Comparison of measurement results obtained from three different calibration systems for performing accelerometer calibration

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Abstract. The vibration laboratory of the National Metrology Institute of South Africa (NMISA) has recently acquired new low frequency exciters, in replacing the old low frequency exciters. These exciters are to be used with the secondary vibration calibration system to disseminate measurement in low frequency ranges down to 0.2 Hz, on the secondary level. A study wherein the calibration results (from the three different laboratory systems) were compared has been undertaken in order to establish how well the new secondary system performed. Calibration measurement results from three different laboratories that used different calibration methodologies, i.e. methods in compliance to ISO 16063-11 and ISO 16063-21 standards, and systems were compared. A transducer that was calibrated at SPEKTRA and at NMISA using the primary calibration method was used as the transfer standard to compare with the results obtained using the new secondary setup. The results showed that the new secondary system performed quite well, with its results agreeing with those from the other laboratories, at primary level, to within at least 90%. This was illustrated by the values of the Pearson correlation coefficient *r* and the *p*-values.

1. Introduction

When re-calibrating an accelerometer for sensitivity and phase response as a function of frequency, the resonance frequency of the transducer should be included in the range of frequencies to be tested. This can be a challenge to the calibration laboratories that try to perform a calibration with minimised measurements uncertainty in a cost effective manner.

Two categories of accelerometer calibration applicable to vibration measurements; primary and secondary, were utilized. By definition, primary calibration provides direct traceability of a measurement to international recognised fundamental or derived units for physical quantities [2]. Secondary calibration, in contrast, uses a reference transducer, which itself has been calibrated and traceable to a primary standard [3]. It therefore, follows that secondary calibration will have uncertainties of measurement that are larger than primary calibrations, since every step in the calibration chain adds to uncertainty of measurement (UOM).

Recently the secondary vibration laboratory of the Acoustics, Ultrasound and Vibration has acquired a full medium frequency vibration system in replacement of an aging system they had. This new vibration system has brought a great improvement as it covers a wider frequency range of 3 Hz to 10 kHz, better than the previous system that could only cover ranges from 10 Hz to 10 kHz.

Additionally, two low frequency exciters (horizontal APS 113 and vertical APS 113, see Figure 1) were purchased to improve the laboratory capability in covering the low frequencies ranges. The two exciters couple with the medium frequency system, expanding the frequency range in order to make measurements from 0.2 Hz up to 200 Hz, overlapping with the medium frequencies.

Two low frequency accelerometers were selected for the experiment, in order to verify and commission the low frequency exciters used with the medium vibration system. The measurement results obtained from the manufacturer SPEKTRA on both accelerometers were considered and compared to the measurement results obtained from the NMISA primary and secondary laboratories, in the range of 0.2 Hz up to 63 Hz.

2. Transfer Standards

Two back-to-back capacitive accelerometers (listed in Table 1) coupled with power amplifier units were selected to be used for the work. Accelerometer B forms part of the low frequency exciters recently acquired, with A already in use as a low frequency standard in the primary laboratory. Both accelerometers were initially calibrated by SPEKTRA before they were supplied to NMISA.

Table 1. Accelerometers used for the comparison, with B used as a transfer standard for A.

Accelerometer	*Lab ID*	*Manufacturer*	*Model Number*	*Serial Number*
A	VS-STD-08	PCB	3701G2FA3G	8790
B	VS-STD-21	PCB	3701G2FA3G	8973

Accelerometer B, was used as reference standard (REF) on the secondary system (Horizontal APS 113, Figure 1) while accelerometer A was used as the unit under Test (UUT). Various combinations of inter-calibration were used to verify the system using the low frequency exciters in the horizontal configuration.

