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PROGRESS IN DEVELOPMENT OF CALIBRATION SYSTEMS FOR ANGULAR VIBRATION PICKUPS

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Abstract – This paper addresses technical challenges unresolved in the calibration of angular vibration pickups. Primary and/or comparison calibration systems for angular vibration pickups can not be realised without the angular vibration exciter and the precision angular accelerometer suitable for the transfer standard. Recent attempts made to tackle these technical challenges and related achievements are introduced in this paper.

Several air-bearing supported angular exciters had been machined and tested to improve their background angular vibration levels and instability conditions due to pressurised air flow characteristics A gross level of 0.01 radian/s^2-rms has been achieved. A new angular exciter whose rotational shaft the precision ball bearings support was designed and machined. This new model includes very improved performance characteristics, such as the reduction of size and mass, the extended frequency range, the efficiency of generated angular acceleration per unit current, much improvement of background vibration, and very low total harmonic distortion characteristics. Experimental results regarding those improved factors are presented in Section 2. The general features, including angular vibration-related, mechanical and electrical parameters, are summarised

The first prototype angular accelerometer made by B&K has been used for the measurement of angular vibration in this work after it had been calibrated in KRISS, Recent measurement results of the sensitivity of the prototype angular accelerometer are presented in Section 3. The results are used to obtain the fitted model-based frequency response curve used for frequency compensation of measurements. Finally, test results, obtained to examine the transverse sensitivity characteristics, are presented. They reveal several technical issues that shall be resolved in the future.

Keywords: Angular vibration, angular exciter, angular accelerometer, angular vibration calibration

1. BACKGROUNDS OF THIS WORK

Angular vibration pickups such as rate sensor or angular accelerometers have been widely used in the industrial sectors of automotive companies, shipyards, off-road vehicles, guided vehicles, aeronautic and astronomic industry, etc. One of challenging technical issues in those sectors is to buy calibrated angular vibration pickups and then to calibrate them later according to their own quality control policy. Most of national metrology institutes (NMIs) except PTB and KRISS are not yet reported to set up the primary or comparison calibration systems dedicated for angular vibration pickups[1-6]. Unlike the limited availability of calibration services, integrated MEMS-based manufacturing technologies of angular rate and accelerometer sensors have recently led to the mass production of low cost models with the measurement accuracy sufficient for industrial applications. But, any commercialised calibration system for the products of MEMS-typed manufacturers is not available yet in the market.

On the onset of this work, it was apparent that an angular vibration calibration system is not realised without developing the angular vibration exciter guided in ISO 16063-15 [7]. In addition to the angular vibration exciter, the laser interferometer dedicated for the primary calibration is needed and, furthermore the transfer standard angular accelerometer is also needed for the comparison calibration. It is readily feasible to set up the laser interferometer for the primary angular vibration calibration when either one of three models in ISO 16063-15 or the angle prism based model [3,4] developed by KRISS is chosen. But, neither the angular vibration exciter nor the angular transfer standard accelerometer is commercialised so far. They are real challenging items for realisation of the angular vibration calibration system

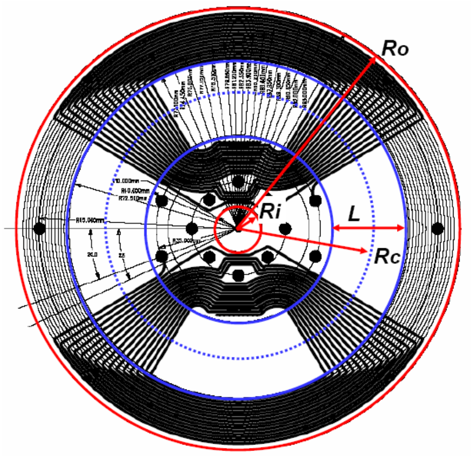
In Section 2, a new angular vibration exciter is introduced, which was developed to realise the first commercialised product of an angular vibration exciter for the primary and/or comparison calibration of angular vibration pickups. In Section 3, calibration results of the first prototype of an angular accelerometer made by B&K are addressed.

