) at present exist in 40 Hz to 5 kHz range. However, future efforts are continuously targeted for inclusion of the CMCs in entire range of 5–10 kHz and in low frequency range (0.1 Hz to 40 Hz).

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