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## **Progress in development of primary angular vibration calibration systems**

Wan-Sup Cheung <sup>(\*1)</sup> and Sang-Myong Park <sup>2</sup>

(\*1)Acoustics and Vibration Group / KRISS, 1 Doryong-Dong Yuseong, Daejeon, 305-340, Republic of Korea, Tel: +82-42-868-5302, FAX:+82-42-868-5643, e-mail: [wansup@kriss.re.kr](mailto:wansup@kriss.re.kr)

(2) Acoustics and Vibration Group / KRISS, e-mail: [302sm@naver.com](mailto:302sm@naver.com)

### **Abstract**

The angular vibration calibration system is not well established even in most of NMI's. Moreover, it is not certain that suppliers of angular vibration pickups have well maintained the traceability of their calibration systems, unlike the linear vibration calibration systems well established in the industrial sector. This paper points out several technical issues encountered in setting up the angular vibration calibration system in KRISS. The first was to develop a new angular vibration exciter that is not commercialized yet. The angular vibration calibration system can not do without the angular vibration generation apparatus. The multi-layered PCB manufacturing technology is exploited to make the rotating coil designed to generate the Lorenz force. The first prototype model of the angular vibration exciter built up in KRISS is illustrated in this paper. It is shown to meet the requirements of the amplitude stability, the total harmonic distortion, and the hum and noise components, recommended in Clause ISO16063-15. Furthermore, it is shown the measured frequency responses that it can generate angular vibration over the frequency range of 5 Hz to 1 kHz (or more). Main features of the angle prism based interferometer set up in KRISS are addressed. Three uncertainty components are introduced and their evaluated uncertainty contribution is demonstrated. Those results are very useful to judge the measurement capability of the angle prism based interferometer.

**Keywords:** Angular vibration, angular exciter, primary vibration calibration, laser interferometer

## 1. Introduction

Korean customers, working in the automotive companies and the aerospace industry, had many times raised technical issues encountered in establishing the quality control of the test and measurement of angular vibration. Several strategic ways of establishing the quality control in Korea were considered. The first one among them was to set up the primary calibration system for angular vibration pickups and then to deliver the high quality calibration service. To meet such demand for the calibration service of angular vibration pickups, KRISS had decided to set up the primary calibration system in 2004. Table 1 shows the progress of setting up the apparatus required for the primary calibration system. The requirements for the apparatus of the primary calibration system of angular vibration transducers are described in Clause 4 of ISO 16063-15:2006<sup>[1]</sup>.

Required Apparatus	2005	2006	2007	Progress
4.2 Frequency generator	Done			100 %
4.3 Exciter & power amplifier				95 %
- Low & mid frequency exciter model	Done			(100 %)
- Mid & high frequency exciter model		Designed	<b>Planned</b>	(90%)
4.4 Seismic block for the exciter	Done			100 %
4.5 Laser	Done			100 %
4.6 Interferometer	Done			100 %
4.7 Instruments for interferometer	Done			100 %
4.8 Instruments of pickup outputs		Done		100 %
4.9 Distortion analyzer		Done		100 %
4.10 Oscilloscope (Optional)	Done			100 %
4.11 Other requirements:		Not related		

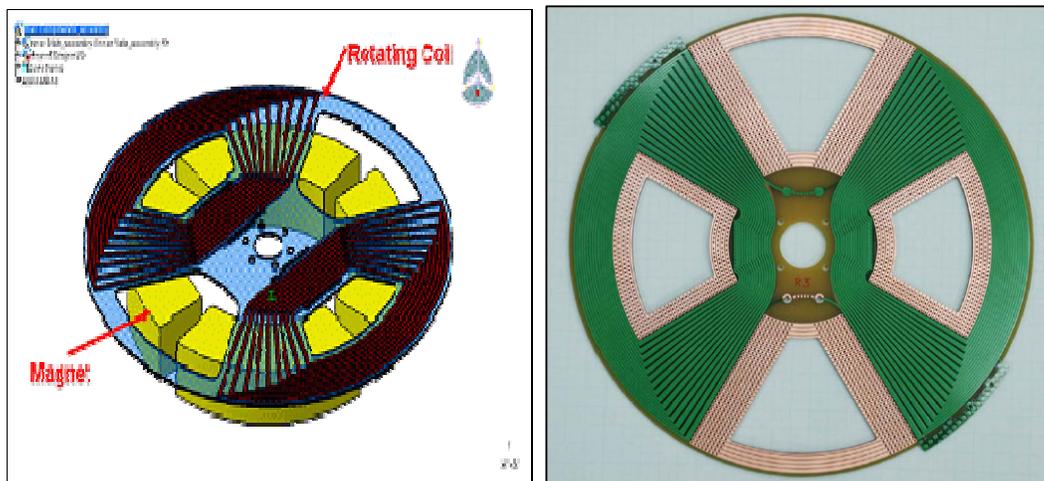
Table 1. Progress of setting up the primary calibration system for angular vibration transducers

