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DEVELOPMENT OF PORTABLE ANGULAR VIBRATION EXCITERS

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Abstract - This paper introduces a new ‘portable’ angular exciter model developed in KRISS during last two years. Its development was successfully completed in 2010 such that most technical issues have been resolved and a product model is ready to be delivered to the industrial sectors. Interestingly, a new company being incubated in KRSSS emerged to make and distribute a final version of angular vibration exciters to the market. This paper introduces recent measurement and test results, such as the usable frequency range, the capacity of generating angular acceleration, harmonic distortion ratios, etc, carried out in the technology incubation stage supported by KRISS. One of the topics of the technology incubation project was to develop the portable angular vibration calibration system targeted to the market. Its tested technical performance indicators and specifications are in details presented in this paper. In summary, its inertia moment is designed to be less than 2×10^{-5} kg·m² and to cover not only the frequency range of 10 Hz to 1 kHz but also the peak angular acceleration of 2,000 radian/s² or higher.

Keywords: Angular vibration, vibration exciter, angular exciter, vibration calibration, electro-dynamic exciter

1. INTRODUCTION

A vibration research team in KRISS has carried out many efforts [1-6] to develop new measurement and calibration systems focused in angular vibration during last five years. One of successfully developed systems was a unique angular exciter model for generation of angular vibration, which plays a significant role in calibrating angular vibration sensors. The model was shown to have salient features [3,4]: the disk-typed and 20-layered PCB-typed moving coil with mass production capability and ultra precision size tolerance, the flexible PCB device for supply of very high current to the moving coil, and the very tight tolerance rotational shaft, etc. The model was shown to provide the angular acceleration generation capacity of 151.4 [radian/s²] per Ampere, the very low harmonic distortion ratio of 0.8 % or less, and the high frequency range extended to 5 kHz. Since it satisfies the requirements for angular exciters specified in ISO 16063-15 [7], it seems

to be very appropriate for the primary and/or comparison calibration of angular vibration pickups over the frequency of 8 Hz to 5 kHz. The model was actually designed to generate an angular acceleration level of 1,000 [radian/s²]-peak sufficiently even for the inertial moment of 0.002 kg·m² whose components include the optic devices of the interferometer, the ultra-precision rotary encoder, the angular vibration table for fixing an angular vibration transducer under test, and the main shaft, etc. Its target application is to be used for the primary and/or comparison calibration exciter model.

Recently, MEMS-based manufacturing technologies of both angular rate sensors and linear accelerometers have led to mass production of low cost models with the measurement accuracy sufficient for industrial applications such as automotives and smart phones. Their main features are small-sized (i.e. 3 mm-by-3 mm) and ultra-low power-consuming. Their usage is very increasing and is expected to be in much demand in the near future. But, any commercialised calibration system for the MEMS-typed angular rate sensors is not available yet in the market. Both Korean automotive companies and smart phone makers have asked this research team to make a ‘portable’ angular exciter model appropriate for the field calibration of MEMS-typed angular rate sensors at several fixed frequencies. In 2009, KRISS had determined to support the development of such angular exciter model. This paper introduces recent results achieved in KRISS.

2. DESIGN SPECIFICATIONS

Experiences of developing the angular exciters in KRISS have allowed authors to set up systematic ways of designing a new angular exciter: (1) designing the magnet circuit, (2) designing the rotational coil fitted to the magnet shape, and (3) designing the rotational shaft supported by the precision ceramic ball bearings. The first step is to design the magnetic circuit appropriate for the targeted ‘portable’ model. Unlike the previous four-segmented annular magnet model, a new eight segmented model was considered. A key technical issue in designing the magnet circuit is to achieve the magnetic field strength B as large as possible. Its target strength was to be close to 1.0 Tesla.

