XX IMEKO World Congress
Metrology for Green Growth
September 9–14, 2012, Busan, Republic of Korea

IMPROVED FEATURES OF ANGULAR VIBRATION EXCITERS

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Abstract: This paper introduces main features of an improved angular exciter model focused on the angular vibration calibration and performance tests of MEMS gyroscopes. The improved model has extended more capacity of generating angular acceleration of 5,000 rad/s^2-peak up to 1 kHz. Other features, such as the frequency response, the total harmonic ratios, and the load capacity will be introduced, in addition to the mechanical and electrical specifications.

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

1. INTRODUCTION

During last three years, the use of MEMS linear and gyroscopes has explosively increased in the market of the smart phones, tablet computers and ESC-installed automotives. This demand trend for the linear and angular vibration transducers should be going on at least in this decade. Many experts, designing and developing new products of those IT and automotive applications, have many technical challenges in testing their performance and endurance.

At the onset of this work, a survey of MEMS-based accelerometers and gyroscopes used in the smart phones, the tablet computers and the ESC (electric stability control) units of automotives had been made. The linear acceleration range of popular accelerometers was found to be 2 ~ 18 g-peak and the angular velocity range of widely used gyroscopes to be 50 ~ 400 °/s-peak. The upper frequency range of both linear and angular MEMS models was found to be 40 ~ 400 Hz. Most of linear accelerometers were commonly a servo-typed 3-axis model. Korean customers have tested well the dynamic performances of 3-axis linear accelerometers, such as the linearity in the full scale range, the total harmonic distortion (THD) ratios and the frequency response functions, etc.

However, they were very suspicious of suppliers of 3-axis gyroscopes since all of MEMS gyroscopes were supplied without detailed test data, for instance, the sensitivity curve over the working frequency range and the THD ratios. Most of Korean customers are very expecting to develop an angular vibration exciter appropriate for testing gyroscopes under the angular velocity of 400 °/s or less to the upper frequency range of 100 ~ 400 Hz.

In the last four years, attempts to develop the angular vibration calibration exciters [1-3] have been made uniquely in KRISS. Since their angular acceleration capacity was limited to 1 krad/s^2-peak, they were found to be not sufficient to cover fully the angular velocity range of 400 °/s even to the upper frequency of 100 Hz. In order to extend such angular acceleration limit, several new attempts have been made. This paper will introduce new features of improved angular exciters realized in KRISS in aid of VAU Co., Ltd.

2. DESIGN PARAMETERS

First of all, a target value of peak angular acceleration was chosen to be 5 krad/s^2-peak, since it is sufficient to cover the angular vibration of 400 °/s-peak over the frequency band of 1 to 100 Hz. The level of 400 °/s-peak at 100 Hz is equivalent to 4.4 krad/s^2-peak. In order to realise the capability of generating the target angular acceleration of 5 krad/s^2-peak, two significant design parameters, the number of turns of a new PCB-based rotation coil and the strength of magnetic filed, had been considered carefully. By choosing the very recent multi-layered PCB manufacturing technology, the turns of the rotation coil were increased two times, compared to the previous rotation coil [3], without any increase of the thickness of a newly designed coil. Resultantly, the doubled torque capacity was realised by the new rotation coil. Since the increased turns of the new coil could increase its electric impedance, more treatment of additional conductive materials (i.e. gold coating) on the copper layer was made such that the total resistance of the coil can be kept to be nearly 1 Ohm.

Another significant parameter required to improve the torque of the angular exciter is the magnetic field strength passing through the rotational coil. The magnetic field strength depends on several parameters of assembled permanent magnets, i.e. the surface magnet strength, size and thickness of each magnet, the gap between the upper and lower magnets, and the yoke material and structure, etc. First of all, the gap between the upper and lower magnets was minimised to increase the magnetic field strength. The yoke structure was also modified to minimise the loss of the magnetic close-loop.

The third attempt was made to reduce the mechanical friction of the paired ceramic ball bearings. A Korean ceramic bearing manufacturer (SBB Co. Ltd.) has played a critical role in reducing the friction loss by pairing uniform-sized ceramic balls, inner and outer races and retainers within the very tightly tolerated quality control limit.

