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DEVELOPMENT OF ANGULAR VELOCITY CALIBRATION FACILITY USING SELF-CALIBRATABLE ROTARY ENCODER

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Abstract: A novel type of angular velocity calibration standard is under development at NMIJ. The system is equipped with a self-calibratable rotary encoder (SelfA) [1-3], which is same apparatus as one of the national angle standards in Japan. SelfA is also useful to ensure angular traceability in a simple and robust way. This facility will be mainly utilized to provide angular velocity standard for MEMS gyroscopes which become widely used in automobile industries. In this paper, demands for angular velocity standard, advantage of using a SelfA and initial experimental results of the facility will be presented.

Keywords: Angular velocity calibration, Rotary table, Self-calibratable rotary encoder, MEMS gyroscopes

1. INTRODUCTION

Owing to the recent advancement of Micro Electro Mechanical Systems (MEMS) technology, many models of high-performance MEMS gyroscopes are available on the market with reasonable prices. Particularly, they have begun to be used in systems that require significant reliability and safety, such as automobiles. Thus, demands on angular velocity standard in industry are rapidly growing.

The most popular calibration method of gyroscopes in automobile industry is angular velocity calibration using rotary tables. Usually, scale factor (in other words, sensitivity) and linearity of gyroscopes are evaluated. However, these rotary tables are not traceable to the SI unit. Considering regulations on test equipment of on-board safety system in automobiles, we recognize that angular velocity standard at national metrology institutes are required.

Compared with angular velocity standards, some angular acceleration (or angular vibration) standards complied with ISO 16063-15 [4] have been established. For example, at PTB (Germany), angular acceleration standard using electro-dynamic angular vibration exciter and laser interferometer has been set up [5]. At KRISS (Korea), angular acceleration standard has been developed [6]. CIMM (China) is also developing angular acceleration standard [7].

Different from those standards, we are developing a novel type of angular velocity calibration facility using a SelfA. Its target angular velocity is from 6 deg/s to 300 deg/s. A prototype system has been developed and stability of reference rotation generated by the rotary table has been evaluated. In this paper, we explain our facility and show the relevance.

2. NEEDS FOR ANGULAR VELOCITY CALIBRATION

Automobile active safety systems: Recently, automobile industry begins to apply gyroscopes to car-embedded electronics, particularly in active safety system such as Electronic Stability Control (ESC) or rollover detection system. ESC monitors a yaw rate of a car by using an on-board gyroscope and compares it with steering angle to detect hazardous slips of the car.

Since ESC is confirmed to be considerably effective to reduce the number of traffic accidents, equipment of ESC is required by law in many countries and regions including Japan. Thus, regulations on performance of testing equipment of ESC have been established in some countries and regions. For example, FMVSS 126 [6] issued by the U.S. department of transportation requires accuracy of gyroscopes to be less than 0.05% of full scale as shown in Table 1. We recognize that certification of the sensors will be required by the regulations in the near future. At that time, angular velocity standard will be needed to ensure traceability.

Table.1 Requirements for gyroscope in FMVSS 126

Measurement Range	±100 deg/s
Resolution	< 0.004 deg/s
Accuracy	< 0.05 % Full Scale

3. CALIBRATION SYSTEM

Concept: To meet requirements for traceability of gyroscopes in ESC testing equipment, we plan to develop an angular velocity standard based on a rotary table. Most MEMS gyroscope manufacturer usually applies rotary tables to before-shipping inspection of the sensors. These calibration systems have a rotary encoder to detect angular motion. The most significant difference between these ordinary rotary tables and our standard facility is the use of a SelfA. This is because SelfA can measure standard rotation angle more precisely and robustly.

Calibration range: Most of gyroscopes in automobile safety systems such as ESC or rollover detection system have maximum measurement range from 30 deg/s to 300 deg/s. As described later, gyroscope calibration is usually conducted at multiples of a fifth of maximum angular velocity range at factories. Thus we choose calibration range of the facility as from 6 deg/s to 300 deg/s to meet the requirements.

It should be noted that calibration range has to be expanded to 20000 deg/s maximum if gyroscopes for automobile crash tests should be calibrated. Such upgrading of the facility will be considered in the future.

