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ESTIMATION OF UNCERTAINTY CONTRIBUTION OF TRANSVERSE SENSITIVITY AND VIBRATION DISTRIBUTION ON PRIMARY ACCELEROMETER CALIBRATION

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Abstract − Primary accelerometer calibration is carried out under the assumption that a vibration exciter gives a rectilinear motion to an accelerometer to be calibrated. However practical vibration given by the vibration exciter includes parasitic motion such as transverse, rocking, and bending motion. The parasitic motion especially gives two serious effects on primary calibration results, transverse sensitivity effect and vibration distribution effect. Transverse sensitivity effect is caused by an inner product of the vectors of both transverse motion and transverse sensitivity. On the other hand, the vibration distribution effect is caused by motion disturbance and relative difference between acceleration at sensing point of accelerometer and at the spot sensed by the interferometer.

These uncertainty sources have close interaction between vibration exciter and accelerometer, and close interaction between vibration exciter and the laser interferometer, respectively. Therefore, it is very difficult to estimate independently their uncertainty contribution.

In this study, we propose simple methods to estimate uncertainty contribution due to these effects in the primary calibration, respectively. The proposed methods would enable more practical estimation of uncertainty budget.

Keywords ISO16063-11, transverse sensitivity, vibration distribution

1. UNCERTAINTY SOURCES ON PRIMARY CALIBRATION

In ISO 16063-11[1], uncertainty sources are listed for each calibration method as annex A. Table 1 shows the uncertainty sources for fringe counting method in them. These uncertainty sources can be fundamentally classified in three categories, which are effect of voltage amplitude measurement, effect of acceleration amplitude measurement and the other residual effect. Although National Metrology Institutes (NMIs) have attempted to estimate uncertainty contributions as for these sources, it is very difficult to estimate independently each uncertainty contribution as for some kinds of uncertainty source. Therefore, some NMIs have a possibility not to reflect their own real reliability in their uncertainty budgets due to overestimation to proceed to safety side.

Table 1. Uncertainty source for fringe counting method.

i	Uncertainty source
1	accelerometer output voltage measurement (voltmeter)
2	effect of total distortion on accelerometer output voltage measurement
3	effect of transverse, rocking and bending acceleration on accelerometer output voltage measurement (transverse sensitivity)
4	effect of displacement quantization on displacement measurement
5	effect of trigger hysteresis on displacement measurement
6	filtering effect on displacement measurement (frequency band limitation)
7	effect of voltage disturbance on displacement measurement (e.g. random noise in the photoelectric measuring chain)
8	effect of motion disturbance on displacement measurement (e.g. total distortion; relative motion between the accelerometer reference surface and the spot sensed by the interferometer)
9	effect of phase disturbance on displacement measurement (e.g. phase noise of the interferometer signal)
10	residual interferometric effects on displacement measurement (interferometer function)
11	vibration frequency measurement (frequency generator and indicator)
12	residual effects on sensitivity measurement (e.g. random effect in repeat measurements; experimental standard deviation of arithmetic mean)

Consequently, to keep appropriate technical equivalency between NMIs, the simple estimation method for them has to be established.

In this study, uncertainty estimation method for the two typical uncertainty sources, transverse sensitivity and vibration distribution (“3” and “8” in Table 1), are discussed. These are common sources in all methods.

2. ESTIMATION OF TRANSVERSE SENSITIVITY EFFECT

Transverse sensitivity of accelerometer and transverse motion are expressed as two vectors on the horizontal plane as shown in Fig.1. When the transverse motion is generated with the intended motion, parasitic output voltage, which is an inner product of transverse sensitivity and transverse motion, is convoluted in output voltage from accelerometer. The amount of this inner product strongly depends on the magnitude of transverse motion and the angle between both vectors. The effect cannot be easily removed in the primary calibration. Therefore, although the evaluation of both vectors have been tried respectively, it is very difficult to evaluate both vectors independently.

In this study, we propose simple method to estimate uncertainty contribution due to the effect by turning the accelerometer orientation. In the past, although the method to turn the orientation has been applied to reduce the uncertainty [2], the estimation method of uncertainty contribution has not been developed.