2. NEW ANGULAR EXCITER MODEL

Since the first prototype of the angular vibration exciter [4-6,8] had been made in 2007 by KRISS, many attempts have been made to improve its performance. For examples, the structural modification of the first resonance frequency up to 5 kHz, the reduction of total mass below 50 kg, effective ways of delivering supply current to the rotational coil, and alternatives to the air-bearing structure, etc. Those attempts in KRISS enabled us to develop a new angular exciter model that is targeted to introduce the first commercialised product of an angular vibration exciter for the primary and/or comparison calibration of angular vibration pickups. Recent achievements are addressed in this section .

2.1. Reduction of Size and Mass

As well known in the classical mechanism of generating Lorentz force in the angular direction, critical factors that determine the torque of an angular exciter are actually related to the effective length L of the rotational coil and its effective radius R_c (the distance from the centre of the rotational shat to the mid point of the rotational coil in the radial direction). Fig. 1 shows the rotational coil designed for the new angular exciter.



(a) Details of rotational coil.

(b) 20-layered PCB-typed rotational coil.

Fig.1. Rotational coil designed for the new angular vibration exciter.

The dimension of the factors for the first prototype of the angular exciter made in 2007 was L = 60 mm and R_c = 70mm. The inner and outer diameters of the coil were R_i = 20 mm and R_o = 250 mm. When those design factors were chosen, the total mass of the first prototype was found to be 81 kg. It was too massive for one person to carry it.

It was obvious in the initial stage of developing the new angular vibration exciter that the effective length of the rotating coil is the most significant factor not only to improve the generation capacity of angular acceleration vibration but also to determine the size and mass of the angular exciter. An optimal value for the effective length is determined by examining whether the angular acceleration generation capacity is increased or decreased in change of the effective length L of the coil. When the effective length is changed to be (L-l), the ratio of the angular acceleration levels are described as

$$\frac{\alpha(l)}{\alpha(0)} = \frac{(L-l)\cdot(R_c-0.5l)}{L\cdot R_c}\cdot\frac{D_O^4-D_i^4}{(D_O-2l)^4-D_i^4} \qquad (1)$$

In equation (1), the symbols α(0) and α(l) denote the angular acceleration generated by the first prototype and the one generated by the length-changed model. Fig. 2 shows the calculated results in change of the effective length.

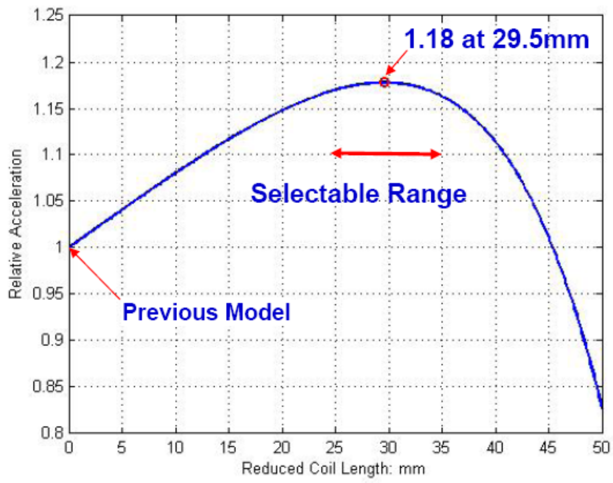


Fig.2. Normalised angular acceleration level in reduction of the effective coil length.

As shown in Fig. 2, the generation capacity of angular acceleration can be increased by 18 % even though the effective length of the new model is reduced by 30 mm. This point was very significant in reducing the size and mass of the angular exciter, i.e. the reduction of the out-diameter by 60 mm and the 42 % mass reduction (the mass of the new model = 47 kg).

