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EXPERIMENTAL INVESTIGATION INTO THE EFFECTS OF EXCITER MOTIONS ON THE PRIMARY CALIBRATION OF SINGLE-ENDED ACCELEROMETER

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Abstract – It is widely known that in the primary calibration of accelerometers by using a laser interferometer, a unit under test (UUT) and the laser interferometer should measure vibration at the same position. However, this is not applicable to single-ended accelerometers because of the limitation of their design. One way of overcoming this limitation is to measure the vibration at several positions on the plate which connects UUT to a vibration exciter. However this can present the effects of rocking motions of the exciter. Although the motions of vibration exciters are presented in several studied, the different model of exciters might have different characteristics. This paper aims to study the motions of an air-bearing exciter (model 2911) used at National Institute of Metrology (Thailand) in order to expose their characteristics, their effects on the calibration results and the measurement errors due to these effects. The motions of the exciter are shown in terms of magnitude and phase shift distributions of sensitivities. These can be obtained by measuring the magnitudes and phase shifts at several positions on the plate. The effects of exciter motions are measured in terms of how much the magnitudes and phase shifts at each measured positions deviate from the average values. To illustrate these effects, parametric studies were conducted. The influences of four parameters, i.e. the angular positions of the laser points, the distance of the laser positions from the centre of the plate, the number of measured positions to be averaged and the mass loading effect, were examined experimentally. The frequency of interest is between 10 Hz and 15 kHz.

Keywords: shaker motions, primary vibration calibration, single-ended accelerometer.

1. INTRODUCTION

Vibration exciters are widely used for the calibration of accelerometers. However, it is often the case that the motions of the exciters affect the calibration results. Their effects have been discussed in several studies. Ripper *et al.* [1] has shown seven issues due to vibration exciter. Those are the problems concerning low stiffness and heating of moving element, rocking and transverse motions, resonance, air bearing, and harmonic distortion. The solutions to these problems have been suggested. For example, the effect of rocking motion of moving table can be minimised by taking

the mean of measurements on 3 points, 6 points or 2 diametrically opposed points.

Oota *et al.* [2] has investigated the effects due to transverse, rocking and bending motions of vibration exciter and suggested the simple methods to estimate the uncertainties due to these motions. The uncertainties considered in [2] concerned transverse sensitivity and vibration distribution effects. The uncertainty due to transverse sensitivity was estimated using spacers having three different thicknesses. These spacers were placed between accelerometer and exciter table. The uncertainty due to vibration distribution effect was obtained by measuring the sensitivity at the centre of the dummy mass attached to the top of accelerometer and at six positions around the mass.

Although the magnitude distribution of sensitivity has been studied, not very much has been published concerning the phase shift distribution, especially the phase shift due to the exciter model 2911. Consequently, experiments on this exciter were conducted to illustrate both magnitude and phase shift distributions.

Following this introduction, the parametric studies are presented. Section 3 focuses on the empirical models for the deviation of phase shift as a function of the significant parameters. Those are the angular positions of the laser points and the distance of the laser positions from the centre of the exciter plate. Hence errors in the deviation of phase shift due to these parameters are estimated. Section 4 contains some conclusions.

2. PARAMETRIC STUDIES

The aim of parametric studies is to investigate the influence of four parameters on the magnitude and phase shift distributions of sensitivities. These studies consider the distributions across the plate connecting UUT to the exciter. The investigations were conducted experimentally using the set-up shown in Fig. 1. The plate was connected to the exciter table, which was placed on the top of the exciter model 2911. Vibration control system, which also acted as a signal generator, generated an input signal to drive exciter through a power amplifier. A built-in accelerometer model 2770M18 was used to measure magnitude and phase shift at the centre of the plate. The measured signal from the built-in accelerometer was input to vibration control system. A

Polytec laser vibrometer model CLV-1000 was used to measure velocity at several positions on the more or less circle plate shown in Fig. 2. All two measured signals were input to PC and hence the sensitivity and phase shift were calculated.

2.1. Effects of changing angular laser positions

The first parameter studied is the angular position of the laser point. In this study, the laser is pointed to eight positions on the exciter plate. Those positions are positions 9 to 16 shown in Fig. 2. Each position is 45 degrees apart and is 11.5 mm from the centre of the plate. There is no mass connected to the top of the plate. Figs. 3 and 4 show the effects of angular laser position on the magnitude and phase shift respectively. It was seen that these effects can be divided into two regions. At frequencies below 100 Hz, the angular positions have no significant effect on the magnitude and phase shift distributions. However, this is not the case when frequencies are higher than 100 Hz. The maximum deviations of magnitude and phase shift from the average values occur at frequencies between 200 to 315 Hz approximately.

