

ACCELEROMETER TRANSVERSE SENSITIVITY CALIBRATION AT THE NMISA

C.S. Veldman

National Metrology Laboratory of South Africa, Acoustics, Ultrasound and Vibration Laboratory, South Africa
Private Bag X34, Lynnwood Ridge, 0004, South Africa

Abstract: The National Metrology Institute of South Africa (NMISA) has implemented a system to measure the transverse sensitivity of vibration transducers. As a mechanical device, the principle sensing axis of an accelerometer is not 100 % perpendicular to the mounting axis. This gives rise to the effect that the accelerometer will produce an electrical output even when a mechanical input perpendicular to the principle measurement axis is applied. The quantification of this “defect” parameter is of importance when high accuracy acceleration measurements are performed using accelerometers. This paper gives a brief overview of the system developed by the NMISA to measure the transverse sensitivity of vibration transducers and explores the uncertainty of measurement associated with the calibration system.

Keywords: accelerometer, calibration, transverse sensitivity, uncertainty of measurement, *ISO 16063-31*.

1. INTRODUCTION

Due to their ease of use and low cost, accelerometers are widely considered as the vibration sensor of choice. A variety of different models are required to cover the wide range of vibration measurement applications. To select the accelerometer best suited for a specific application, the user will typically scrutinize the manufacturer’s specifications. Apart from the general (usually the most relevant) specifications such as size, sensitivity, frequency- and acceleration ranges, the manufacturer also specifies the relative transverse sensitivity (RTS) of an accelerometer.

For specialized application, the transverse sensitivity is of importance. For some applications, a more accurately known value of the transverse sensitivity might be required [1, 2, 3]. In addition, knowledge of the angle (mechanical orientation) of the transverse sensitivity is also required.

The NMISA developed a capability to accurately measure the transverse sensitivity of accelerometers as part of its research in vibration metrology. The NMISA modified its existing low frequency accelerometer calibration system to facilitate the measurement of accelerometer transverse sensitivity and will offer this calibration service to industry in the near future.

ISO (the International Organization for Standardization), through its Technical Committee, ISO/TC 108, “Mechanical vibration and shock”, Subcommittee SC 3, “Use and calibration of vibration and shock measuring instruments”, has developed and published a series of methods for the calibration of vibration and shock transducers. The standard, *ISO 16063-31* [4], specifies the instrumentation and procedure(s) to be used for performing transverse sensitivity measurements. It prescribes procedures and minimum requirements for the instrumentation to be used. The aim of this work is to evaluate the implementation of one of these described methods, using the instruments specific to the NMISA.

2. TRANSVERSE SENSITIVITY

The transverse sensitivity of an accelerometer is defined as the sensitivity to acceleration applied at right angles to its geometric axis [5]. The sensitive axis of the transducer is not necessarily aligned with the geometric axis, as shown in Fig. 1. As a result, any motion not in line with the geometric axis will produce an output.

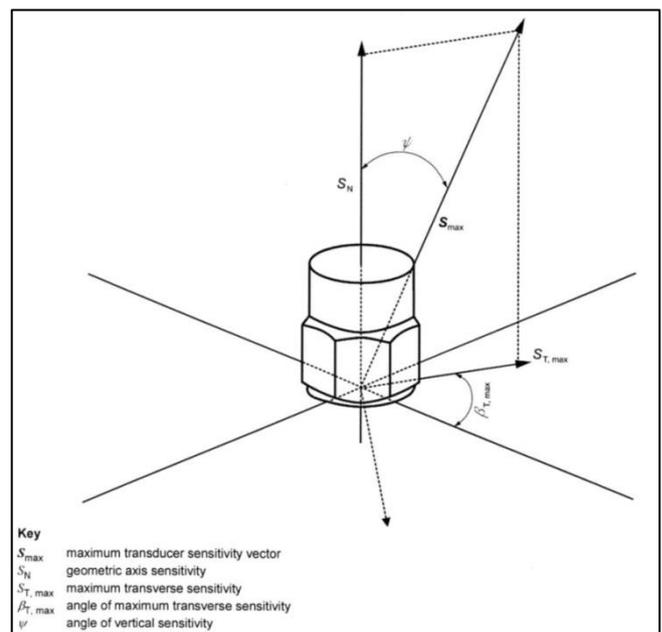


Figure 1. Graphical illustration of transverse sensitivity

If the transducer is placed in a rectangular co-ordinate system, as shown in Fig. 1, the vector, S_{\max} , representing the maximum transducer sensitivity can be resolved into the components: the geometric axis sensitivity, S_N , and the maximum transverse sensitivity, $S_{T,\max}$.

The theoretical transverse sensitivity curve is shown in Fig. 2. The transverse sensitivity, expressed as a percentage of the geometric axis sensitivity is referred to as the Relative Transverse Sensitivity (RTS). The RTS is dependent on the excitation angle.