Moss of efforts to set up the calibration apparatus in 2007 have been made to manufacture the prototype for the mid and high frequency exciter model that had been designed in 2006 to meet the frequency range of 10 Hz to 1 kHz (or more). The first prototype model of a new electromagnetic angular vibration exciter was successfully manufactured in the July of 2007. Its performance tests

are in progress. In Section 2, the features of the electromagnetic angular exciter are introduced. Another technical challenge was to set up the high precision angular displacement measuring instrument. The angle-prism based laser interferometer<sup>[2]</sup> was exploited in KRISS. It is quite different from the interferometers introduced in ISO16063-15. In Section 3, main features of the angle-prism laser interferometer in KRISS are introduced. The measurement uncertainty contributed by angle-prism laser interferometer is reported. Finally, main results in this paper are summarized.

## 2. Electromagnetic Angular Vibration Exciter

The first model for the electromagnetic angular vibration exciter was developed in PTB in the last decade. The torque generating structure, introduced in Clause 4.3.2 of ISO16063-15, consists of the paired permanent magnets and the coil holding disk rigidly fixed in the rotating shaft. The paired magnets are assembled to generate the magnetic field in the vertical direction. Dual loop-shaped multi-turn coils that are designed to make the current flow in the radial direction, are inserted in the holding disk. The holding disk is located between the paired upper and lower magnets such that the radial direction current flow generates the Lorentz force in the angular direction. The Lorentz force multiplied by the effective radial distance of the coils contributes the generation of the resultant torque exerted on the rotating shaft. This torque generation mechanism, which might be found at the very beginning generation of motor inventors, is very simple and straightforward. But, a commercialized model for the angular vibration exciter is not available yet.

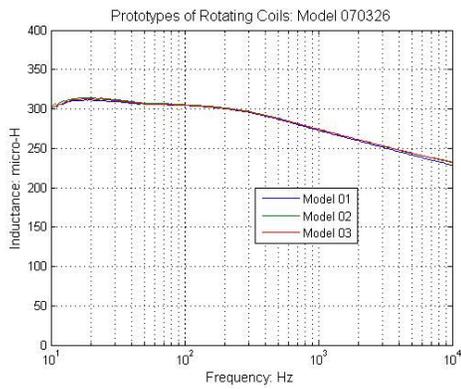


(a) Conceptual model

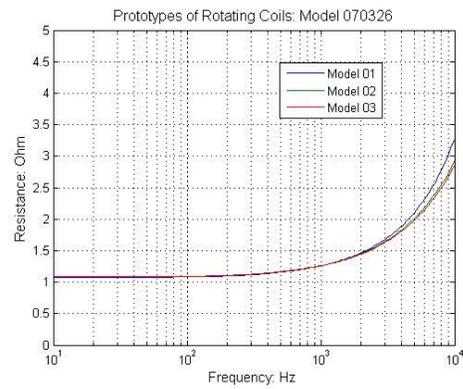
(b) 20-layered prototype model

Figure 1. Multi-layered PCB-typed rotating coil developed for angular vibration exciter.

At the beginning of this work, the hand-made coil holding disk made in KRISS was found to have many problems, such as the unbalanced mass due to the irregularly inserted coils, the insufficient stiffness for supporting rigidly the multi-turn coils, and the unbalance torque due to the irregularly positioned coils, etc. Those technical matters were thought to be major difficulty in making a commercialized angular vibration exciter successfully. This research team devised an idea that the multi-turn coil can be made using the printed circuit board (PCB) technology. Figure 1 (a) shows the conceptual model of the PCB-typed rotating coil. The advanced PCB design technology enables the determination of the width and thickness of the copper patterns sufficient to carry the desired current and, furthermore, the selection of the number of copper layers that are related to the effective number of coil turns. Of course, the electric factors (inductance, resistance and capacitance) of the designed rotating coil unit are also well characterized, in addition to thermal analysis. Figure 1 (b) shows the prototype of the 20-layered PCB based rotating coil developed for the angular vibration exciter. Figure 2 shows the measured electric properties (inductance and resistance) of three 20-layered PCB based rotating coils manufactured in KRISS. Any noticeable difference between three prototype coils is not observed. The resonance frequency of the complex impedance of the prototype models was found to be close to 125 kHz. It may imply that the manufactured prototype coils work well below the upper frequency limit of 5 kHz. The coil, referred to “model 02,” was assembled in the rotating shaft. Figure 3 illustrates the 3D design model of the angular vibration exciter and the first prototype model manufactured in the machining center of KRISS.



