Improvement on the Transducer Sensitivity Measurement Results using Vibration Exciters

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Abstract. Abstract. The most important equipment in a calibration system used to calibrate vibration transducers is the exciter used for generating motions. A perfect exciter when excited in a geometrical direction, should provide a stable, single directional and distortion free vibratory movement, without generating any additional source of uncertainty. Unfortunately, this condition cannot be easily realised in real situation. Most commercial exciters experience high limitations when used during sensor calibrations.

The accelerometer will be sensitive to any movements generated along its input axis when the seismic is not symmetric to the input axis. The parasitic exciter's features will undesirably affect the accelerometer's response, which may degrade calibration's accuracy.

The paper will show how the exciter's total transverse motion, amongst other effects was resolved into vectors (x- and y vectors) in representing the parasitic effects that will influence the accurate calibration results of the accelerometer.

These vectors were calculated and quantified as the error affecting the accelerometer results. The error was added to the results in the form of UoM contributing to the accelerometer's sensitivity results. A model will be used to verify the total uncertainty to be added to the results.

Keywords: Transverse motion, exciter, z-axis, uncertainty of measurement, accelerometer, sensitivity.

1. Introduction

The National Metrology Institute of South Africa (NMISA) is mandated by the Measurement Units and National Measurement Standard Act. No 18 of 2006, under the auspices of the Department of Trade and Industry (the dti) to maintain, develop and disseminate the National Measurement Standards for South Africa.

The NMISA provides the international link to traceability for all measurements in South Africa and hence contributes to South Africa's global competitiveness. A signal of a certain frequency and amplitude will generate motion when applied to an exciter. A perfect exciter should provide a stable, single direction and distortion-free vibratory movement at any desired frequency and amplitude, but unfortunately such condition cannot be easily achieved. It could reasonably be correct, that the transverse sensitivity of the accelerometer and the transverse motion generated from exciter influence the accuracy of the calibration of the accelerometer when using these exciters [5].

Normally an electrodynamic exciter or shaker is used in a vibration calibration system to provide an oscillatory (sinusoidal) excitation. The procedure for transducer or accelerometer sensitivity measurement is described in the international standard (ISO 16063-21, 2003) [2], as a calibration by comparison or as back to back method. The sensitivity of the UUT is measured at a particular frequency at which the vibration exciter is excited.

Some models are classified as calibration exciters and some are general-purpose exciters. The calibration exciters are mainly designed for comparison in the calibration of accelerometers [1]. The quality of the vibration motion is very important for an accelerometer calibration system, presenting a significant influence on the accuracy of the results. Some NMIs have developed their own calibration exciters to overcome this challenge [7]. These developed designs, use the electrodynamic moving coil principle, while others use piezoelectricity to generate these motions.

Measuring instrument, UUT, environment, the operator and other sources can generate measurement uncertainties which can be associated with the measurement result. The obtainable uncertainty of measurement depends directly on many components of influence which are caused by the exciter, e.g. rocking and transverse motion, harmonic distortion, base bending, temperature gradients, noise, hum, internal resonances, etc. are some of the problems that can be generated by the excitation system.

This paper will discuss the transverse sensitivity and transverse motion, with the emphasis on the transverse motion effect, and their effects on the measurement results of a transducer when performing calibration on a transducer. It will also discuss the method used in measuring and quantifying these effect, by calculating the UoM to be added to the measurement results of the transducer with the aim of correcting the reported sensitivity result.

2. Transducer Calibration

This calibration system consists of an exciter, a controlling PC, power amplifier, conditioning amplifier, laboratory standard transducer (WSTD).
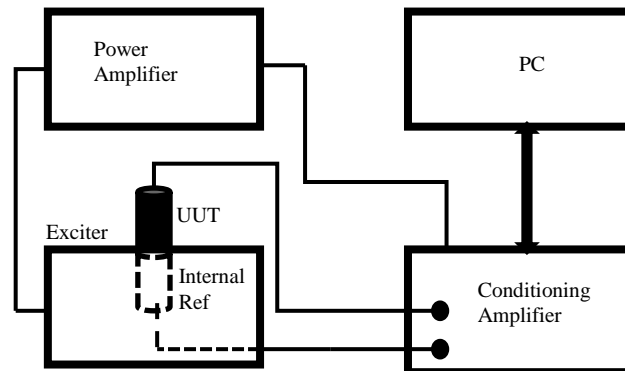