2.2. Extension of First Resonance Frequency to 5 kHz

As pointed out in the previous work [4-6], the 1^{st} and 2^{nd} resonance frequency components of the rotational shaft of the first prototype was 676 and 1.92 kHz (nodal point at the measurement). It was found that those resonances came from the hollow shaft machined to carry the current supply cable inside the shaft. Moreover, the through hole perpendicular to the shaft was needed to connect the cable to the disk-shaped rotational coil. This structure was found to cause the reduction of torsion stiffness of the shaft.

When a solid shaft model is considered, it is quite straightforward to design the rotational shaft with the 1^{st} resonance frequency of 5 kHz or higher. Fig. 3 illustrates the frequency response characteristics of the new angular exciter. The first resonance frequency was seen to be 5.034 kHz and well matched to the design frequency of 5 kHz. This result indicates that the new angular exciter provides the calibration frequency up to 5 kHz.

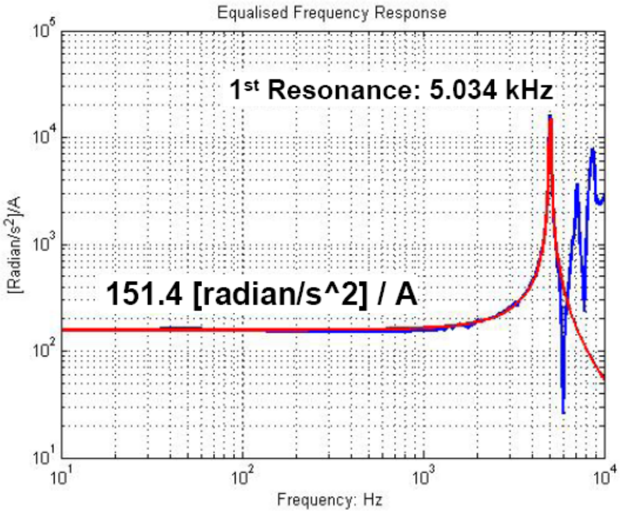


Fig.3. Frequency response of the new angular vibration exciter developed in KRISS.

The 20-layered PCB-typed rotational coil, as shown in Fig.1 (b), was newly designed to have the limited current of 10 A-peak for the protection of thermal problems without external forced air cooling. To examine what amount of angular acceleration this coil can generate, different levels of AC currents were applied to the new angular. Fig. 4 shows measured angular acceleration levels (denoted by the red circle) by changing the applied current levels of 160 Hz.

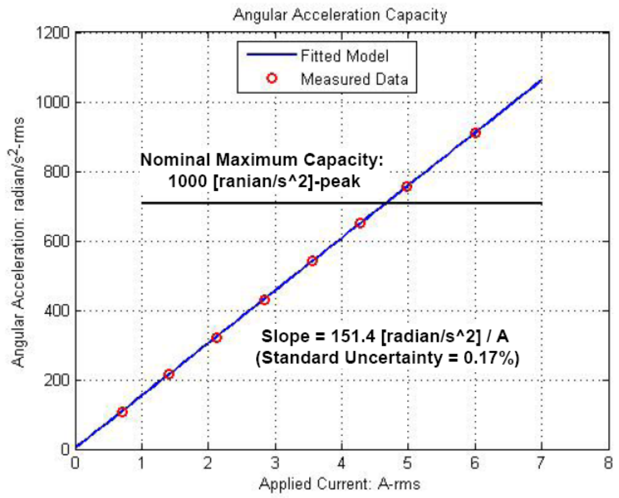


Fig.4. Generation capacity of angular acceleration tested at 160 Hz.

The slope of measurement points indicates the generated angular acceleration per unit AC current, i.e. the performance index. Whilst the index of the first prototype was 141.9 [radian/s^2]/A, that of the new model is shown to be 151.4 [radian/s^2]/A (6.7 % improvement for the new angular exciter).