These design factors were informed to a Korean permanent magnet manufacturer to design the magnet circuit. Table 1 shows the details of the designed magnet circuit. The final field strength was 0.9 Tesla when the vertical air gap between the upper annular yoke and the lower magnet was separated by 2.5 mm and the width and thickness of the annular magnet were 15 mm and 10 mm. Figure 1 (a) shows the layout drawing of the permanent magnets.

Table 1. Design specifications

Magnet Circuit	Field strength (B)	0.9 Tesla
	Angle width (θ_M)	35°
	Vertical air gap (g_M)	2.5 mm
	Outer diameter($d_{O,M}$)	60 mm
	Inner diameter($d_{I,M}$)	30 mm
	Thickness(t_M)	10 mm
Rotational Coil	Limit current (I_L)	200 mA/layer
	Turns per layer (N_C)	19×8
	Angle width (θ_C)	20°
	Layers (M_C)	8
	Outer diameter ($d_{O,M}$)	80 mm
	Thickness (t_C)	1.2 mm
	Moment of inertia	$\approx 10^{-5}$ kg·m ²
Shaft	Length (l_s)	70 mm
	Outer diameter (d_{Os})	24 mm
	Moment of inertia	$\approx 8 \times 10^{-6}$ kg·m ²
	Materials	Al & SUS

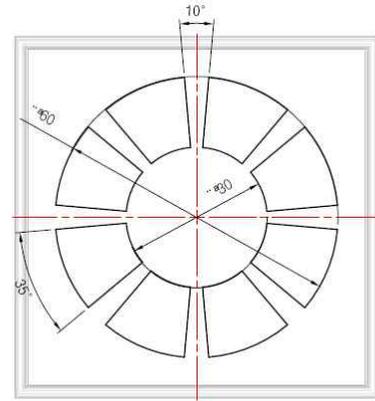
The second design step is to design the rotational coil using the computer aided PCB design technology. This step aims to determine the number of turns of the rotational coil lying in the magnetic field and the nominal current level supplied to the coil. The 200 mA current limit per PCB layer was used to determine the line width of the PCB typed coil. Figure 1 (b) illustrates the dimensional details obtained from the PCB design software. As shown in Table 1, eight PCB layers were allowed to fit in the thickness of 1.2 mm. One forth of the 200 mA current limit was chosen to be the nominal supply current level (denoted by $i = 50$ mA) such that the eight layers can afford to flow the total 400 mA current, i.e. $M_C i = 400$ mA. After the second design step, the target torque, the usable stroke of angular displacement and the moment of inertia of the rotational coil are determined readily. The target torque realizable from the design specifications is evaluated by (1).

$$T = N_C \cdot M_C \cdot i \cdot B \cdot \frac{1}{8} (d_{O,M}^2 - d_{I,M}^2) \tag{1}$$

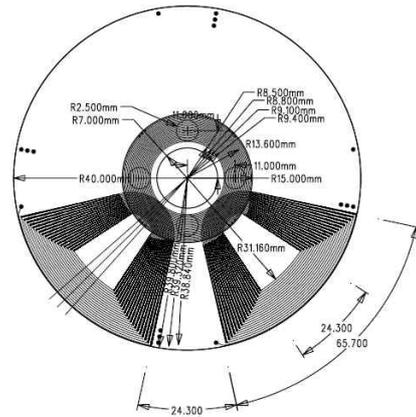
The resultant torque, evaluated by the design specifications of Table 1, was found to be 0.0185 Nm. The total stroke of angular displacement was 15° (the angle width of a segmented magnet minus that of the rotational coil) and the moment of inertia of the coil was about 10⁻⁵ kg·m².