3. IMPROVED FEATURES

3.1 Angular Acceleration Capacity

Fig. 1 illustrates the angular acceleration generation capability realised at 100 Hz by the first prototype of a new angular vibration exciter. The angular acceleration level of about 4 krad/s^2-rms (or 5.6 krad/s^2-peak) was realised for the nominal supply current of 7 A-rms to the newly manufactured rotational coil. The slop of the blue line in Fig. 1 was found to be 561 (rad/s^2)/A. It indicates what amount of achievable angular acceleration per unit supply current. This capability is seen to be 3.7 times higher that the previous one (151 (rad/s^2)/A) [3]. The newly developed angular exciter is shown to meet the targeted acceleration value of 5 krad/s^2-peak.

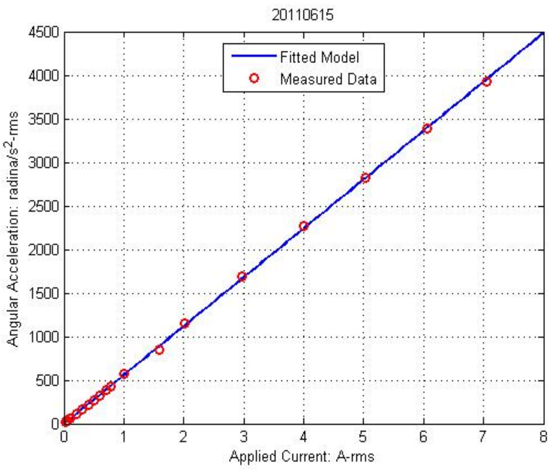

Fig. 1 Angular acceleration generation capability of the prototype of a new angular vibration exciter (tested in 100 Hz).

3.2 Frequency Response Characteristics

As introduced in Section 2, the developed rotational coil for the new angular exciter has some change of the stiffness and the moment of inertia in comparison to the previous model [3]. The first torsion resonance frequency of the shaft system, consisting of the bare shaft and the new coil, was observed to be 4.9 kHz. It indicates that the resultant mechanical properties (the stiffness and the moment of inertia) of the new rotational coil were kept similar to those of the previous model. Since the same shaft as the previous model was used, the frequency response of the new angular vibration exciter to torsion vibration is seen to be similar to that of the previous one [3]. Fig. 2 shows the relative gain of the frequency response functions tested in the frequency range of 10 Hz ~ 1 kHz. The supply current of 1.0 A-rms to the angular exciter was chosen in this test. It shows quite a flat response over the test frequency range.

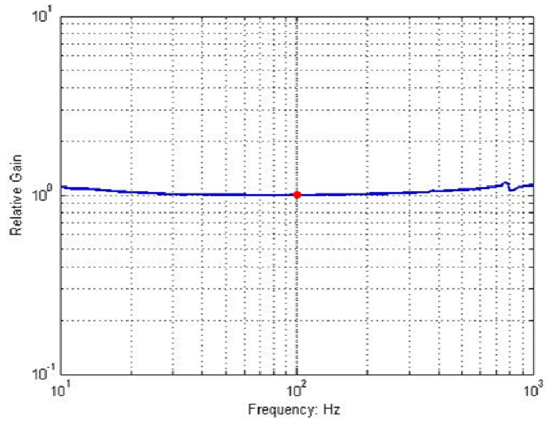

Fig. 2 Relative magnitude of the frequency response function of the new angular vibration exciter. A red circle means a reference value of 561 (rad/s^2)/A at 100 Hz.

3.3 Harmonic Distortion Ratios

As notified in Clause 4 of ISO 16063-15 [4], an angular vibration exciter for the primary calibration of angular vibration transducers should provide 2 % or less harmonic distortion ratio (HDR) over the calibration frequency range. Fig. 3 shows the harmonic distortion ratios of the developed exciter tested in the frequency range of 1 Hz ~ 1 kHz. The blue line and diamond marks indicate the harmonic distortion ratios of the supply current to the angular exciter (i.e. the current monitor output of the power amplifier, B&K type 2719). The red line and circle marks indicate the harmonic distortion ratios of the generated angular acceleration signals (the output signal of the calibrated angular accelerometer, B&K type 4381-ROT) measured from the top side of the developed angular vibration exciter.