Fig. 2 shows three types of spacer (A, B, C) with different thickness (A: 3.000 mm, B: 3.266 mm, C: 3.531 mm, including processing error) for accelerometer of Brüel & Kjaer type 8305. These spacers are made of stainless steel (SK31) with TiN/Ti coating (0.4 µm / 0.1 µm) and are used for the mounting base. The thickness of these spacers is different by 1/3 screw pitch (0.265 mm) of mounting screw. Therefore the transverse sensitivity axis can be rotated by every 120 degree on the mounting surface of vibration exciter as shown in Fig. 3. Although the rotation by every smaller angle can be achieved within the range of processing accuracy for spacer thickness, it is necessary to evaluate the calibration results by three different orientations of transverse sensitivity axis at least on the estimation of its uncertainty contribution. So, we demonstrate the evaluation by three different orientations as a first trial in this study.

Fig. 4 shows typical primary calibration results on the application of three different types of spacer A, B, and C. At some specific frequencies, remarkable deviation is observed. One data plotted in this figure is average of 10 times measurements. Fig. 5 shows typical variation of sensitivities due to transverse sensitivity effect at 250 Hz. The vertical axis shows voltage sensitivity ($S(\theta_i)$), and the horizontal axis shows orientation (θ_i) of transverse sensitivity for a reference orientation (0 degree) arranged with the spacer A.

The parasitic voltage due to transverse sensitivity is defined by inner product between both two vectors of the

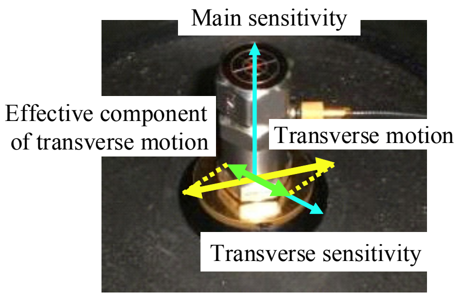


Fig.1 Transverse sensitivity effect

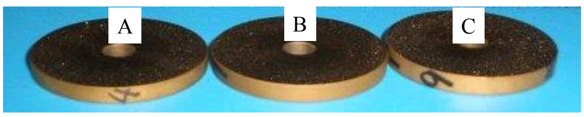


Fig. 2 Three types of spacers with different thickness

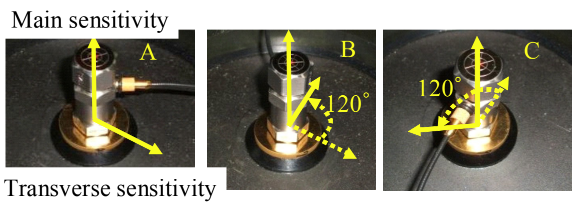


Fig.3 Turn of accelerometer orientation

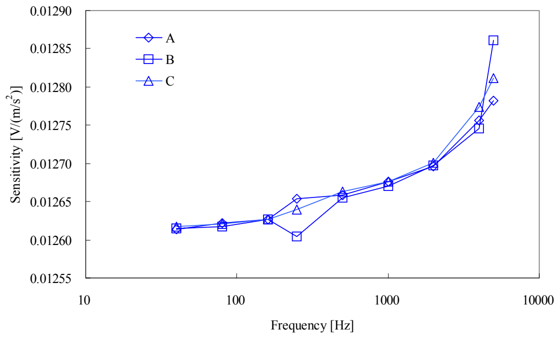
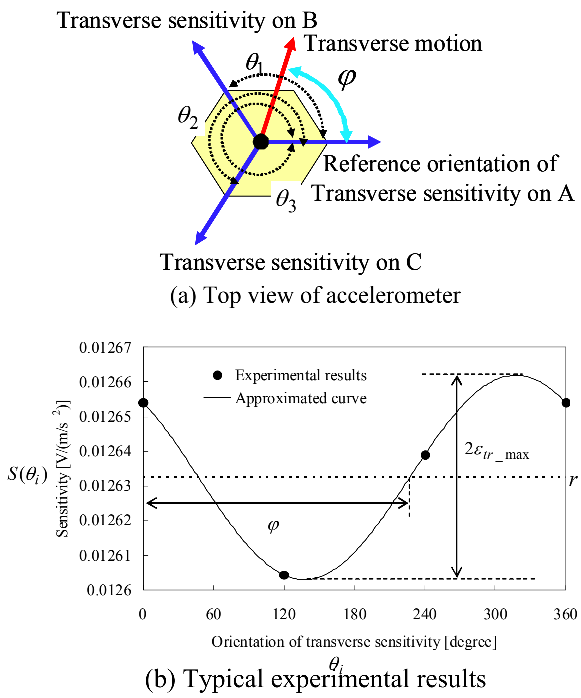