The third step is to design the rotational shaft including the support bearings. A key issue in this step is to reduce the moment of inertia of rotationally moving components of the shaft as small as possible. The smaller their moment of inertia becomes, the larger the angular acceleration is

achieved. Interestingly, commercialised MEMS rate sensors are very tiny and light (i.e. << 0.2 cc and < 0.5 g) unlike traditional PZT or ICP typed linear accelerometers. The moment of inertia, even including the metal housing used to protect and fix the MEM sensor soldered on the PCB board, is negligible in comparison to that of the metal shaft. Actually, rotationally moving components of the shaft consist of many mechanical elements such as the rotational coil, the inner rings of the paired ceramic ball bearings, the fixing jig for assembling an angular sensor under test, and the shaft components, etc. As shown in Table 1, an approximate value of the total inertia moment was seen to be 1.8×10⁻⁵ kg·m². Resultantly, the design value of the angular acceleration was to be about 1,000 radian/s²-rms (i.e. angular acceleration = T / I_{rot} = 1,028 radian/s²-rms).



(a) 8 segmented permanent magnets



(b) Dimension of rotational coil

Fig. 1. Designed magnets and rotational coil.

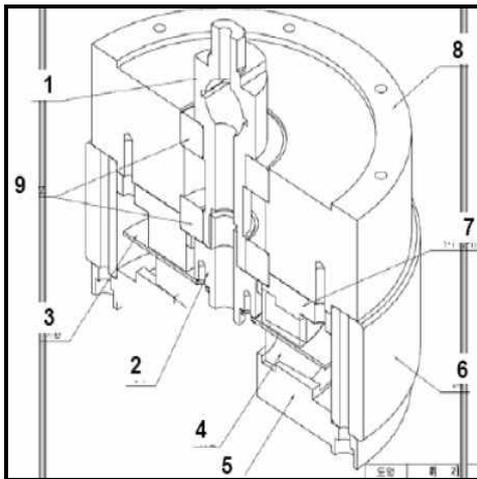
3. FEATURES OF PORTABLE ANGULAR EXCITER

After the design specifications, as introduced previously in Section 2, were decided at the beginning of this project, several trials and errors had been made in machining, assembling and testing the prototype models. Those attempts were focused not only to reduce the moment of inertia of rotationally moving parts but also to increase the magnetic field strength generated by the magnet circuit. Figure 2 shows the picture of the prototype model of the portable angular exciter and the cross-section view of its 3D assembling drawing. This portable model had been actually designed to have identical mechanical features adapted to

the previous angular exciter models [3-6]. Rotationally moving components consist of the main shaft (part 1 and 2 in Fig. 2 (b)), the torque generating coil (part 3 in Fig. 2 (b)), and the upper and lower support bearings (part 9 in Fig. 2 (b)). Stationary mechanical components are the eight segmented permanent magnets (part 4 in Fig. 2 (b)) positioned on the bottom yoke plate (part 5 in Fig. 2 (b)), the upper yoke plate (part 7 in Fig. 2 (b)), the annual cylinder (part 6 in Fig. 2 (b)) for fixing the lower and upper yoke plates, and the bearing support block (part 8 in Fig. 2 (b)). Paired yoke plates were designed to realise the closed loop magnetic field generated by the eight permanent magnets. A mounting stud (UNF 10-32 thread) was designed to be on the topside of the shaft to fix an angular vibration sensor under test.



(a) Photo of prototype model



(b) 3D assembling drawing

Fig. 2. Portable angular exciter model.

Furthermore, a flexible PCB device was specially designed not only to deliver the supply current to the rotational coil but also to isolate effectively unwanted vibration transferred from the cable connected to the power amplifier. The ‘relatively thick’ current supply cable put on the ground or hung on the side wall was found to make it impossible to isolate ground vibration components propagated from the building. A thin PCB device was chosen to deliver the supply current to the rotational coil since it has much lower specific mechanical impedance in comparison to the thick cable. Figure 3 shows the flexible

PCB device used to supply the driving current to the rotational coil.



Fig. 3. Flexible PCB device (green coloured item) designed to supply the driving current to the rotational coil (patent pending).