2.3. Characteristics of Ball-bearing Supported Shaft

Several models of air-bearing systems for the angular vibration exciters have been machined and tested in KRISS to reduce the background vibration levels of air-bearing systems as small as possible. As shown in the previous work [4-6], the background vibration level of 0.01 radian/s^2–rms was shown to be achievable except either the combined resonance frequency regions of the angular accelerometer and the rotational shaft or the instability region of air-bearing systems due to complex flow characteristics of pressurised air. Of course, the cost of machining air-bearing systems is comparably high, in addition of the precision assembling cost. Recently, experimental attempts had been made to examine what amount of background vibration is achieved when high-precision ball-bearing systems are chosen instead of the air-bearing system. Fig. 4 shows the background vibration levels.

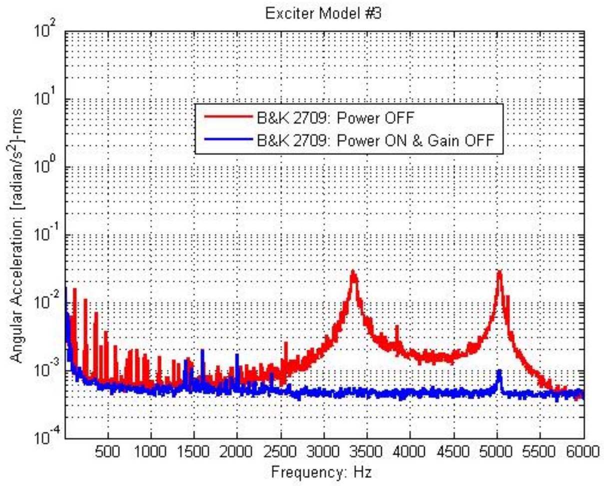
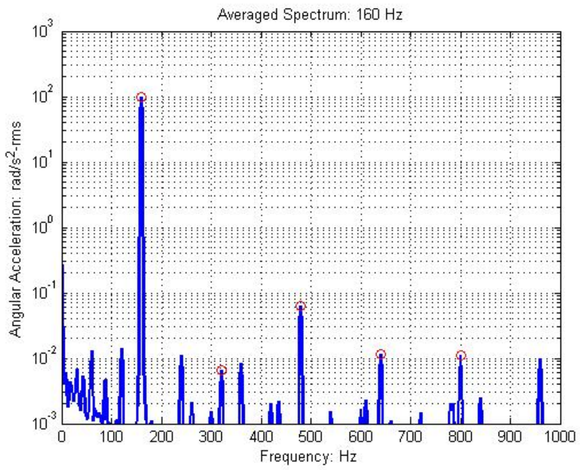


Fig.5. Background vibration levels measured from the high-precision ball-bearing supported angular vibration exciter.

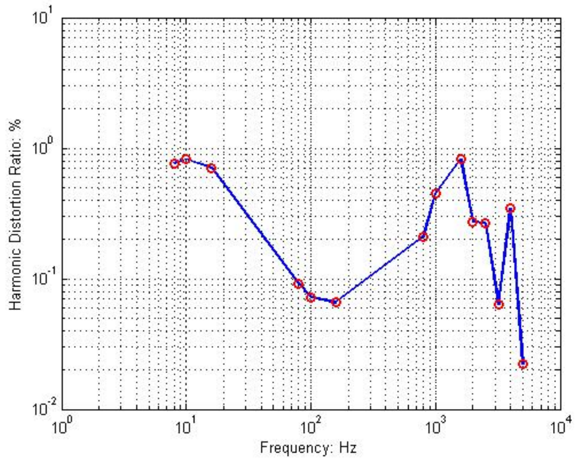
When the power amplifier (B&K 2719) was turned off the background vibration level was observed to be 0.004 ~ 0.006 radian/s^2-rms. But it was on, the internal current noise of the power amplifier was seen to excite the new angular exciter system such that two noticeable peaks were measured. The first one at 3.343 kHz was related to the resonance of the angular accelerometer (B&K prototype 1) and the second at 5.034 kHz was generated by the 1st torsion resonance of the rotational shaft Since the first peak at 3.343 kHz is irrelevant to the exciter system, the background noise level of 0.004 ~ 0.006 radian/s^2-rms is expected to be very sufficient to use the new angular exciter for the calibration of angular vibration pickups.