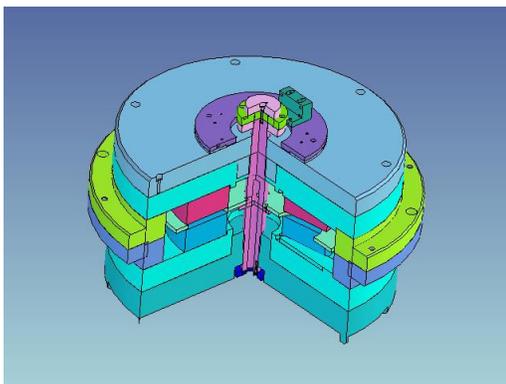
(a) Inductance



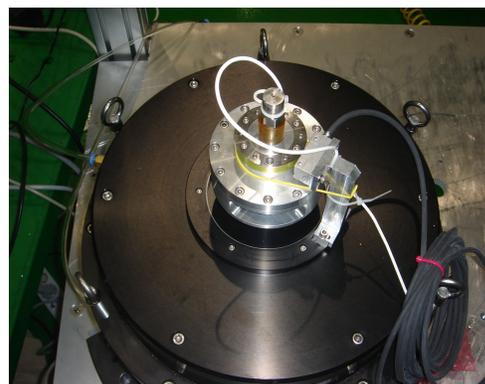
(b) Resistance

Figure 2. Electric characteristics of prototype rotating coils.

The design specifications of the electromagnetic angular vibration exciter are as follows: the gap between the upper and lower magnets = 6 mm, the strength of the magnetic field (at the mid point) = 1.0 Tesla, the thickness of the rotating coil = 4 mm, the effective length of the coil = 60 mm, the span of the maximum angular displacement =  $59^\circ$ , the peak supply current = 20 A (0.5 A per each layer), the Lorentz force = 57.6 N, the peak torque = 4.1 N·m, and the peak angular acceleration = 4,100  $\text{radian/s}^2$  (inertia moment =  $0.001 \text{ kg}\cdot\text{m}^2$ ). The upper and lower air-bearings are designed to support the rotating shaft. Figure 3 (b) shows the first prototype model assembled in KRISS. To examine the overall performance of the prototype model, many test items are under investigation.



(a) 3D design model



(b) Prototype model

Figure 3. Electromagnetic angular vibration exciter

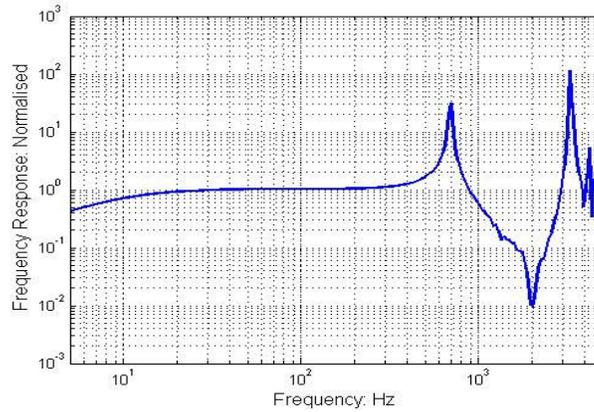


Figure 4. Frequency responses measured from 5 Hz to 5 kHz (vibration level = 100 radian/s<sup>2</sup>-rms).

Figure 4 illustrates the frequency response measured up to 5 kHz. The first and second resonance frequencies were found at 699 Hz and 3.17 kHz and the first node was also observed at 1.92 kHz. Those frequency responses are related to the torsion vibration characteristics of the rotating elements, i.e. the rotating shaft, the rotating coil, the top vibration table (used to fix pickups), and the column of the lower air-bearing. An equivalent torsion vibration system with three masses and two springs is considered to shift the fundamental frequency to 5 kHz (or more). Table 2 shows the general features of the prototype angular vibration model. The amplitude stability over the consecutive 20 samples is found to be less than the limit level of  $\pm 0.05\%$ . Furthermore, the total harmonic distortion is seen to be far less than the limit level of 2% recommended in ISO 18063-15.