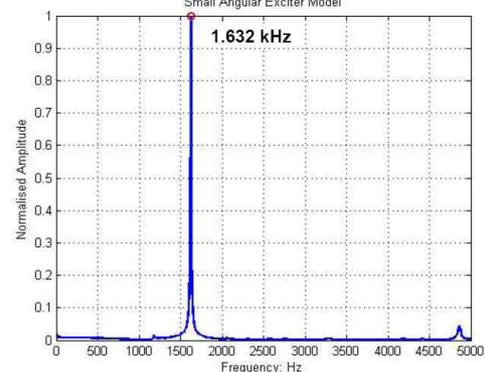
4. PERFORMANCE TEST RESULTS

4.1 Resonance Frequency of Rotational Shaft

A rigid shaft model was adapted to transfer to the mounting stud the torque generated by the rotational coil laid in the magnet field.



(a) Photo of rotational shaft



(b) Fundamental frequency

Fig. 4. Resonance test result of rotational shaft.

Fig. 4 (a) illustrates the photo of the rotational shaft under resonance test. The calibrated angular accelerometer (B&K model 1, same size as linear accelerometer type 4370) was attached to the topside of the shaft to measure angular vibration. The designed shaft is seen to be relatively small in comparison to the angular accelerometer. Such size was realised from efforts to reduce the moment of inertia of the shaft as small as possible. Fig. 4 (b) shows the fundamental frequency observed at 1.632 kHz. Although the inner rings of the support bearings were not assembled to the shaft under resonance test, the fundamental frequency of the fully assembled shaft is expected to be less than the initial target frequency of 1.25 kHz since the moment of inertia of the inner rings are smaller than that of the angular accelerometer attached to the shaft. Resultantly, it may confirm that the designed shaft is very appropriate for the portable angular exciter sufficient for the upper frequency range of 1 kHz or higher.

4.2 Resonance Frequency of Rotational Shaft

One of the important performance indicators of angular exciters is the frequency response to applied current. It actually determines the frequency range of angular exciters over which the flat response is achieved. To measure the frequency response, the dynamic signal analyser (HP 35670A) was used. Its source signal output was connected to the power amplifier (B&K 2719) used to drive the current to the rotational coil. Similarly, the calibrated angular accelerometer (B&K model 1) was attached to the topside of the shaft to measure angular acceleration generated by the rotational coil.

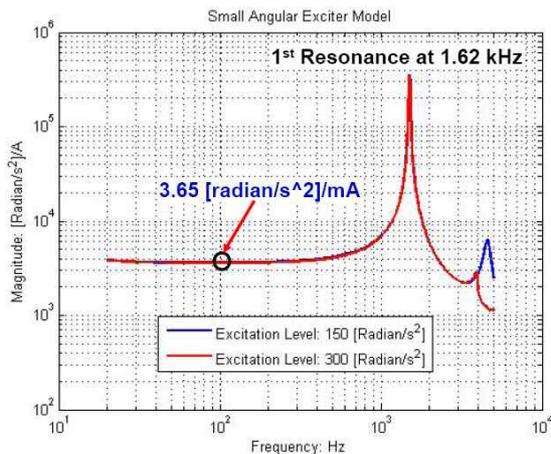


Fig. 5. Frequency response characteristics of portable angular exciter.

Fig. 5 illustrates the measured frequency response characteristics of the developed portable angular exciter. The blue and red coloured graphs were obtained by changing the excitation levels of 150 and 300 radian/s²-rms. Their difference is not noticeable below the frequency range of 4 kHz. Both results may indicate that the developed portable angular exciter can provide the usable frequency range of 20 Hz to 1 kHz. As shown in Fig. 5, the fundamental frequency of the torsion vibration of the fully

assembled exciter was found to be 1.62 kHz. It looks to be well matched to the resonance test result of the ‘bare’ shaft without the inner rings of the support ball bearings (refer to Fig. 4 (b)). The efficiency indicator of generating angular acceleration was found to be 3.65 radian/s² per mA. It is very encouraging to note that when the nominal maximum current of 400 mA-rms is applied an amount of angular acceleration of 1,460 radian/s²-rms can be resultantly achieved. This level is found to be 46 % improvement more than the initial design value. It was actually achieved by reducing the moment of inertia of rotationally moving components and increasing the magnetic field strength by means of reducing the air gap between the upper yoke plate and the permanent magnets.