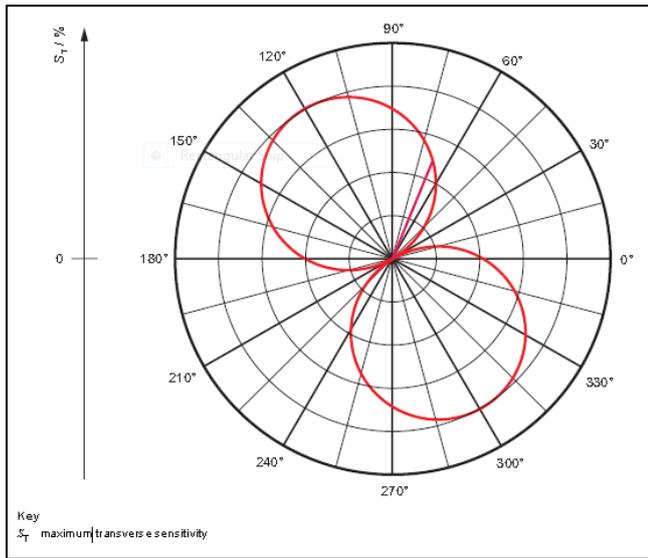


Figure 2. Theoretical transverse sensitivity curve for an accelerometer

For high quality accelerometers, manufacturers supply devices with low RTS, typically $\leq 1\%$, and with the direction of the lowest transverse sensitivity, $\beta_{T\min}$, indicated with a red dot on the accelerometer. The manufacturer supplies these low transverse sensitivity devices through selection. That is, they physically measure the transverse sensitivity and select the units that meet the required RTS specification.

3. SYSTEM DESCRIPTION

The transverse sensitivity calibration system of the NMISA [6] was developed in compliance with *ISO 16063-31* [4]. The transverse sensitivity capability was developed as an extension of the existing primary low frequency accelerometer calibration system. The system utilizes the existing long stroke (152 mm peak to peak) electro-dynamic exciter, connected to an air bearing linear translation stage (ABT). A stepper motor controlled turntable is mounted on top of the ABT (Fig. 3). Table 1 provides the system parameters.



Figure 3. Turntable mounted on top of air-bearing translation stage

Vibration frequency range	5 Hz to 20 Hz
Transverse acceleration range	5 m/s ² to 50 m/s ²
Analogue inputs	Four simultaneously sampled 12 bit channels
Sampling frequency	500 kHz
Turntable rotation angle	0° to 360°
Turntable rotation resolution	1°
Reference	Heterodyne laser interferometer system

Table 1. Parameters of the NMISA transverse sensitivity calibration system.

For the vibration generator with turntable system implemented by the NMISA, once the unit under test (UUT) is mounted on the turntable and all the hardware and cable connections are completed, the in-house developed software is executed.

The software performs a set of procedural steps as part of each transverse sensitivity measurement per turntable angular position:

- Move the turntable to the angular position of interest, (from 0° to 350° in 5° steps)
- Ramp the exciter to the selected vibration level, in frequency and amplitude
- Sample two analog inputs simultaneously. Streaming the data (time series data) directly to computer storage
- Apply the three parameter sine fit algorithm (3PSF) [7] to the REF and UUT output voltages time series to calculate acceleration amplitude and the UUT voltage output
- Calculate the relative transverse sensitivity (RTS) using Eq. 1 and Eq. 2
- Record the RTS in the result sheet
- Plot the RTS on a polar diagram

These steps are executed for each angular position from 0° to 360° using the selected step size, without the need of any intervention by the metrologist. For the calculation for transverse sensitivity, S_T , the following formula was used;

$$S_T = \frac{\hat{u}_{\text{out}}}{\hat{a}_T}, \quad (1)$$

where S_T is the transverse sensitivity; \hat{u}_{out} is the amplitude of the output signal of the transducer vibrating perpendicularly to its sensitivity axis; and \hat{a}_T is the acceleration level in the test direction.

The acceleration level is measured by means of a reference transducer,

$$\hat{a}_T = \frac{\hat{u}_{Ref}}{S_{Ref}}, \quad (2)$$

where \hat{a}_T is the acceleration level; \hat{u}_{Ref} is the voltage output of the transducer; and S_{Ref} is the sensitivity of the reference transducer.

The relative transverse sensitivity, S_T^* , is calculated for

$$S_T^* = \frac{S_T}{S_N} \times 100, \quad (3)$$

where S_N is the transducer geometric axis sensitivity.

Once all the measurements have been completed, the results are saved using an Excel template file. The result sheet also displays the RTS in graphical format, similar to Fig 2.

4. UNCERTAINTY OF MEASUREMENT

A pessimistic approach was followed w.r.t. the consideration of uncertainty components. The “worst case” (but still scientifically valid) values were used for the uncertainty contribution. This allows for a single uncertainty calculation that is valid for a wider range of measurement conditions. It also reduces the need to re-calculate the uncertainty budget for each calibration. However, it does not relieve the metrologist of the responsibility of having to consider the uncertainty for each calibration performed. By using the uncertainty values estimated for a specific calibration, instead of the generalized values, an RTS calibration with a smaller uncertainty might be possible. Should this parameter (RTS) be an accredited parameter, the laboratory should remember to remove claims of an accredited calibration result if the uncertainty stated on the certificate is smaller than the Measurement Capability (MC) on its accreditation schedule.