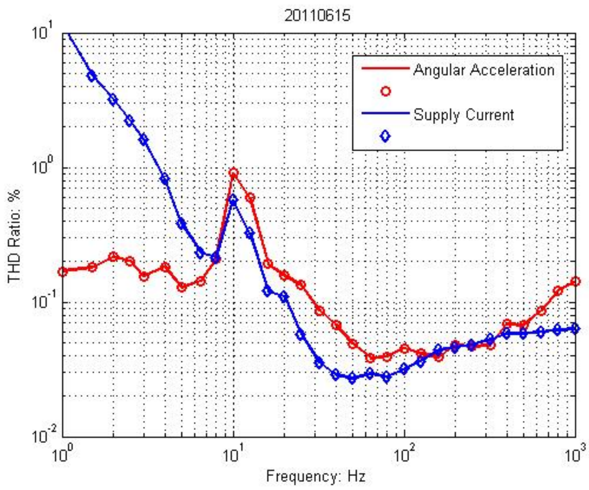

Fig. 3 Total harmonic distortion ratios measured from the top side of the developed angular vibration exciter.

The harmonic distortion ratios were shown to be equal to or less than 0.2 % except the two test frequencies of 10 Hz and 12.5 Hz. The power amplifier near 10 Hz was found to generate higher harmonic distortion ratio (closely 0.6 %) such that the harmonic distortion ratios of the generated angular acceleration signals increased to 1 % at 10 Hz and 0.6 % at 12.5 Hz, respectively. It may mean that a rapid increase of HDRs at 10 Hz and 12.5 Hz is contributed mainly by the harmonic characteristics of the selected power amplifier. If each HDR of the power amplifier can be kept below 0.2 % at 10 Hz and 12.5 Hz, the HDRs of the angular exciter is seen to be less than 0.4% at 10 Hz and 12.5 Hz.

3.4 Background Angular Vibration Levels

Fig. 4 shows the background angular vibration levels measured the topside of the angular exciter. The background levels were measured using the dynamic signal analyzer (HP 35670A) whose frequency resolution Δf was chosen to be 1 Hz by applying one second Hanning window (additionally, overlapping 50%).

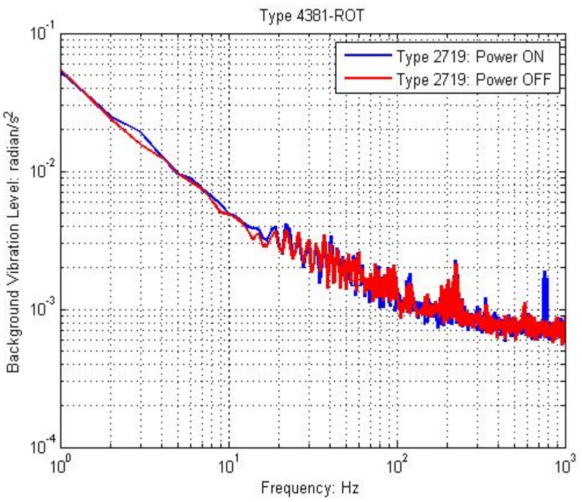

Fig. 4 Background angular vibration levels measured from the topside of the developed angular exciter.

A fitted model of the background angular acceleration level was approximately as follows;

0.05/f (rad/s^2)/Hz$^{1/2}$ for 1 Hz ≤ f ≤ 12.5 Hz,
0.004 (rad/s^2)/Hz$^{1/2}$ for 16 Hz ≤ f ≤ 40 Hz,
0.2/f (rad/s^2)/Hz$^{1/2}$ for 50 Hz ≤ f ≤ 100 Hz, and
0.002 (rad/s^2)/Hz$^{1/2}$ for 100 Hz ≤ f ≤ 1 kHz.

When a record length T of the time window (or record length) increases, the background angular acceleration level is inversely proportional to $T^{-1/2}$.

3.4 General Features of New Angular Exciter Model

Fig. 5 shows the picture and the 3D drawing of the angular vibration exciter model with the extended angular acceleration generation capacity of 5 krad/s^2. This model provides the direct angular displacement by installing optionally the ultra precision encoder (Renishaw ϕ115 mm REXM model) and the dual read-heads (Renishaw Tonic model). When this optional angle measurement equipment is installed, the highest angle measurement resolution of $10^{-6\circ}$ can be realized.