4.3 Capacity of Generating Angular Acceleration

The 8-layered PCB-typed rotational coil, as shown in Fig. 3, was newly designed to have the nominal maximum current level of 400 mA-rms for the protection of thermal problems without external air-forced cooling. To examine what amount of angular acceleration this coil can generate, different levels of AC currents, generated by the power supply (B&K 2719), were applied to the portable angular exciter. Fig. 6 shows measured angular acceleration levels (denoted by the red circle) by changing the applied current levels of a 100 Hz source signal generated from the function generator (HP 33120A). The slope of measurement points indicates the generated angular acceleration per unit AC current, i.e. the efficiency indicator (or performance indicator) of generating angular acceleration, which was found to be 3.65 radian/s² per mA. This performance indicator is shown to be constant over the fully covered supply current levels.

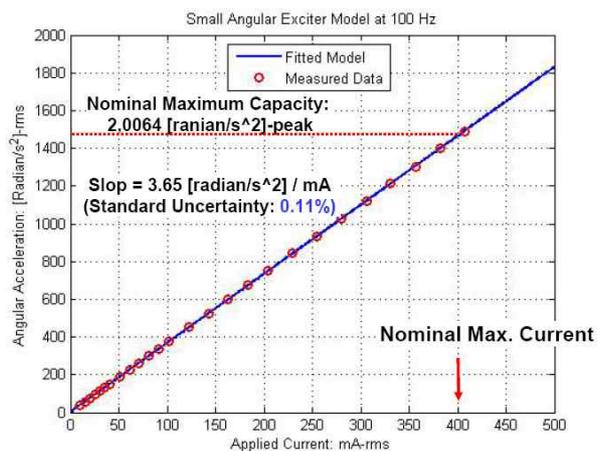


Fig. 6. Angular acceleration generation capacity of developed portable angular exciter measured at 100 Hz.

4.4 Characteristics of Total Harmonic Distortion

Unwanted harmonic components encountered in calibrating vibration sensors are inevitable 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. The power

amplifier (B&K 2719) and the function generator (HP 33120A) were used to generate the sinusoidal angular vibration, and the dynamic signal analyser (HP 35670A) was used to analyse the characteristics of total harmonic distortion. Fig 7 illustrates the total harmonic distortion ratios measured over the frequency range of 20 Hz to 1.5 kHz.

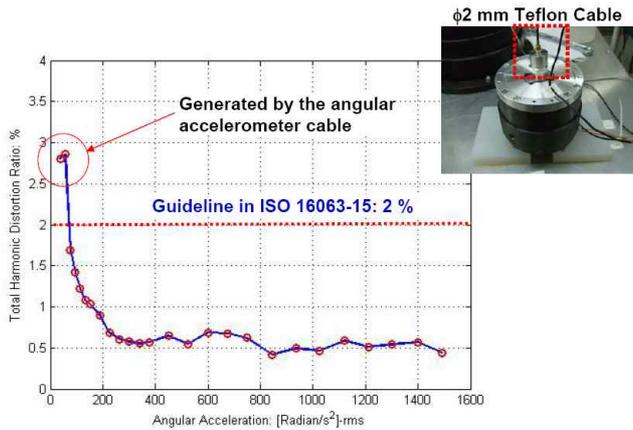


Fig. 7. Total harmonic distortion ratios measured from the developed portable angular exciter.