2.2 Effects of changing distance of the laser position from the centre of the exciter plate

In this section, the influence of the distance of the laser position from the centre of the plate is investigated. The angular position is fixed to 45 degrees and no mass is attached to the plate. Figs. 5 and 6 show the deviations of magnitude and phase shift from the average values respectively. The dashed lines shown in both figures are the deviations measured at position 2, which is 6.5 mm from the centre. The solid lines are measured at position 10, which is 11.5 mm from the centre. It can be seen that the distance of the measured positions from the centre of the plate has significant effects on the magnitudes especially at the frequencies higher than 100 Hz. However this parameter has significant effect on the phase shifts only at frequencies between 200 to 315 Hz approximately. Longer distance from the centre of the plate presents higher deviations of magnitude and phase shift. Again, the maximum deviations occur at frequencies between 200 to 315 Hz.

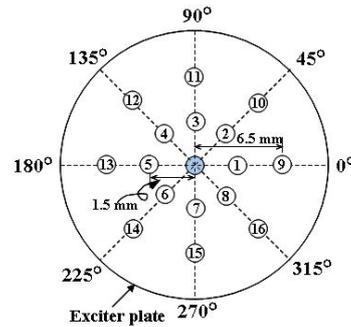


Fig. 2. Sketch of the exciter plate geometry and the laser positions.

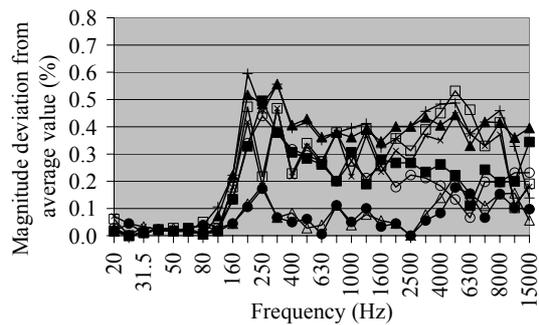


Fig. 3. Deviation from the average value of the magnitude of sensitivity measured at eight angular positions: ⊕ position 9; ▲ position 10; ⊖ position 11; ● position 12; × position 13; + position 14; ■ position 15 and △ position 16.

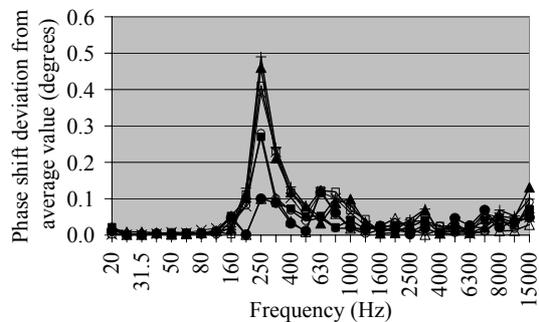


Fig. 4. Deviation from the average value of the phase shift of sensitivity measured at eight angular positions: ⊕ position 9; ▲ position 10; ⊖ position 11; ● position 12; × position 13; + position 14; ■ position 15 and △ position 16.

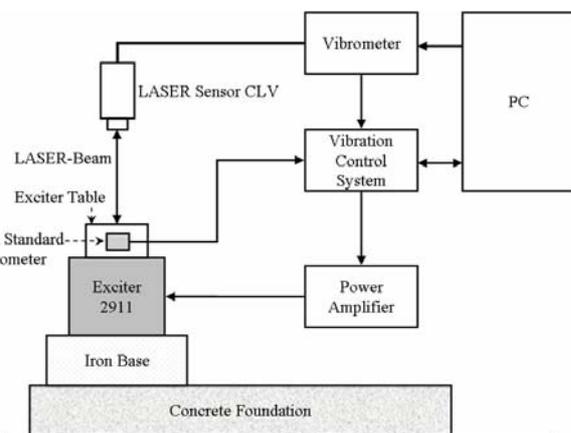


Fig. 1. Experimental set-up [3].

2.3 Effects of mass loading

The influence of mass loading on the deviations of magnitude and phase shift of sensitivity is studied in this section. The mass of 17.6 g was attached to the top of the exciter plate. The deviations were measured at positions 9 to 16 at frequency 250 Hz. Figs. 7 (—⊕—) and (—●—) show magnitude deviations measured with and without mass attaching on the top of the plate respectively. It can be seen that mass loading has no significant effect on the magnitude distribution.

Fig. 8 shows the phase shift deviations measured with and without loaded mass. It is found that the phase shift decreases when the loaded mass is presented.

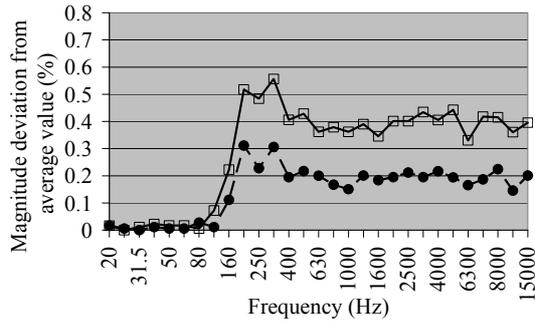


Fig. 5. Deviation from the average value of the magnitude of sensitivity measured at -●- position 2, 6.5 mm from the centre and -□- position 10, 11.5 mm from the centre.