Fig.4 Calibration results in experimental setup with three types of spacer with different thickness



(a) Top view of accelerometer

(b) Typical experimental results

Fig. 5 Typical variation of sensitivities due to transverse sensitivity effect (at 250 Hz) transverse motion and the transverse sensitivity. Therefore the frequency distribution of sensitivity due to this effect would be regarded as sinusoidal distribution under the two assumptions as following;

1) Transverse motion characteristics such as amplitude, phase shift and orientation is constant during calibration in any orientation at single frequency
2) The frequency distribution of orientation of accelerometer is equivalent to uniform distribution

Consequently, the distribution width ($\varepsilon_{tr\_\max}$) due to this effect can be estimated from sine approximation of the calibration results under the setups with different spacers, as shown in Fig. 5. To solve sine approximation with experimental data (θ_i and $S(\theta_i)$) using least squares, the following model is applied,

$$S(\theta_i) = p\cos\theta_i - q\sin\theta_i + r$$

where

$i = 1,2,..., N$;

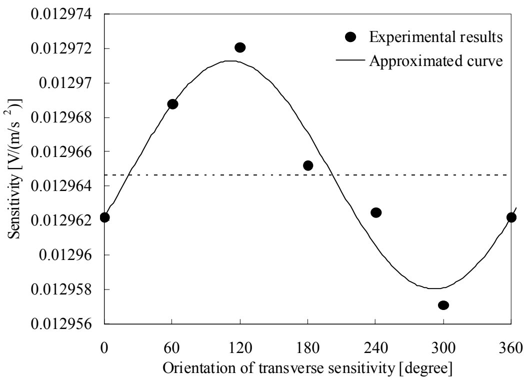
$p = \varepsilon_{tr\_\max} \cos\varphi$

$q = \varepsilon_{tr\_\max} \sin\varphi$

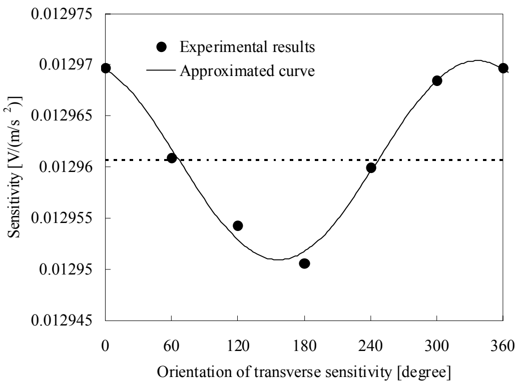
r is main sensitivity;

$\varepsilon_{tr\_\max}$ is distribution width of sensitivity due to this effect;

φ is constant angle between transverse motion and reference orientation (0 degree) of transverse sensitivity arranged with the spacer A.



(a) 250 Hz



(b) 315 Hz

Fig. 6 Typical sensitivity variation due to transverse sensitivity effect at 250 Hz and 315 Hz

Finally, the main sensitivity is given by r and its uncertainty contribution due to this effect can be estimated by dividing $\varepsilon_{tr\_\max}$ by $\sqrt{2}$. r is not the mean value of the experimental results.

The most important advantage of this method is to directly estimate the main sensitivity and the uncertainty contribution due to transverse sensitivity effect without identification of both directions of transverse sensitivity axis and transverse motion. As mentioned later, however, if the drastic vibration distribution on top surface of accelerometer is generated during calibration, more accurate position alignment for spot sensing by interferometer is required to estimate the uncertainty contribution because the transverse sensitivity effect might be mixed into the vibration distribution effect. The more accurate estimation of transverse sensitivity effect would be achieved by trade-off between accuracy of position alignment and amount of vibration distribution.

In order to confirm validity of our proposal, additional experiment with another set of six spacers with different thickness (2.000 mm, 2.131 mm, 2.262 mm, 2.397 mm, 2.529 mm, 2.662 mm) was carried out for another accelerometer of Brüel & Kjaer type 8305. Fig. 6 shows the typical results for 200 times measurements at 250 Hz and 315 Hz. The frequency distribution would be equivalent to sinusoidal distribution from these figures. The small deviation from approximated curve at some experimental points might be due to the vibration distribution as mentioned later. The uncertainty contributions due to this effect are 0.036 % at 250 Hz, and 0.053 % at 315 Hz, respectively.