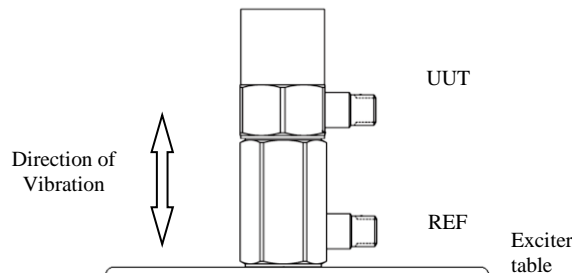**Figure 1. Setup for a typical secondary accelerometer calibration system**

Figure 2. The back to back accelerometer calibration setup

Since motion is generated when an electrical signal is applied to the exciter at a certain frequency and amplitude. In calculating the sensitivity of the UUT as demonstrated in Fig. 2, it is assumed that the motion input is the same for both the REF and the UUT devices. Therefore, the ratio of their outputs is also the ratio of their sensitivities [3]. The UUT's sensitivity can be expressed by the following equation:

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

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 accelerometer sensitivity in (mV/g, mV/(m·s^{-2}), pC/g or pC/(m·s^{-2}),
U_{ref} is the UUT output from the unit under test channel (in mV),
U_{uut} is the output from the reference channel (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).

3. Measurement Setup

For the exercise, the air bearing exciter was used, since it eliminates the transverse motion easily, together with a combination of accelerometers and tri-axial accelerometers. The experiments were performed at third octave frequencies from 10 Hz up to 10 000 Hz at accelerations levels ranging from 5 m·s^{-2} to 100 m·s^{-2}. The measurements on all three axes (x-, y- and z axis) as shown on Fig. 4, were measured simultaneously with the z-axis as the geometric excitation axis. The motion in the x- and y- direction represent the transverse motion when excited in the z-axis [6], as shown in fig 6. Several measurements were performed at each frequency point, and the mean thereof was used to determine the mean transverse acceleration at that frequency.

4. Transverse Sensitivity and Motion Effects

There are various other factors such as excessive transverse rocking / cross motions, maximum displacement limit, etc. harmonics, resonance, heating of the moving elements resulting in waveform distortion and phase that can degrade the exciters performance. Therefore, the transverse sensitivity of the accelerometer in the presence of the transverse motion of the exciter influences the accuracy of the calibration of the accelerometer when using these exciters [4].

- If the sensitive axis of the transducer is not necessarily aligned with the geometric axis, any motion not in line with the geometric axis will result in producing an output.

- If the transducer is placed in a rectangular co-ordinate system as shown in Fig. 3, the vector, S_{max} , representing the maximum transducer sensitivity, can be resolved into the following components; the geometric axis sensitivity S_N, and the maximum transverse sensitivity, S_{Tmax}

Key:

S_{max} maximum transducer sensitivity vector
S_N geometric axis sensitivity
$S_{T,max}$ maximum transverse sensitivity
$B_{T,max}$ angle of maximum transverse sensitivity
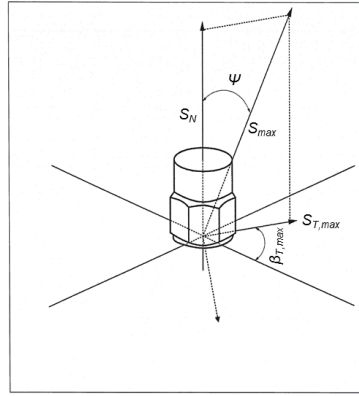Ψ angle of vertical sensitivity.

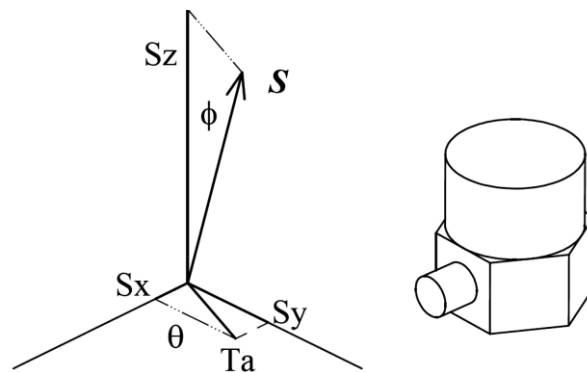**Figure 3. Graphical illustration of transverse sensitivity**

Figure 4. Accelerometer coordinates and sensitivity vectors

The vector of maximum sensitivity S, in Fig. 4 is tilted at an angle Φ, from the ideal vertical (z-axis) direction, and decomposes to three orthogonal components S_x, S_y and S_z. The z-axis component S_z is the value normally reported as the accelerometer sensitivity. Peak transverse sensitivity S_a (T_a) is composed of S_x and S_y components of S and it can be calculated using Eq. 2. Transverse acceleration in the direction θ will produce maximum output, and the inputs in the x-y plane at $\theta \pm 90°$ would theoretically produce no output [5].