Development status: A prototype, which can be a calibration facility with some improvements, has been developed. A graphic of the system is shown in Figure 1. The system consists of a rotary table supported by an air-bearing, a SelfA, a blushless electric motor, a slipring for transmitting signals, an FPGA-based motion controller, and a PC-based data acquisition unit.

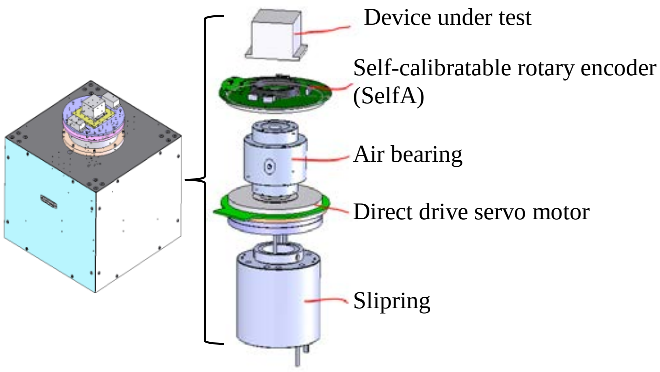

Figure 1. Prototype of angular velocity calibration system excluding motion controller and data acquisition unit.

Self-calibratable rotary encoder (SelfA): The most important feature of the facility is SelfA (shown in Figure 2). SelfA is used in one of the national angular standards at NMIJ, and its calibration capability is registered in CMC. The expanded uncertainty (k = 2) of the national standard is 0.01 arcsecond, which is one of the best calibration capability for rotary encoders.

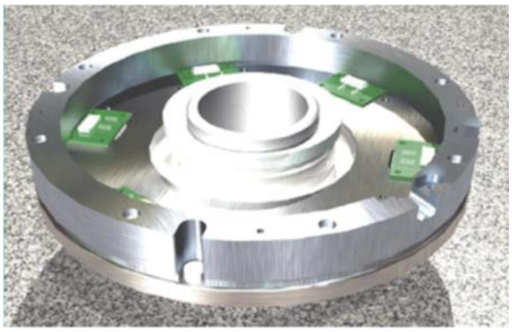

Figure 2. Picture of a SelfA

Principle of SelfA is based on equal division averaged method [2]. This method is applied to a SelfA as follows. A SelfA has multiple readout heads at equal interval on an incremental rotary encoder scale. Each head outputs the pulse signal simultaneously. Here we assume that a SelfA has n number of heads. Then, the output angle from the i-th heads, $s_i(\mathrm{k})$, are expressed as

$$s_{\mathrm{i}}(\mathrm{k}) = \mathrm{k}\Delta\theta + \frac{360}{n}\mathrm{i} + a_{\mathrm{i}}(\mathrm{k}).$$

Here k is an index of the pulses and $\Delta\theta$ denotes the nominal angle between pulses. Here $a_i(\mathrm{k})$ represents an angle deviation from the ideal angle for the i-th head. Note that the total number of pulse in a revolution, m, is

$$\mathrm{m} = \frac{360}{\Delta\theta}.$$

Then the angle deviation of the encoder scale at pulse number of k, expressed as $a(\mathrm{k})$, can be extracted by processing data from the heads [1]. The method uses the principle that $a_i(\mathrm{k})$ must be a shifted signal of $a(\mathrm{k})$, i.e.,

$$a_i(\mathrm{k}) = a\left(\mathrm{k}+\frac{\mathrm{m}}{\mathrm{n}}\mathrm{i}\right).$$

Here k is regarded as a cyclic index. For example, angle deviation curves from the first three heads are plotted in Figure 2. Symmetry of the three curves is seen in Figure 3. At the same time, they have a little difference from each other, since eccentricity of axis and angular velocity fluctuation affects the three signals differently.

Using this symmetry, angle deviation of the rotary encoder is extracted by calculation. Detailed calculation procedures and explanations can be found in [1].