3. ESTIMATION OF VIBRATION DISTRIBUTION EFFECT

The practical motion given by vibration exciter during calibration accompanies parasitic motion such as a transverse, bending, and rocking motion. The parasitic motion would give serious influence in the interferometer measurement, so called to “Abbe’Error”.

For example, when the intended vibration accompanies bending motion as shown in fig. 7, the vibration distribution in proportion to both of tilting angle ϕ and position offset Δd would be generated at all position “N” on the top surface of accelerometer (or dummy mass), except for the position “M” on the axis of main sensitivity. The effect due to this vibration distribution is called to “Abbe’Error”.

Such vibration distribution effect becomes greater at the specific frequency such as a mechanical resonance frequency of the vibration exciter.

To evaluate this effect, the various research have been attempted in the past [2], [3]. The simplest estimation method is to measure directly the acceleration amplitude at multiple points on the top surface and to compare the acceleration amplitude at arbitrary point with the

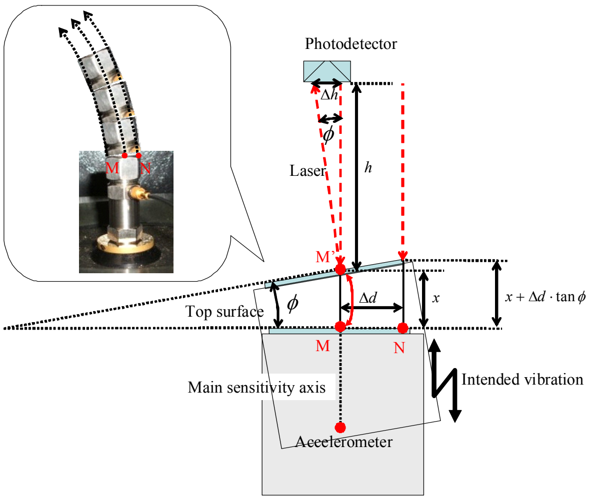


Fig.7 Vibration distribution effect

acceleration amplitude at the reference point "M", where is located on the main sensitivity axis. But it is very expensive to prepare interferometers such as a scanning interferometer to enable measurement at the multiple points, and even if the scanning interferometers can be prepared, the vibration exciter can not always control constant acceleration amplitude at reference point during measurement with high accuracy. Consequently, this method would be not practical.

In this study, to avoid such difficulties, the sensitivity distribution is obtained by separately measuring the sensitivities at multiple points, instead of the acceleration distribution. The sensitivity distribution is quite similar to the acceleration distribution. Additionally, the sensitivity is relatively kept constant even if the calibration conditions such as applied acceleration amplitude are varied.

Fig. 8 shows typical sensitivity distribution at central point on dummy mass and different 6 measurement points (A to F) around it. The central point would be generally located on the main sensitivity axis. These measurement points of A to F draw regular hexagon centering central point as indicated in the photograph in Fig. 8. The dummy mass is made of stainless steel and has marking to achieve easily position alignment with high accuracy. The experimental results show the large deviation at specific

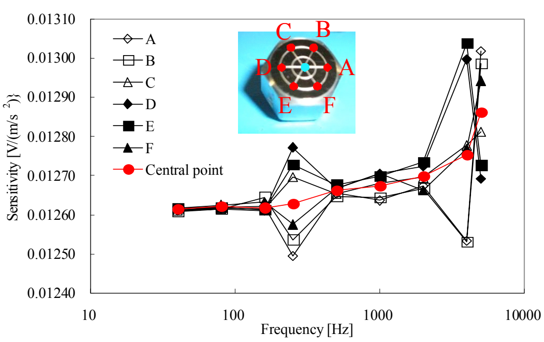


Fig. 8 Typical sensitivity distribution due to vibration distribution effect

frequency series. The couple of result for symmetrical points has point symmetry with respect to the result at central point as shown in fig. 7. For example, the results for point A and B are symmetry with respect to result for central point. Fig. 9 shows averaging results for symmetrical points. These results are good agreement with result for central point. Consequently, if the couple of the symmetrical point is selected, the vibration distribution effect would be greatly corrected.