By convention in this paper, the x-y plane is defined by the transducer mounting surface, and the z-axis is arbitrarily assigned to be the direction of the transducer connector. The maximum absolute transverse sensitivity S_a and its direction θ are given by:

$$S_a = \sqrt{S_x^2 + S_y^2}. \tag{2}$$

$$\theta = \tan^{-1}\frac{S_y}{S_x}. \tag{3}$$

S_a is defined in units of the transducer sensitivity, for instance mV/(m·s^{-2}). However, transverse sensitivity is generally reported as a relative value. Commonly it is calculated as the percentage ratio:

$$S_T = \frac{S_a}{S_z} \times 100\% \tag{4}$$

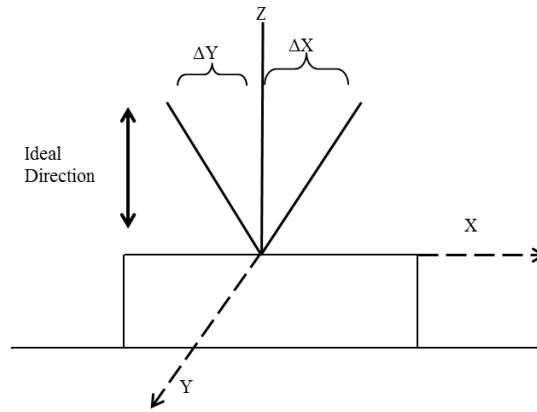S_T is the relative transverse sensitivity [5].

Figure 5. The vector error components of x- and y- motion direction.

The calculated transverse motion generated by the vibration exciter is also defined as a relative value, a percentage ratio with respect to the acceleration applied to excite the exciter and is commonly expressed as a_T. Therefore, the combination of the two effects, transverse sensitivity, and transverse motion, was used in calculating the UoM when expressing the accurate sensitivity of the accelerometer. Often this is not the most significant source of uncertainty in measurements in the field, and as such the accuracy with which transverse sensitivity needs to be known is usually not rigid. The transverse motion as represented by the vectors was calculated as follows:

$$a_T = \sqrt{a_x^2 + a_y^2}. \tag{5}$$

where:

a_T is the total transverse acceleration, or motion experienced /caused by the exciter,
a_x is the acceleration in the x-axis direction,
a_y is the acceleration in the y-axis direction.

Since part of the transverse sensitivity experienced by the transducer emanates from the above calculated transverse motion, the total percentage error from the transverse motion was calculated as shown in Eq. 6.

$$e_T = \frac{a_T}{a_z} \times 100\%. \tag{6}$$

where:

a_T is the total transverse acceleration caused by the exciter,
a_z is the acceleration measured in the z-direction.

From the measurement performed and recorded in Table 1 it can be recognized that the transverse acceleration calculated using Eq. 5 is indicated as a_T, and this can be used to determine a correction factor a_z. The percentage error is denoted by e_T in Eq. 6 or a_T in the table below.

The total transverse error is the error introduced by the transverse sensitivity of the accelerometer and transverse motion of the exciter. Having measured and calculated the transverse sensitivity and the transverse motion, Eq. 5 and Eq.6 can be used to calculate the total transverse error [2] as in the equation below.

$$e_{xT} = S_T a_T = s_{T,max}\, a_{T,max}\, \cos \beta. \tag{7}$$

Where:

e_{xT} = Total transverse error
s_T = Transverse sensitivity
a_T = acceleration amplitude
Cos β = it is the angle between the direction of the maximum transverse sensitivity and the direction of transverse excitation.

The uncertainty of measurement, U_a, can be added as an uncertainty component when calculating the total uncertainty of measurement for the transducer sensitivity calibration.

5. Measurement Results

Any measurement performed and expressed as a number without been accompanied by any statement of uncertainty is incomplete.