THD ratios over the high frequency range of 200 Hz to 1.5 kHz were also observed to be 0.4 ~ 0.7 %. They are very encouraging. But, they were observed to increase rapidly below 160 Hz. As shown in the caption of Fig. 7, they were found to be caused by the influence of the motion of the ‘relatively stiff’ Teflon cable of the angular accelerometer fixed on the topside of the shaft. It should be noted that harmonic components of a used vibration exciter THD ratios do not increase measurement uncertainty specifically in case of the comparison calibration rather than the primary calibration using laser interferometers sensitive to unwanted harmonic motions.

4.5 Electrical Characteristics of Rotational Coil

As commented in Section 2, the rotational coil was designed in aid of the PCB design software. The 200 mA current limit per PCB layer was used to determine the line width of the PCB typed rotational coil. Each layer consists of four identical looped coil patterns, as shown in Fig. 1 and Fig. 3, which are connected in a serial form. Although the PCB design software provides its resistance for a given thickness of copper layer, its real values over the frequency range of interest was not correctly predicted. The designed single layered coil pattern was manufactured by the chemical etching process widely used to make multi-layered PCB boards. The averaged total resistance per layer, obtained from twenty samples, was founded to be 95.8 Ohms at 160 Hz. Such resistance was too high to drive AC current such that impedance matching for the power amplifier must be inevitable. To reduce the total resistance, eight layers connected in a parallel form were chosen such that one eighth of the total resistance was realised. Fig. 8 shows the averaged complex impedance measured over the frequency range of 10 Hz to 100 kHz.

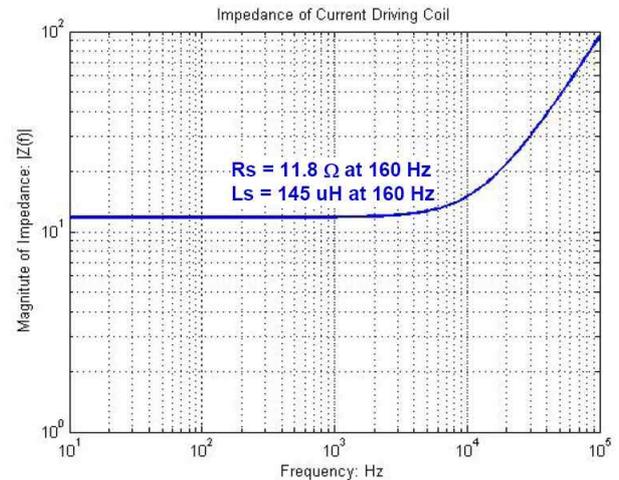


Fig. 8. Averaged complex impedance characteristics of 8-layered rotation coils.

As shown in Fig. 8, the resistance of the eight-layered rotational coil was found to be 11.8 Ohms at 160 Hz and its inductance to be 145 uH at 160 Hz, respectively. If any power amplifier can provide 5 V-rms AC to the resistive load, it should be sufficient to drive the rotation coil of the portable angular exciter. Commercialised 2 ~ 3 W power amplifiers are seen to be sufficient to drive the portable angular exciter.

5. GENERAL FEATURES OF PORTABLE ANGULAR EXCITER

As introduced in previous sections, the developed portable angular exciter is demonstrated to have distinctive features. Table 2 lists the general features of the new portable angular vibration exciter that is targeted for the calibration of light-weighted angular vibration pickups such as MEMS-typed angular rate sensors.

Table 2. General specifications of developed portable angular exciter model.