But, we should note that the misalignment error of measurement position cannot be avoid at specific frequency such as a resonance even if this correction is appropriately carried out, and the vibration distribution effect is still remained within limited narrow equivalent to misalignment

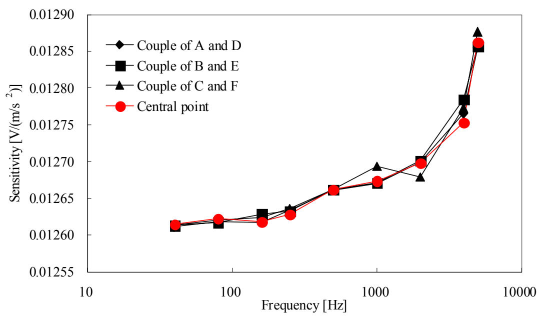
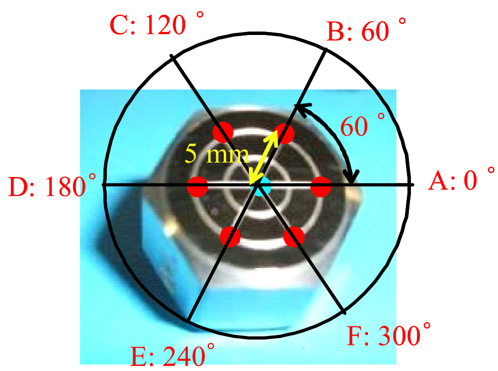
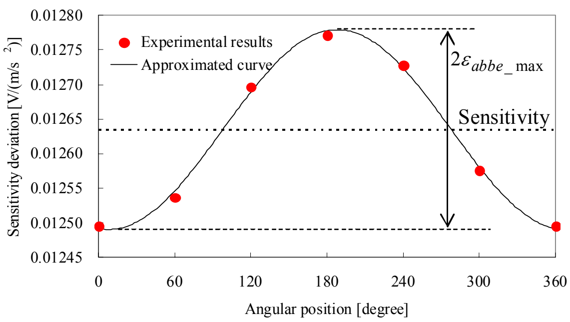


Fig. 9 Averaging results for symmetrical points



(a) Orientation of measurement position



(b) Identification of sensitivity and its deviation by sine approximation

Fig. 10 Typical variation of sensitivities due to vibration distribution effectat 250 Hz (A to F) error. Some disagreements in Fig. 9 would be caused by this remained effect.

So, we propose following method to estimate this effect. The sensitivity deviation due to this effect strongly depends on the orientation and the distance from central point to the measurement position. Under the assumption that the measurement position is in an equal distance from central point, the frequency distribution of the sensitivity deviation would be equivalent to sinusoidal distribution. On the other hand, under the assumption that the measurement position is located in same orientation from central point, the frequency distribution of it would be equivalent to triangular distribution. Consequently, the uncertainty contribution due to this effect can be estimated by following procedure,

1) Measuring the sensitivities separately for multiple points whose positions are specified (orientation and distance from central point)
2) Calculating the sensitivity and the maximum deviation ($\varepsilon_{abbe\_\max}$) from the results by sine approximation using least square method as shown in Fig. 10
3) Estimating the maximum alignment error of measurement position in the calibration
4) Obtaining the ratio of the maximum alignment error to the distance from central point which is specified in procedure 1)
5) Dividing the maximum deviation by the ratio and then, dividing it by $\sqrt{12}$

The uncertainty contribution obtained by experimental results in fig.10 according to this procedure is 0.033 % under maximum alignment error of 0.5 mm. This value is almost equivalent to that (0.036 % at 250 Hz) of transverse sensitivity effect obtained in previous section. Therefore, the more accurate position alignment is required to separately estimate each uncertainty contribution as mentioned above.

4. CONCLUSIONS

The transverse sensitivity effect and the vibration distribution effect become dominant uncertainty sources in primary calibration at specific frequency series. Therefore their uncertainty contribution has to be appropriately estimated. In this study, we proposed the estimation methods of uncertainty contribution as for two uncertainty sources, and clarified the validity of our proposal.

These estimation methods would contribute to appropriately keep the technical equivalency of NMIs for international vibration standard.

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