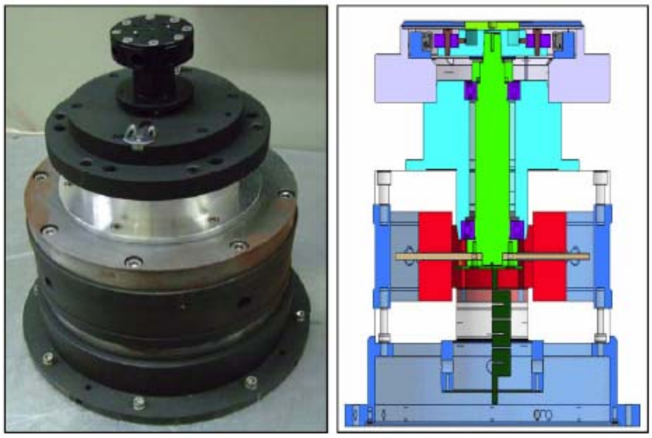

Fig.7. New ball-bearing supported exciter model.

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

Table 1. General features of the developed angular exciter.

Angular Vibration Characteristics	Angular Displacement	60° (1.05 rad)
	Stopper Position	±40°
	Peak Acceleration	5 krad/s^2-peak
	Frequency Range	1 Hz ~ 5 kHz
	THD Ratio	0.2 % ~ 1 %
Mechanical Characteristics	Inertia Moment (Bare)	0.0018 kgm^2
	Mass (Moving Part)	1.8 kg
	Threads for Pickups	5×M6 (Deep 8mm)
	Body Outer Diameter	245 mm
	Base Outer Diameter	290 mm
	Total Mass	49 kg
Electric Characteristics	Coil Resistance at 100Hz	1 Ω
	Coil Inductance at 100Hz	220 μH
	Maximum Current	7 Arms
	Power Connector	NEUTRIK NL4MP

4. CONCLUDING REMARKS

This paper addresses technical challenges encountered in testing MEMS-based accelerometers and gyroscopes used in the smart phones, the tablet computers and the ESC (electric stability control) units of automotives. The linear acceleration range of linear accelerometers used in those applications was found to be 2 ~ 18 g-peak and the angular velocity range of gyroscopes to be 50 ~ 400 °/s-peak. The upper frequency range of both linear and angular MEMS models was found to be 40 ~ 400 Hz. Most of linear accelerometers were commonly a servo-typed 3-axis model.

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A target value of peak angular acceleration was chosen to be 5 krad/s^2-peak. In order to realise this capability, two significant design parameters, the number of turns of a new PCB-based rotation coil and the strength of magnetic filed, had been considered carefully. By applying the very recent multi-layered PCB manufacturing technology, the turns of the newly designed rotation coil were increased two times without any increase of the thickness. Resultantly, the doubled torque capacity was realised by the new rotation coil. Since the increased turns of the new coil could increase its electric impedance, more treatment of additional conductive materials (i.e. gold coating) on the copper layer was made such that the total resistance of the coil can be kept to be nearly 1 Ohm. The second parameter required to improve the torque of the angular exciter is the magnetic field strength passing through the rotational coil. The gap between the upper and lower magnets was minimised to increase the magnetic field strength. Furthermore, the yoke structure was also modified to minimise the loss of the magnetic close-loop. The third attempt was made to reduce the mechanical friction of the paired ceramic ball bearings. A Korean ceramic bearing manufacturer (SBB Co. Ltd.) has played a critical role in reducing the friction loss by pairing uniform-sized ceramic balls, inner and outer races and retainers within the very tightly tolerated quality control limit.

In this work, the use of an ultra precision rotary encoder was tried to measure the angular displace generated by the newly developed angular exciter. In technical aid of Renishaw, a prototype of the four reference marked encoder was firstly manufactured and delivered to KRISS. It was designed to provide the angle measurement resolution of 10^{-6}°. Its performance tests are in progress. Specifically, the encoder is expected to provide sufficiently low measurement uncertainty below the target frequency of 400 Hz.

ACKNOWLEDGEMENT

This work was supported by the KRISS project, “Establishment of National Physical Measurement Standards and Improvement of Calibration Measurement Capability.”

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