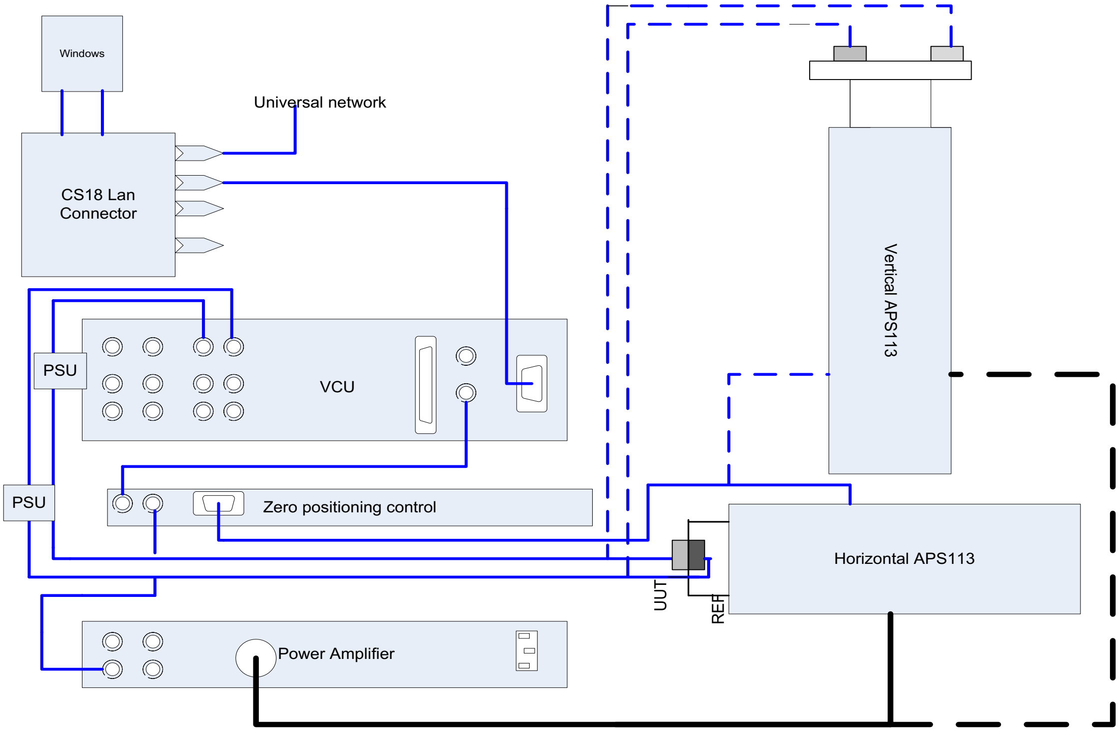

Figure 1. Secondary calibration system schematic.

3. Calibration System

Discussion about accelerometer calibration often refers primarily to the measurement of voltage sensitivity over a certain frequency range. The most commonly used way to calibrate accelerometer sensitivity is by comparison to a reference transducer, generally another accelerometer designed to have stable low noise sensitivity in the conditions of calibration. This secondary method is performed by back-to-back measurements, typically as a stepped sinusoid across an appropriate frequency range. The UUT is mounted in a back-to-back arrangement against a reference accelerometer and both sensors are subjected to a common mechanical excitation (see Figure 2). Since the motion input is assumed the same for both devices, the ratio of their outputs is also the ratio of their sensitivities, and the UUT sensitivity can be expressed by the following equation:

$$S_{uut} = S_{ref} \cdot \left(\frac{U_{uut}}{U_{ref}}\right) \cdot \left(\frac{G_{ref}}{G_{uut}}\right) \tag{1}$$

where:

S_{uut} is the UUT sensitivity in mV/g, mV/(m· s^{-2}), pC/g or pC/(m· s^{-2}),

S_{ref} is the reference transducer sensitivity in mV/g, mV/(m· s^{-2}), pC/g or pC/(m· s^{-2}),

U_{ref} is the reference channel output voltage in mV,

U_{uut} is the UUT channel output voltage in mV,

G_{uut} is the UUT conditioner gain in mV/mV or mV/pC,

G_{ref} is the reference conditioner gain in mV/mV or mV/pC.