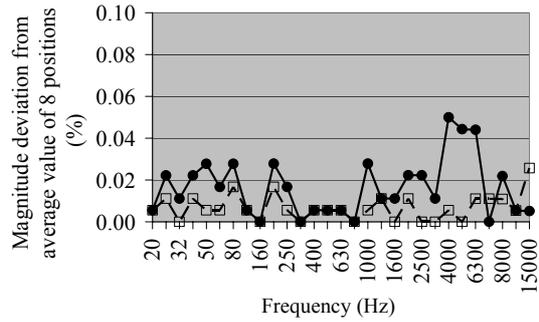


Fig. 9. Deviation of the magnitude of sensitivity averaged from -□- four symmetric positions (positions 10, 12, 14 and 16) and -●- two symmetric positions (positions 9 and 13).

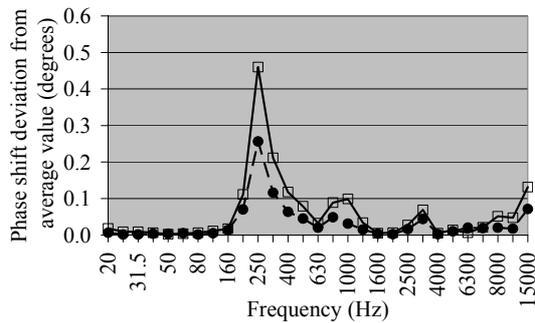


Fig. 6. Deviation from the average value of the phase shift of sensitivity measured at -●- position 2, 6.5 mm from the centre and -□- position 10, 11.5 mm from the centre.

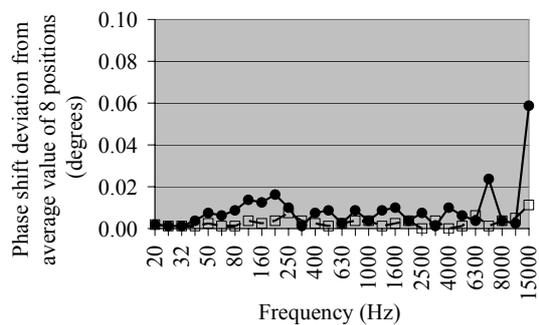


Fig. 10. Deviation of the phase shift of sensitivity averaged from -□- four symmetric positions (positions 10, 12, 14 and 16) and -●- two symmetric positions (positions 9 and 13).

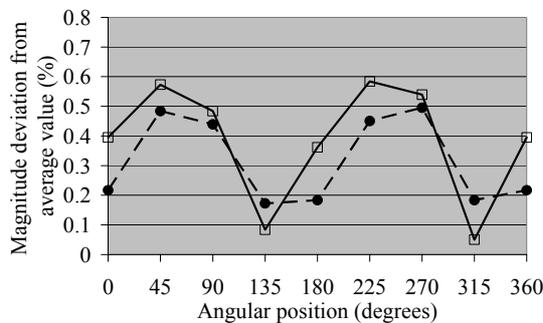


Fig. 7. Deviation from the average value of the magnitude of sensitivity measured: -□- with and -●- without mass loading.

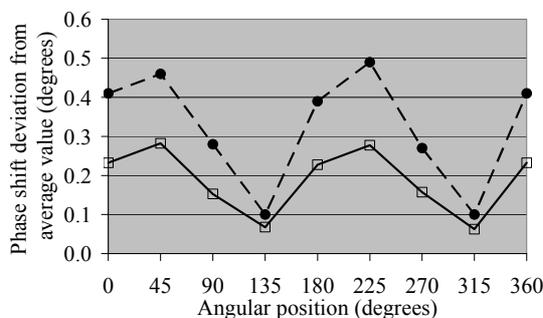


Fig. 8. Deviation from the average value of the phase shift of sensitivity measured: -□- with and -●- without mass loading.

2.4 Effects of changing the number of measured positions to be averaged

In this section, the effects of the number of measured positions to be averaged are investigated. The averages of measurements on two and four symmetric positions are compared. The comparisons of sensitivity and phase shift are shown in Figs. 9 and 10 respectively. It can be seen that the average results of two and four symmetric positions are not significantly different from those of eight symmetric positions.