Frequency {Hz}	8	16	40	80	160
Amplitude Stability	0.023 %	0.013 %	0.011 %	0.012	0.015
Harmonic Distortion	0.15 %	0.077 %	0.049 %	0.038	0.069

Table 2. General features of electromagnetic angular vibration exciter

Figure 5 shows the spectral components observed when the excitation frequency was 8 Hz and the vibration level was chosen to be 100 [radian/s<sup>2</sup>-rms]. The symbol, marked by the circle, denotes the harmonic components of 5 Hz. Except the harmonics of 60 Hz (AC power frequency), any noticeable low frequency hum and noise are not observed. Such low level of hum and noise

components is thought to be achieved only by the electromagnetic mechanism of generating the torque. Those test results may indicate that the electromagnetic angular vibration exciter developed in KRISS is sufficiently appropriate for the primary calibration system of angular vibration pickups recommended in ISO 18063-15.

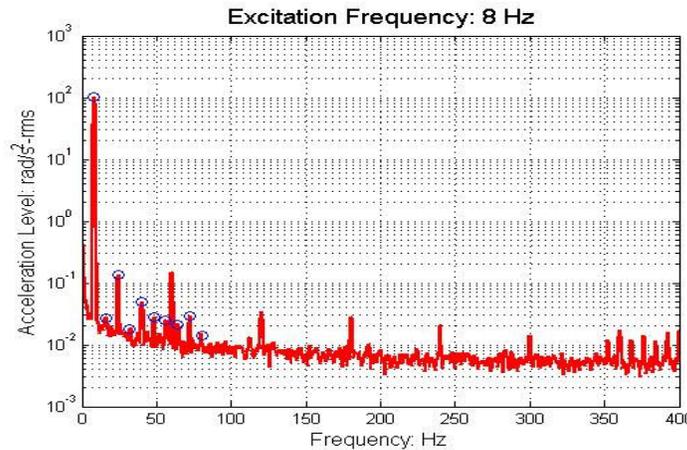


Figure 5. Spectral components observed under the vibration level of 100 [radian/s<sup>2</sup>-rms].

### 3. Measurement Uncertainty of Angle-Prism Based Laser Interferometer

The standard of ISO16063-15<sup>[1]</sup> considers two interferometers: the retro-reflector interferometer and diffraction-gating interferometer<sup>[3]</sup>. The former one has the very limited angle measurement range of  $\pm 3^\circ$  and much difficulty in the alignment of the retro-reflector(s). Whilst the latter enables the measurement of the unlimited range, it has the highest difficulty in manufacturing a precision sine-shaped diffraction-gating device and aligning its centre within 2  $\mu\text{m}$  apart from the rotation axis. Moreover, the technical challenge of calibrating the pitch of the sine-phase diffraction-gating is encountered. Although such machining difficulty and the time-consuming angle calibration of the diffraction-gating disk are overcome in the initial setting-up stage, another technical difficulty is still encountered in maintaining the unwanted transverse motion of the vibration exciter as small as possible during the calibration of vibration pickups. An insensitive interferometer to the unwanted transverse motion, if available, enables the use of commercialized rotation motion generators, i.e. direct driven motors. It is the reason that the angle prism based laser interferometer<sup>[2]</sup> was selected in this work. Figure 6 illustrate the angle prism

based laser interferometer installed with the direct driven rotary (Kollmorgen model DH0603M).