2.4. Characteristics of Total Harmonic Distortion

Unwanted harmonic components are inevitable in the vibration calibration jobs such that ISO 16063-15 [7] recommends to use the angular vibration exciter with the total harmonic distortion (THD) of 2 % or less over the calibration frequency range. Fig. 6 (a) shows the multiple harmonic components measured at the preferred frequency of 160 Hz. Much smaller THD (close to 0.01 %) was observed over the frequency range of 80 ~ 500 Hz. To the contrary, THD's over the low frequency range of 8 ~ 40 Hz were seen close to 0.8 %. It was the reason that a rubber band was used to protect the slow movement of the zero position of the shaft caused by the non-ideal DC-offset characteristics of both the power amplifier (B&K 2719) and the function generator (HP 33120A). As shown in Fig. 6 (b), THD's over the high frequency range of 800 ~ 400 Hz were also observed to be 0.2 ~ 0.8 %. Some high THD values were contributed mainly by the resonance characteristics of the angular accelerometer, not directly from the angular exciter system itself.



(a) Harmonic components measured at 160 Hz.



(b) Total harmonic distortion ratios.

Fig.6. Characteristics of harmonic distortion generated by the new angular exciter.

More delicate device for the reduction of THD over the low frequency range of 20 Hz or less is under development. Of course, much improvement of THD below 40 Hz is expected to be achieved when conventional PID motion controllers are used.

2.5. General Features of New Angular Exciter Model

Fig. 7 shows the picture and the 3D drawing of the new angular vibration exciter model developed for the calibration of angular vibration pickups. One of main features is to exploit the precision ball-bearing support for the rotational shaft. This structure was illustrated to provide much less background vibration level than the air-bearing supported model, as already introduced in Section 2.3.This ball-bearing supported exciter model has more cost benefits than the air-bearing model, specifically costs required in machining and assembling the exciter. As illustrated in precious sections, the new angular vibration exciter is obviously shown to satisfy at least the requisites for the angular vibration generating device specified in ISO 16063-15 [7]. It sounds good news to all NMI's and other vibration measurement and calibration laboratories in the world. KRISS has already started to review and sort out practical ways of delivering the final product models of the new angular vibration exciter.

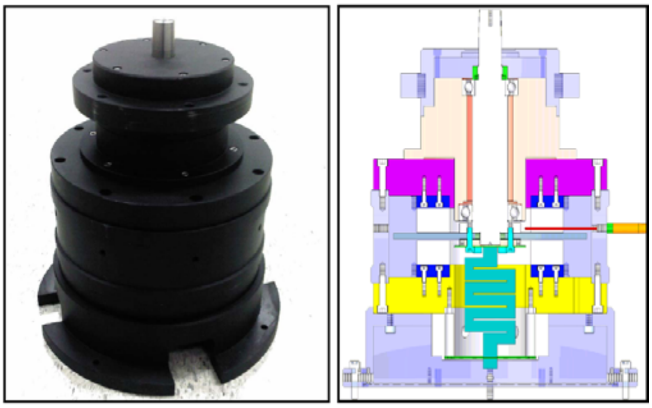


Fig.7. New ball-bearing supported exciter model.

Table 1 lists the general features of the new angular vibration exciter that is targeted for the calibration of angular vibration pickups. As shown in the electrical characteristics of Table 1, power amplifier models that have been used in the calibration of linear accelerometers or vibration pickups are good enough to drive the new angular vibration exciters.

Table 1. General features of the new angular exciter.