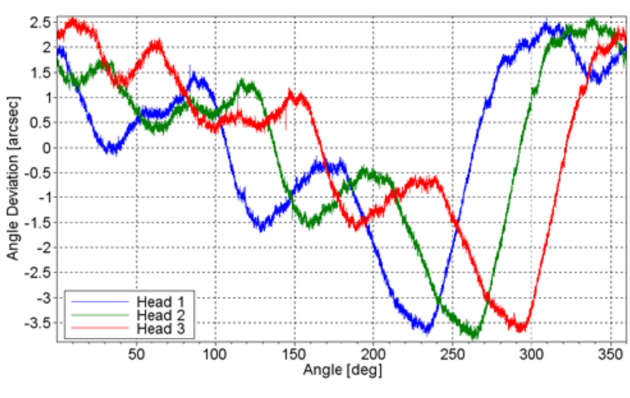

Figure 3. Angle deviation curves for the first three heads. Other nine curves are omitted.

One of the advantages of SelfA is that angle deviation can be known by itself; it needs not to be calibrated by external artefacts at each time. This means that the angle can be calibrated by itself even if the SelfA is installed and is working in the system. In addition, angular error due to the tilt, vibration and centrifugal force can be measured and compensated. This feature is much more suitable for measuring angular motion like angular velocity.

In the prototype system, a SelfA with 18000 pulses per revolution and 12 readout heads is equipped on its rotating axis. Example of the angular deviation extracted by the SelfA is shown in Figure 4. Due to the eccentricity of the rotating axis, deviation of ~ 6 arcsecond (peak-to-peak) is seen.

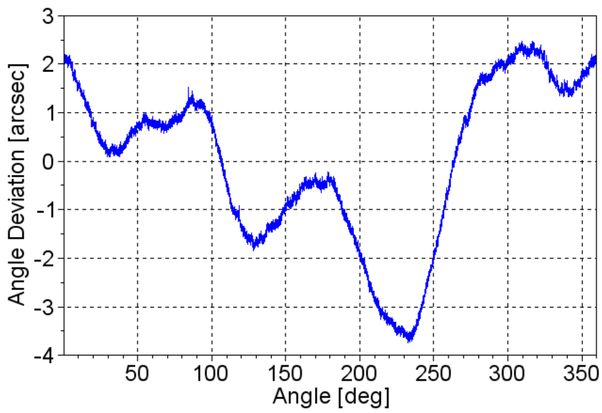

Figure 4. Extracted angular deviation of the SelfA

The angular deviation curve detected by the SelfA varies in every measurement, since rotary table has motion errors. Then, repeatability of the angular deviation is examined. The result is shown in Figure 5. This curve is calculated as follows. First, angular deviation is measured for successive 10 revolutions. Then the average of the 10-revolution data, shown as $\bar{A}$, is calculated. To obtain repeatability, the data for one revolution A_1 is subtracted by $\bar{A}$.

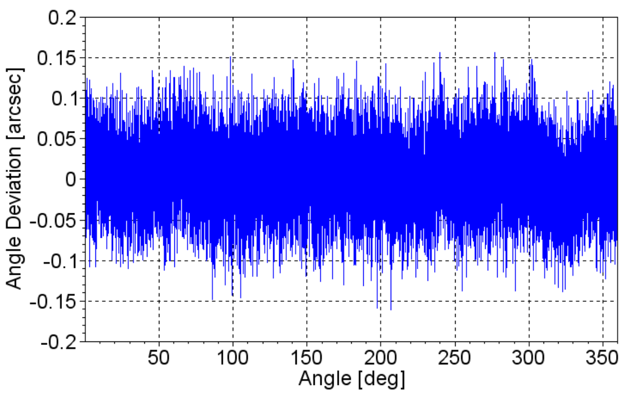

Figure 5. Repeatability of extracted angular deviation

As shown in Figure 5, the repeatability of the rotary table is estimated to be around 0.1 arcsecond. This is sufficient performance for gyroscope calibration. We speculate that the unrepeatability mainly comes from electric noise of the signal, mechanical instability of the air bearing and the effect of temperature instability.

Another advantage of SelfA is that it is cheaper but more accurate than conventional rotary encoders. Uncertainty around 0.1 arcsecond cannot be achieved easily in conventional rotary encoders. If possible, they have to be calibrated with very precise angle standard, thus, it costs much higher than SelfA.

It should be noted that SelfA has one limitation; the n-th and its multiple Fourier components of the angle deviation, $a(\mathrm{k})$, cannot be extracted in principle [1]. However, the undetectable component has been estimated to be sufficiently small to contribute to the uncertainty.