The uncertainty of measurement (UoM) was estimated in accordance with the GUM [8]. The root uncertainty contributors were identified from the mathematical model Eq. 1, which was expanded to Eq. 4 by inserting Eq. 1 and Eq. 2 into Eq. 3:

$$S_T^* = \frac{S_{Ref}}{S_N} \frac{\hat{u}_{out}}{\hat{u}_{Ref}} \times 100. \quad (4)$$

Through consideration of the mathematical model (4) and the measurement procedure, a detailed set of uncertainty contributors were identified. This full set was reduced to a sub-set containing the uncertainty contributors with a significant contribution. This process produced the list of “dominant” uncertainty contributors listed in table 2.

Uncertainty Contributor	Source of Uncertainty
Reference transducer sensitivity	Calibration certificate
Acceleration Level	Reference voltage measurement
Accelerometer Output Voltage	Accelerometer voltage measurement
Geometric Axis Sensitivity	Calibration certificate
Type A Uncertainties	Statistical means (Expanded Standard Deviation)

Table 2. Significant uncertainty contributors.

A preliminary uncertainty budget indicated that an expanded uncertainty of measurement (UoM), $U_c \approx 5\%$ ($k = 2$). This uncertainty value was then used to set a selection criterion for the uncertainty contributors to be considered of $u_i \geq 0,1\%$. The uncertainty components considered were deemed to be non-correlated.

The voltages for both the reference signal as well as the accelerometer output signal were captured using an A to D converter and applying the 3PSF. It has been established that the 3PSF method is influenced by the SNR ratio [9]. In this application, the SNR is measured. However, a minimum SNR limit of 15 dB is set for the purpose of calculating the 3PSF uncertainty contribution. For a SNR of 15 dB, the uncertainty in the magnitude determination, σ_A , is about 0,3%. σ_A is calculated using

$$\sigma_A = \frac{\sqrt{\sigma^2 + \frac{Q^2}{12}}}{\sqrt{\frac{N}{2}}}, \quad (5)$$

where σ_A is the 3PSF amplitude precision; σ is the zero mean white Gaussian noise; Q is the quantization error [9, 10]; N is the number of samples.

Due to the inherent small transverse sensitivity of accelerometers, additional steps are required to achieve the SNR limit requirement. This was accomplished by band pass filtering the time signals.

4.1 Reference Sensitivity Uncertainty

For this transverse sensitivity calibration system, the metrologist may choose to use either an accelerometer as the reference device or a laser interferometer (vibrometer). For both options, the sensitivity of the reference device is known from a prior calibration. The uncertainty associated with the sensitivity, along with its coverage factor, is obtained from the calibration of the reference.

4.2 Acceleration Level Uncertainty

The voltage amplitude of the reference signal is determined using the 3PSF algorithm [11]. From [12], the uncertainty associated with the amplitude is eq. 5;

4.3 Accelerometer Output Voltage Uncertainty

The uncertainty associated with the accelerometer output voltage is estimated in the same manner as described in paragraph 4.2 since the amplitude is also determined using the 3PSF. However, the calculated uncertainty for this parameter is expected to be larger, due to the smaller SNR, in light of the smaller output voltage.

4.4 Geometric Axis Sensitivity

The uncertainty contribution of the geometric axis sensitivity will depend on the source of the value of geometric axis sensitivity. Generally, this sensitivity will be obtained from a valid calibration certificate. In such an instance, the uncertainty will be taken from the certificate. It is possible to determine the sensitivity of the geometric axis using the calibration system, prior to performing the RTS measurements. In this instance, the uncertainty contribution needs to be calculated separately.

4.5 Type A Uncertainty

At each measurement point, 0° to 360° in 5° steps, the system captures an equidistant sampled time series, containing 100 vibration cycles for both the reference- as well as the accelerometer channels. To eliminate the undesired effects introduced by the bandpass filtering, the 3PSF is applied to the centre 50 cycles only. The final voltage amplitude is calculated as the mean and expanded standard deviation of these 50 voltage amplitudes (per channel).

The largest Type A uncertainty was determined by calibrating an accelerometer with a low RTS ($\approx 0,1\%$). Using this accelerometer the largest standard deviation calculated, considering all the measurement points through the complete 360° rotation was $3,5\%$. As was to be expected, the Type A uncertainty reached a peak value at an angular position with the lowest RTS.

5. CONCLUSIONS

A transverse sensitivity calibration system was implemented in compliance with *ISO 16063-31* by the NMISA. The transverse motion is generated using an electro-dynamic vibration exciter with a stepper motor controlled turntable for the angular positioning control.

The requirement for a relatively high SNR (≥ 15 dB) was highlighted. This minimum level of SNR is maintained through the use of digital narrow band band-pass filtering.

Four major sources of uncertainty were identified; the reference transducer sensitivity, the acceleration level, the accelerometer output voltage and the geometric axis sensitivity. For this system, the upper limit for the Type A uncertainty was calculated to be $3,5\%$.

6. REFERENCES

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