3. THE EMPIRICAL MODELS FOR PHASE SHIFT

As shown in previous sections, magnitude and phase shift of the sensitivity vary significantly with changing the angular position of laser and the distance from the centre of the exciter plate. The effects of these variations can be reduced by averaging the results measured from symmetric positions. However, pointing laser to the perfectly symmetric positions is difficult to achieve. As a result, the uncertainty due to laser position errors should be considered. The position errors consist of angular and linear position errors. As the deviation of the magnitudes of sensitivity due to these errors have been suggested in [2], this study focuses only on that of the phase shifts of sensitivity. This can be estimated from the empirical models developed in this section. The models are presented in terms of angular and linear laser positions.

3.1 The Empirical model for the deviation of phase shift as a function of angular position

An empirical model for the deviation of phase shift in term of the angular position was determined from the measurements at positions 9 to 16 shown in Fig. 2. The measurements were conducted without mass loading. The frequency at which the maximum deviation shown in Fig. 4 occurs is 250 Hz. The deviation of phase shift from the average value measured at different angular positions at 250 Hz is shown in Fig. 11 (●). An empirical model was determined by a least square fitting method. The measured deviation of phase shift and the empirical model of

$$P_a = 0.49 \sin(a \pi / 180 + 101.5) + 0.0006 \quad (1)$$

are compared in Fig. 11. Here a is the angular position in degrees. If it is assumed that the error in angular position is 5 degrees, the maximum error in the deviation of phase shift calculated using the empirical model is 0.04 degrees approximately.

3.2 The Empirical model for the deviation of phase shift as a function of linear distance from the centre of the exciter plate

Four sets of measurements whose details are shown in Table 1 were performed. The measured results were employed to develop the empirical models for the deviation of phase shift as a function of linear distance. The deviations obtained from both measurements and empirical models are shown in Fig. 12. As data set no. 2 gives the maximum deviation, its empirical model, which is

$$P_d = 0.04 d - 0.017, \quad (2)$$

is used to estimate the uncertainty due to linear position error. Here P_d and d are the deviation of phase shift in degrees and the linear distance from the centre of the plate in mm respectively. It can be seen from the model that if the linear distance deviates 1 mm, the error in the deviation of phase shift is 0.04 degrees approximately.

4 CONCLUSIONS

The effects of the exciter model 2911 on the calibration of single-ended accelerometers were investigated by conducting the parametric studies experimentally. It was seen from the experiments that the angular laser position and the distance of the laser from the centre of exciter plate have significant effects on magnitudes and phase shifts distributions of the sensitivity at specific frequency range. The magnitude and phase shift show higher deviation as the distance of laser positions from the centre of the plate increases. The maximum deviations occur in the frequency range 200 to 315 Hz approximately. Mass loading has significant effect on phase shift. With mass attached to the exciter table, the phase shift shows higher deviation than without mass. The average results taking from two, four and eight symmetric positions are not significantly different.

The errors in the deviation of phase shift due to the errors in the angular and linear laser positions were estimated using the empirical models developed.

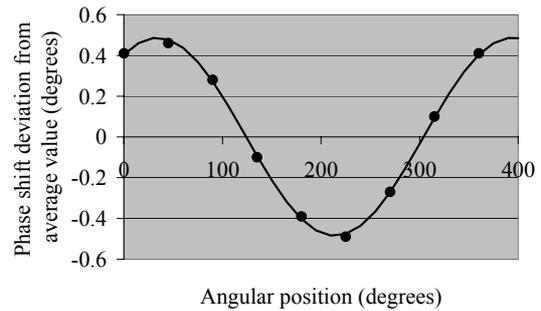


Fig. 11. Deviation of phase shift from the average value as a function of the angular position of laser: ● measurement, — empirical model of (1).

Set No.	Position No.	d (mm)	Set No.	Position No.	d (mm)
1	13	-11.5	3	15	-11.5
	5	-6.5		7	-6.5
	1	6.5		3	6.5
	9	11.5		11	11.5
2	14	-11.5	4	16	-11.5
	6	-6.5		8	-6.5
	2	6.5		4	6.5
	10	11.5		12	11.5

Table 1. Details of four sets of measurements used to estimate the empirical model for the deviation of phase shift as a function of linear distance from the centre of the exciter plate.

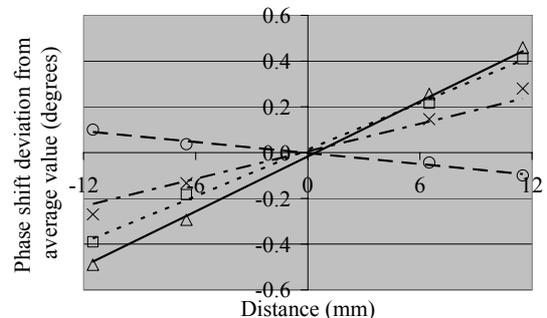


Fig. 12. Deviation of phase shift from the average value as a function of linear distance of laser from the centre of the exciter plate: measurement of set no. □ 1, △ 2, × 3, ○ 4; empirical model of set no. 1, — 2, --- 3, - - 4.

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