The ISO 16063-21 standard stipulates certain limits of transverse motion for different frequency points, as indicated with the straight line in Fig. 6. The line represented by the frequency graph indicates the measured results of the transverse motion of the exciter. From the frequency range of 10 Hz and 1 000 Hz, the transverse motion limit specified by the ISO Standard [2] is 10 %. It is noticed that at the frequencies points 160 Hz to 250 Hz and 500 Hz, the transverse motion exceeds the limits for the shaker used, and at frequency point 10 000 Hz, the transverse motion exceeds the limit of 20 % [2].

Since several measurements were taken but the similar error could still be observed, it can therefore be concluded that this particular exciter does not meet the ISO standard specification at the highlighted or denoted frequency points. The effect still needs to be investigated further, especially at the 160 Hz point, as this frequency point together with frequency point at 100 Hz are normally used as the reference point when measuring the transducer sensitivity.
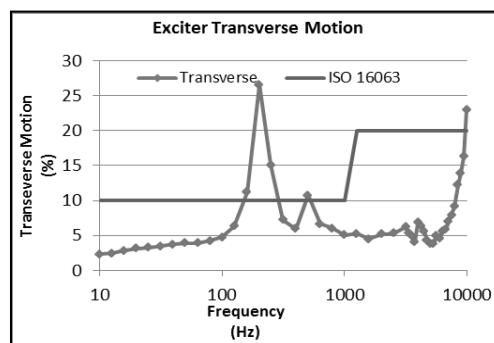

**Figure 6. Transverse motion measurement results over the
frequency range 10 Hz to 10 kHz with ISO 16063-21 limits.**

6. Conclusion

The transverse sensitivity of exciters varies with frequency and is also related and dependent on the vibratory acceleration direction to the input axis. If the accelerometer / accelerometer configuration is neither symmetric nor homogenous to the input axis, the accelerometer can be sensitive to the acceleration along the axis other than the input axis. This paper show that, among other factors that could affect the measurement of transducers during calibration, such as incorrect mounting, tribo-electric, mounting surfaces, studs and incorrect alignment, the exciter's transverse motion on some specific frequencies need to be considered.

After measuring the transverse sensitivity and calculating the transverse acceleration experienced by the exciter, the total transverse error can be calculated as indicated in Eq. 8. It will be emphasized that each exciter has its own characteristics and therefore these measurement results are exciter specific.

Since these two identified and resolved components are not the only parasitic effects affecting the sensor sensitivity when excited using the vibration exciters, the other effects such as the excessive transverse rocking / cross motions, maximum displacement limit, harmonics, resonance, heating of the moving elements resulting in waveform distortion and phase will be experimented in future.

Table 1. Vibration Exciter acceleration results on x-, y- and z-axis

Frequency	a_x	p_x	a_y	p_y	a_z	p_z	a_T	a_T	Angle $_T$	U_a	ISO 16063 Limit
(Hz)	(m/s²)	(°)	(m/s²)	(°)	(m/s²)	(°)	(m/s²)	(%)	(°)	(%)	(%)
10	0,03	-2,59	0,12	2,90	5,17	-0,33	0,12	2,32	1,32	0,55	1
12,6	0,01	-0,15	0,12	-2,13	4,98	0,90	0,12	2,47	1,49	0,55	10
15,8	0,03	-0,31	0,14	3,08	5,05	-0,17	0,14	2,85	1,34	0,55	10
31,6	0,13	2,22	0,32	-0,91	10,01	2,15	0,35	3,46	1,19	0,55	10
126	0,06	-0,56	3,17	-0,18	50,03	3,07	3,17	6,33	1,55	0,71	10
159,1	1,16	-0,23	5,46	-0,56	49,91	3,01	5,58	11,19	1,36	0,71	10
200	8,45	2,47	10,24	1,49	49,91	0,06	13,28	26,60	0,88	0,71	10
251	6,89	0,38	3,00	-0,06	49,83	-0,04	7,51	15,08	0,41	0,71	10
316	3,40	0,39	1,15	-0,17	49,56	0,08	3,59	7,24	0,33	0,71	10
398	2,86	0,40	0,65	-0,63	49,44	-0,01	2,94	5,94	0,22	0,71	10
501	5,18	3,05	1,17	-0,30	49,58	3,09	5,31	10,72	0,22	0,71	10
8910	2,57	-2,67	9,24	-1,78	68,76	1,91	9,59	13,94	1,30	1,10	20
9440	3,38	1,89	13,34	2,08	84,51	-0,54	13,76	16,28	1,32	1,10	20
10000	8,89	2,52	21,47	2,58	101,01	0,02	23,24	23,01	1,18	1,10	20

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