Angular Vibration Characteristics	Peak-to-peak Displacement	15° (0.262 radians)
	Stopper Position	±22.5° (0.39 radians)
	Peak Acceleration	2000 radian/s ² -peak
	Frequency Range	10 Hz ~ 1 kHz
	Total Harmonic Distortion	0.5 % ~ 2.8 %
	Amplitude Stability	0.025 % or less
Mechanical Characteristics	Inertia Moment (Moving Part)	0.000018 kg·m ²
	Mass (Moving Part)	0.092 kg
	Thread (Assembling Pickups)	10/32 UNF (Depth:10mm)
	Body Outer Diameter	110 mm
	Base Outer Diameter	130 mm
	Total Mass	4.5 kg
Electrical Characteristics	Resistance of Rotational Coil	12 Ω (at 160Hz)
	Inductance of Rotational Coil	145 μH (at 160 Hz)
	Maximum Allowable Current	400 mA-rms
	External Connector	BNC

The general specifications are categorised into three parts, the angular vibration characteristics, and the mechanical ones and the electrical ones. As listed in Table 2, the stroke of angular displacement is close to ± 7.5 ° (or 15 ° peak-to-peak). The maximum angular acceleration can be provided

up to 2 k radian/s²-peak when the maximum supply current of 400 mA-rms is applied. THD ratios are equal or less than 2 % except for the lower frequency range than 50 Hz. The portable angular exciter can provide exceptionally good amplitude stability during its running conditions.

The moment of inertia of fully assembled (rotationally) moving parts was found to be 1.8×10^{-5} kg·m² such that it allows maximum performance for generating angular acceleration. Its total weight is 4.5 kg, which may be sufficiently light to carry it in the measurement fields.

As listed in the third row of Table 2, the resistance of the angular exciter of the rotational coil is close to 12 Ohms so that commercialised 2 ~ 3 W power amplifiers should be sufficient to drive it. Consequently, much cost can be saved to buy or make its power amplifier.

6. CONCLUDING REMARKS

This paper introduces a new ‘portable’ angular exciter model developed in KRISS during last two years. Its development was successfully completed in 2010 such that most technical issues have been resolved and a product model is ready to be delivered to the industrial sectors. Interestingly, a new company being incubated in KRSSS emerged to make and distribute a final version of angular vibration exciters to the market. This paper introduces recent measurement and test results, such as the usable frequency range, the capacity of generating angular acceleration, harmonic distortion ratios, etc, which had been carried out in the technology incubation stage supported by KRISS. One of the topics of the technology incubation project was to develop the portable angular vibration calibration system targeted to the market. Its tested technical performance indicators and specifications are in details presented in this paper. In summary, its inertia moment is designed to be less than 2×10^{-5} kg·m² and to cover not only the frequency range of 10 Hz to 1 kHz but also the peak angular acceleration of 2,000 radian/s² or higher.

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REFERENCES

- [1] Wan-Sup Cheung and Cheol-Ung Chung, “Angle prism-based laser interferometer for high precision measurement of angular vibration,” *TC22, IMEKO XVIII World Congress*, Rio de Janeiro, Brasil, 2006.
- [2] Wan-Sup Cheung and Sang-Myong Park, “Progress in development of primary angular vibration calibration systems.” *TC3, TC16 & TC22 IMEKO international conference*, in Merida, Mexico, 2007.
- [3] Sang-Myong Park and Wan-Sup Cheung, “Dynamic characteristics of new electro-dynamic angular exciter.” *15th International Congress on Sound and Vibration*, in Daejeon, Korea, 2008.
- [4] Wan-Sup Cheung, Sang-Myong Park, hyu-Sang Kwon, Torben Licht, “Development of electro-dynamic angular vibration exciter for calibration of angular vibration pickups” *Inter-noise 2008*, Shanghai, China, 2008.
- [5] Wan-Sup Cheung, “Ways of manufacturing the multi-layered PCD based rotating coils for angular vibration exciters,” *Korea Patent 10-0780915*, 2007
- [6] Wan-Sup Cheung, Se-Won Yoon, Jong-Yun Lim, “Angular vibration Exciter,” Submitted to *Korean Patent in 2009 and PCT in 2010*.
- [7] ISO 16063-15, *Methods for calibration of vibration and shock transducers - Part 15: primary angular vibration calibration by interferometer*, 2006