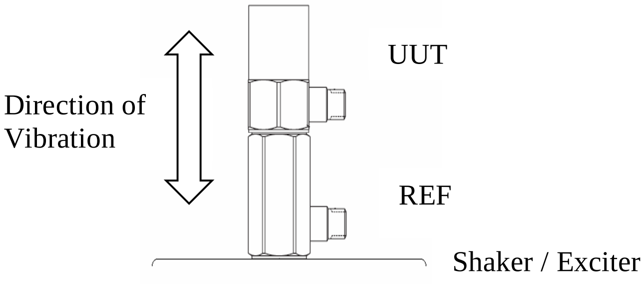

Figure 2. The back-to-back accelerometer calibration setup.

Accelerometer calibrations in the primary laboratories are performed using the primary calibration methods, with laser interferometry, in compliance with ISO 16063-11 method number three (Sine approximation method) [2]. The transducer is exposed to the sinusoidal acceleration which is applied by means of an electrodynamic vibration exciter. The output of the transducer is compared to the acceleration measured with the laser vibration meter on the exciter's surface.

4. Calibration results

4.1. SPEKTRA results

As per ISO 17025 requirement and best metrology practice, all new measurable equipment purchased shall be supplied with a calibration supporting documents, as such the selected accelerometers that were used for the exercise had calibration certificates from the supplier. These results are identified as SPEKTRA results (see Figure 3).

4.2. NMISA Primary vibration laboratory results

Upon receiving any system or measuring equipment from supplier, the system needs to be verified and calibrated as part of the system commissioning and maintenance procedure. The two accelerometers

(VS-STD-08 and VS-WSTD-21) were also verified in the primary laboratory. The VS-STD-08 results obtained from primary calibration were also considered for the exercise (see Figure 4).

4.3. NMISA Secondary vibration laboratory results

The secondary vibration laboratory used the CS18 medium frequency system coupled with the new low frequency vibration exciter and VS-WSTD-21, as the reference standard, in calibrating VS-STD-08. The results obtained are used for the performance comparison of the system and are illustrated in Figure 5.

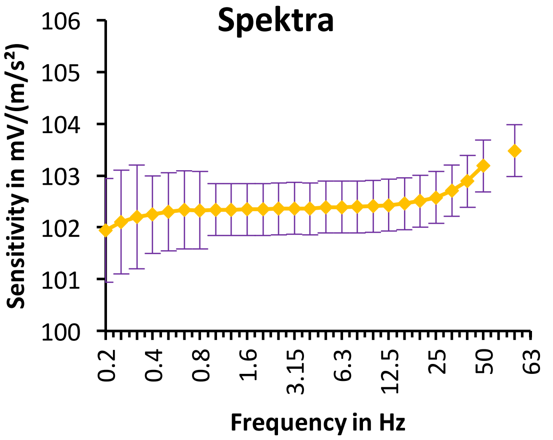

Figure 3. VS-STD-08 sensitivity values from a SPEKTRA calibration certificate plotted against frequency, with uncertainties overlaid as error bars.

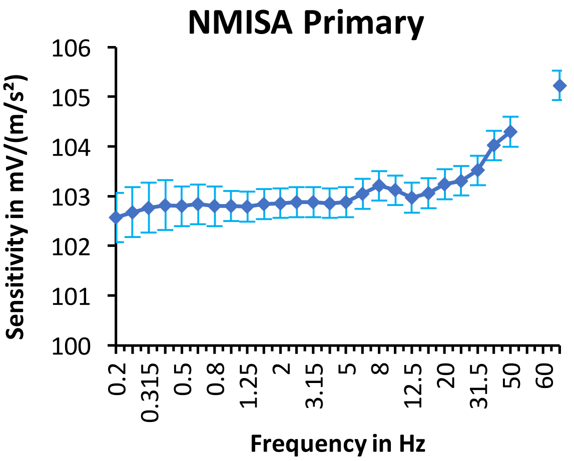

Figure 4. VS-STD-08 sensitivity values from a NMISA primary vibration laboratory calibration certificate plotted against frequency, with uncertainties overlaid as error bars.