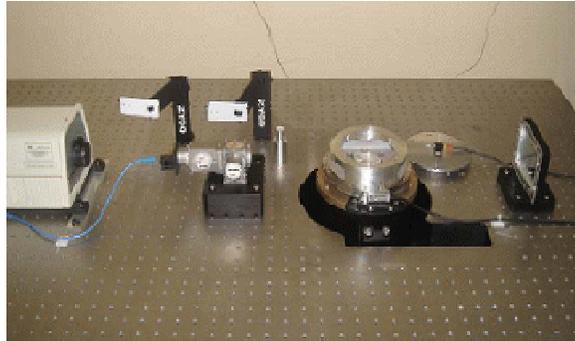


Figure 6. Angle-prism based laser interferometer

The optic components of the angle prism based laser interferometer consists of the DPMI (differential plain mirror interferometer) installed on the optic table and the angle prism installed in the angular vibration exciter. Those optic components contribute the uncertainty of measuring the angular displacement, which is referred to the “laser interferometer” components. As shown in Table 3, they are subdivided into three items: the angle prism calibration error, the polarization induced error and the alignment error of the angle prism installed in the angular exciter. The uncertainty contributions, related to the angle prism calibration error and the polarization induced error, are supplied from the factory. the angle prism calibration error is related to the physical dimensions and optic properties of the prism (the thickness of the upper and lower sides of the prism, the included angle in the prism, and the refraction indexes of the upper and lower sides of the prism, and the averaged wavelength). The polarization induced error is related to all the optic components of the DPMI. The alignment error of the prism, installed in the center of the angular exciter, was measured from the precision inclination reader with the resolution of  $\pm 0.02\text{mm/m}$ .

Uncertainty Components	Uncertainty Sources		Uncertainty Contribution
Laser Interferometer	Angle Prism Calibration Error	Range = $\pm 10^\circ$	0.184 $\mu$ radians
		Range = $\pm 30^\circ$	0.304 $\mu$ radians
	Polarization Induced Error ( related to all optic devices)		0.237 $\mu$ radians
	Angle Prism Alignment Error (Roll and Pitch Slop $\leq 0.1$ mm/m)		0.0028 $\mu$ radians
Angular Displacement Measurement Board (Zygo ZMI 4004A)	Resolution of Angle Measurement		0.00512 $\mu$ radians
	Systematic Error of Optic Components		0.00512 $\mu$ radians
	Dynamic Reading Error: Range = $\pm 2.5$ m/s		0.00615 $\mu$ radians
	Digital Lowpass Filter (Kp = -5 and Kv = -17)	Gain	0.002 %
Phase		0.02°	
Angle Calculation Model	Resolution of Converting Counts to Angle		Negligible
	Initial Position Error		0.00512 $\mu$ radians

Table 3. Listings of uncertainty components and their contribution.

The optic output of the DPMI is delivered through the optic fiber to the angular displacement measurement board<sup>[4]</sup> (Zygo model: ZMI 4004A). The measurement uncertainty, contributed by the angular displacement measurement board, is listed in Table 3. The measurement board converts displacement information into the 36-bit integer values that a user can read via the VME 64x bus. The quantization resolution of the measurement board is equivalent to the angle of 0.00512  $\mu$ radians (equal to one LSB). It is also equal to the length of  $\lambda/2048$  ( $\lambda$ = the wavelength of the He-Ne laser), i.e. the minimal path difference caused by the rotation of the prism. The single board computer, installed in the VME 64x bus, is used to read the quantized value at the rate of 100 kHz and to store them in the bank of RAM in a real time. Given the time series of the sampled 36-bit values, the angular displacement corresponding to each sampled value is obtained by solving numerically the known algebraic formula between the 36-bit integer value and the angular displacement. This numerical method of calculating the angular displacement from the integer value does not yield any uncertainty to the measured angular displacement. But, the calculation program needs the initial angular position where the measurement board was initially reset. The initial position is read from the

mechanical encoder with the resolution of  $0.27 \mu\text{radians}$ . This initial position error is thought to be less than of the LSB of the position measurement board.

#### **4. Concluding Remarks**

This paper introduces the progress of setting up the primary calibration system for angular vibration transducers in KRISS. Attempts to design and manufacture the prototype model of the electromagnetic angular exciter made in KRISS are in details addressed. The design specifications of the prototype model are in detail presented. The multi-layered PCB design and manufacturing technologies are exploited to design and make the rotating coil for the generation of the resultant torque. Test results of the electrical characteristics of three prototype rotating coils are shown to be very appropriate for the operation over the frequency range of 5 kHz. The development of the multi-layered PCP-typed rotating coil has enabled the realization of a new electromagnetic angular vibration exciter. The first prototype model of the angular vibration exciter built up in KRISS is illustrated in this paper. It is shown to meet the requirements of the amplitude stability, the total harmonic distortion, and the hum and noise components, recommended in Clause ISO16063-15. Furthermore, it is shown the measured frequency responses that it can generate angular vibration over the frequency range of 5 Hz to 1 kHz (or more). Main features of the angle prism based interferometer set up in KRISS are addressed. Three uncertainty components are introduced and their evaluated uncertainty contribution is demonstrated. Those results are very useful to judge the measurement capability of the angle prism based interferometer.

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