Angular Vibration Characteristics	Peak-to-peak Displacement	60° (1.05 radians)
	Stopper Position	±40° (1.40 radians)
	Peak Acceleration	1000 rainan/s^2-peak
	Frequency Range	8 Hz ~ 5 kHz
	Total Harmonic Distortion	0.02 % ~ 0.8 %
	Amplitude Stability	0.00.025 % or less
Mechanical Characteristics	Inertia Moment (Rotational Part)	0.00157 kg×m^2
	Mass (Rotational Part)	1.70 kg
	Thread for Assembling Pickups	M6 (Depth =10mm)
	Body Outer Diameter	245 mm
	Base Outer Diameter	290 mm
	Total Masss	47 kg
Electrical Characteristics	Resistance of Rotational Coil	2.0 Ω (at 100 Hz)
	Inductance of Rotational Coil	160 µH (at 100 Hz)
	Maximum Allowable Current	7 A-rms
	External Connector	NEUTRIK NL4MP

3. CALIBRATION OF ANGULAR ACCLEROMETER

One of technical challenges in the calibration of angular vibration pickups has come from the point that any reference or transfer standard angular accelerometer with the frequency range of 5 kHz or less is not available in the market. It has been the main reason that no calibration linkage between KRISS and PRB has been established so far. Advanced accelerometer makers are very encouraged to develop the reference or transfer standard angular accelerometer as soon as possible.

On the onset of this work, B&K had made the first prototype of a charged-typed angular accelerometer and delivered it to KRISS. Its calibration results are introduced in this section.

3.1. Primary Calibration System in KRISS

The primary calibration system for angular vibration pickups [3,4] had been established in 2007. Fig. 8 shows the configuration diagram of instruments. Unlike the three laser interferometers introduced in ISO 16063-15, the angle prism-based differential plain mirror interferometer (DPMI) developed by Zygo was exploited to measure the angular vibration. Details of the angle-prism based DPMI had been already reported in reference [3]. The measurement board (Zygo model 4004) enables the simultaneous measurement of the 32-bit digitised angular displacement with the resolution of 2.6665×10^{-8} radians. Furthermore, the voltage output signal of an angular acceleration under test is also measured by using the 16-bit AD converter (NI PXI 6123). The discrete Fourier transforms is used to evaluate the cosine and sine components from the time series of the sampled reference vibration signals and the sampled voltage output signals simultaneously. Although detailed procedures and results of evaluated measurement uncertainty regarding the primary calibration system are not addressed in this paper due to the page recommendation of this conference paper, they are actually a long story and involve unresolved technical issues. Those are to be addressed in this congress.

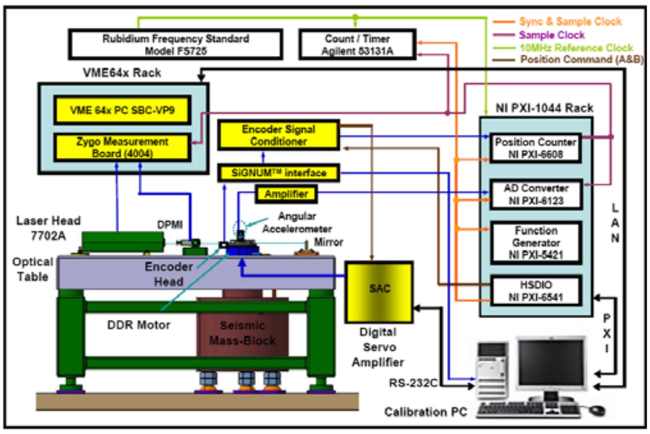


Fig.8. Configuration diagram of the primary calibration system in KRISS.

3.2. Preliminary Results of Charge Sensitivity

Fig. 9 shows the photo of the prototype angular accelerometer model fixed on the upper surface of the angle prism holder. The size is almost identical to the linear accelerometer of B&K 4370. Fig. 10 illustrates the modulus of the complex sensitivity of the prototype angular accelerometer (marked by the red circles) that is normalised by the sensitivity value of 160 Hz, i.e. 0.0665 pC/[radian/s^2]. The solid line indicates the fitted model used for frequency response compensation such as TEDS-supported accelerometers. It is obviously well matched to the response model.