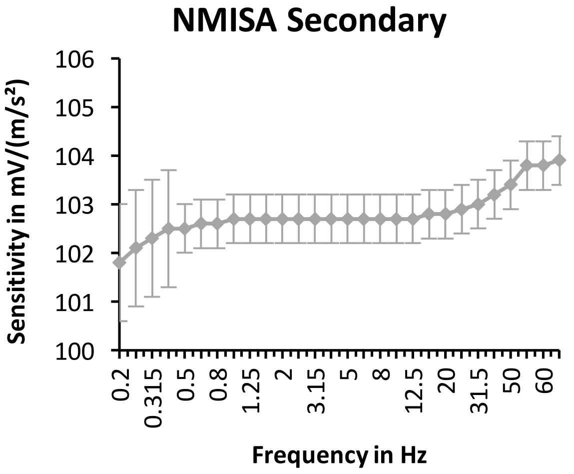

Figure 5. VS-STD-08 sensitivity values from a NMISA secondary vibration laboratory calibration certificate plotted against frequency, with uncertainties overlaid as error bars.

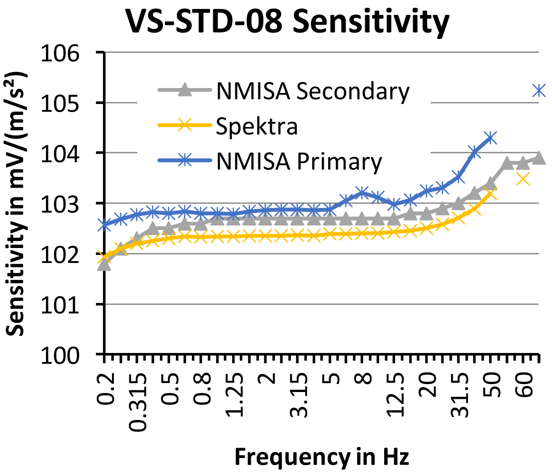

Figure 6. Sensitivities of the VS-STD-08 accelerometer plotted as a function of frequency, obtained from three different laboratories; SPEKTRA, NMISA primary and secondary vibration laboratories.

Figure 6 illustrates overlaid graphs of sensitivity measurements of the vibration's laboratory standard accelerometer VS-STD-08 from the three laboratories plotted against frequency. The results from the SPEKTRA and NMISA primary vibration laboratory are illustrated with the blue and yellow graphs respectively. The grey graph represent the results obtained from the NMISA secondary vibration laboratory. For this set of results, a laboratory working standard accelerometer VS-WSTD-21, traceable to SPEKTRA, was used as a transfer standard.

4.4. Correlation

Results from the three laboratories were then plotted against one another to try and establish any linear relationship between the results obtained from the different laboratories. Figures 7 to 9 illustrate such relationships. Equation (2) was used to calculate the Pearson correlation coefficient *r* between a pair of data from the three laboratories.

$$\boldsymbol{r} = \frac{\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}}(\boldsymbol{x_i} - \boldsymbol{\bar{x}})(\boldsymbol{y_i} - \boldsymbol{\bar{y}})}{\sqrt{\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}}(\boldsymbol{x_i} - \boldsymbol{\bar{x}})^2}\sqrt{\sum_{\boldsymbol{i=1}}^{\boldsymbol{n}}(\boldsymbol{y_i} - \boldsymbol{\bar{y}})^2}} \qquad (2)$$

The *r* values between the results of the VS-STD-08 from the NMISA secondary laboratory and those from SPEKTRA and NMISA primary laboratory were found to be 0.96 and 0.90, respectively, an indication of a very strong linear relationship between the datasets. A significance test was performed on the *r* values to establish confidence that these values were indeed significantly different from zero ($p < 0.001$).

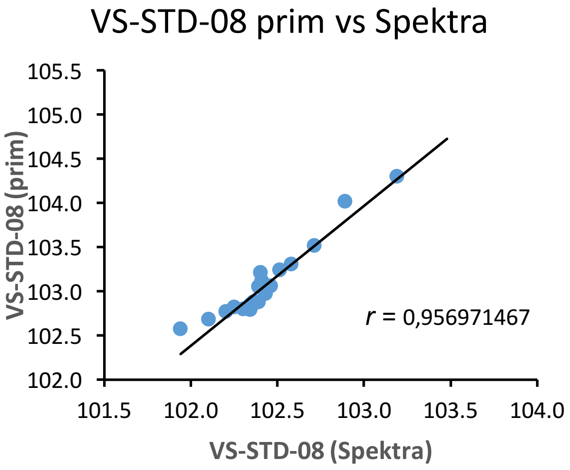

Figure 7. A comparison of VS-STD-08 sensitivity measurements from SPEKTRA and NMISA primary vibration laboratory with the correlation coefficient *r* displayed.

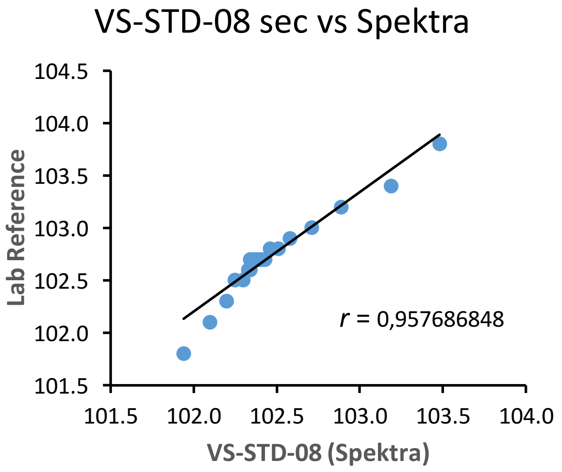

Figure 8. A comparison of VS-STD-08 sensitivity measurements from SPEKTRA and NMISA secondary vibration laboratory with the correlation coefficient *r* displayed.

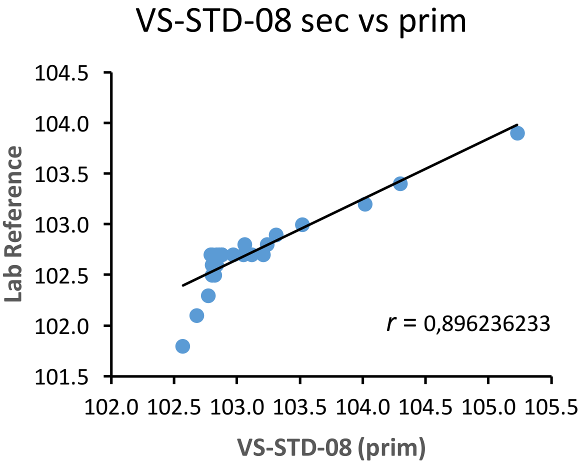

Figure 9. A comparison of VS-STD-08 sensitivity measurements from NMISA primary and secondary vibration laboratories, with the correlation coefficient *r* displayed.

5. Discussion and conclusion

A vibration laboratory standard accelerometer was calibrated in three different laboratories. Figure 6 shows a similar trend observed from all three graphs with the difference less than 1.5% between the furthest points. This agreement is further emphasised by the correlation coefficients displayed on Figures 7, 8 and 9. The correlation results indicated that the strength of association between the variables is very high ($r >= 0.90$), and that the correlation coefficients are significantly different from zero ($p < 0.001$). This linear relationship is also visually observed on these figures. The deviations observed at lower frequencies (or lower sensitivity values) could be attributed to the transverse motion due to the different mounting techniques of the three different systems.

From the exercise, two objectives were attained. The low frequency results from the three laboratories using different systems and methods; SPEKTRA, NMISA Primary vibration laboratory using a primary calibration method and NMISA secondary laboratory using a back-to-back method, were found to be comparable. The verification of the newly acquired low frequency exciter coupled to the medium vibration system has been successfully achieved. Based on this work, the low frequency measurements capability in the range of 0.2 Hz to 63 Hz from the secondary vibration laboratory was assessed and approved by South African National Accreditation System (SANAS) for accreditation.

Therefore, the back to back method is a valid method to be used in the secondary laboratories, for low frequency measurements, with the results comparable to those of the primary laboratories.

References

[1] Davis, K.E. 2001. "Vibration - Performing back to back calibration." Test and Measurements. Conference Digest.

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

[3] ISO 16063-21. 2003. "Methods for the calibration of vibration and shock transducers - Part 21: Vibration calibration by comparison to a reference transducer."