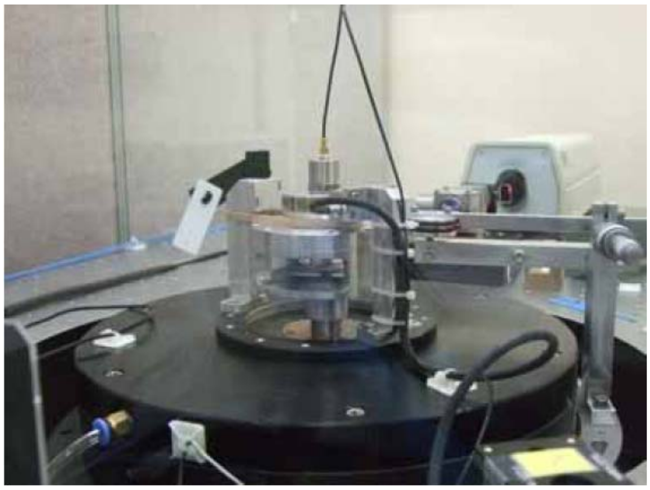


Fig.9. Photo of the first prototype angular accelerometer fixed on the upper surface of the angle prism holder.

The 1st resonance was observed to be 3.343 kHz. It seems to be used for the measurement of angular vibration limited in the frequency range of 1 kHz or les without compensation of the frequency response shown in Fig. 10. Whilst the typical resonance frequency of B&K 4370 model is printed to be 16 kHz in the catalogue that of angular acceleration is shown to be much lower.

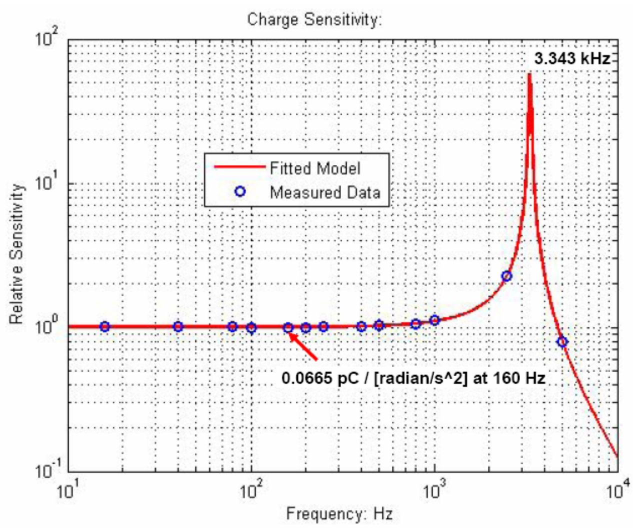


Fig.10. Measured modulus sensitivity characteristics of the first prototype angular accelerometer mad by B&K.

3.3. Transverse Sensitivity

It is significant to examine what amount of the transverse sensitivity an angular accelerometer produces when it undergoes linear vibration. Table 2 lists the cross sensitivity characteristics measured from the prototype angular accelerometer when the vertical linear vibration level was applied to it. The transverse sensitivity values below 2.5 kHz are seen to be closely 0.5 % of the typical charge sensitivity of B&K 4370 model. More interestingly, the magnitude of the cross sensitivity is seen to be larger than that of the angular vibration sensitivity. It may imply several technical issues that shall be resolved in the future.

Table 2. Transverse sensitivity of the prototype angular accelerometer measured under the vertical linear vibration.

Frequency [Hz]	Reference Level [m/s^2]-rms	Sensitivity (pC/(m/s2))
20	10.00	0.517
40	30.02	0.514
80	50.06	0.511
160	50.01	0.648
315	49.93	0.541
630	50.13	0.568
1250	50.07	0.505
2500	50.02	0.515
5000	47.69	1.18

4. CONCLUSIONS

This paper addresses technical challenges unresolved in the calibration of angular vibration pickups. Primary and/or comparison calibration systems for angular vibration pickups can not be realised without the angular vibration exciter and the precision angular accelerometer suitable for the transfer standard. Recent attempts made to tackle these technical challenges and related achievements are introduced in this paper.

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