Angular velocity generator based on a blushless electric motor: A brushless electric servo motor is also attached on the facility. It is able to generate an angular velocity from 6 deg/s to 1080 deg/s, which meets calibration requirements of the facility.

In order to perform international comparison with angular vibration standards in other countries, low-frequency angular vibration should be used. This is because it can generate sinusoidal angular vibrations only below several Hertz due to the insufficient torque of the brushless motor.

Effect of the Slipring: We choose a slipring (Kyoei-denki SRC100) to transfer output signals from gyroscope to electronic measuring instruments. To evaluate disturbance from the slipring, we measured variation of its series resistance. As shown in Figure 6, variation of the resistance is less than 5 mΩ. Considering input impedance of the electronic measuring instruments (i.e. oscilloscope probes), we consider the slipring does not affect output signal from gyroscopes. Note that EMI noise is not considered in this measurement..

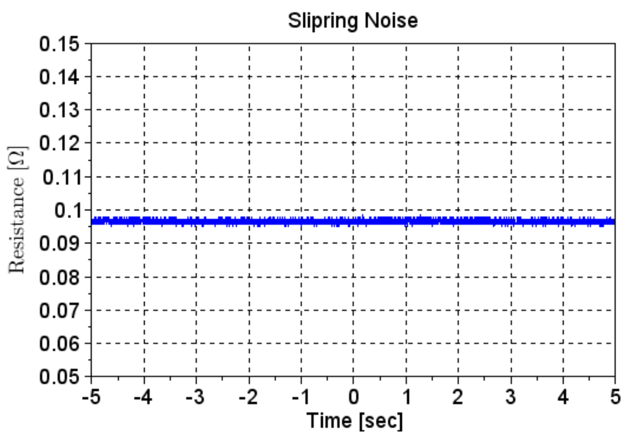

Figure 6. Series resistance of the slipring

Angular traceability: To ensure angular traceability of the facility to the national standard, the SelfA inside the facility should be calibrated at least once, preferably at the time of system assembly. After that, calibration will be conducted every a half or one year. As the SelfA is accepted to have enough stability over years, calibration interval will get longer and it will be recognized as an intrinsic angular standard [3]. Note that whether this scheme can be acceptable or not should be discussed.

4. CALIBRATION METHOD

Calibration Method: Method and calibration quantity of angular velocity calibration is totally different from those of angular or linear vibration since angular velocity is a time-independent motion. Therefore, static calibration method should be applied.

Primary and secondary calibration method for angular velocity is not standardized. There are IEEE standards, IEEE std 1431 [9], However, this is not a calibration standard but specification format guide and test procedure standard for CVG (Coriolis Vibrating Gyroscope). Thus, we have to investigate which method is appropriate to apply on our facility. So far, we consider that the method should be based on the test procedure, of which Figure 6 is a schematic diagram. This kind of gyroscope test is generally carried out in MEMS gyroscope industry.

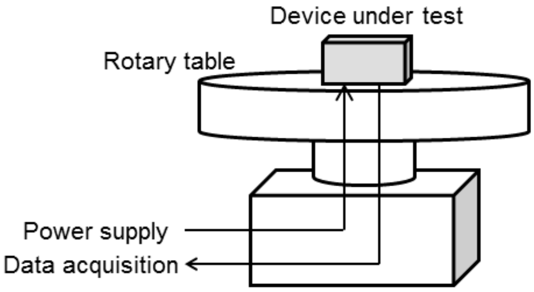

Figure 7. Schematic diagram of the test method carried out in MEMS gyroscope industry.

Described test procedure is the following: The device under test (DUT) is settled on the rotary table. Then the table rotates at a fixed angular velocity. Power is supplied from outside of the table via slipring. Output of gyroscope is monitored with data acquisition (DAQ) system. The DAQ system may have analog or digital input, corresponding to output of gyroscope. At the same time the DAQ system is required to have less noise to avoid contamination of gyroscope signals. Temperature of DUT should be set on a fixed temperature. If temperature coefficient of gyroscope is wanted to be checked, thermal chambers have to be used.

Calibration quantity I – Scale factor: In contrast to accelerometer calibration, the basic calibration quantities for gyroscope are scale factor and nonlinearity. To calibrate these quantities, measurement should be done as expressed in Figure 7.

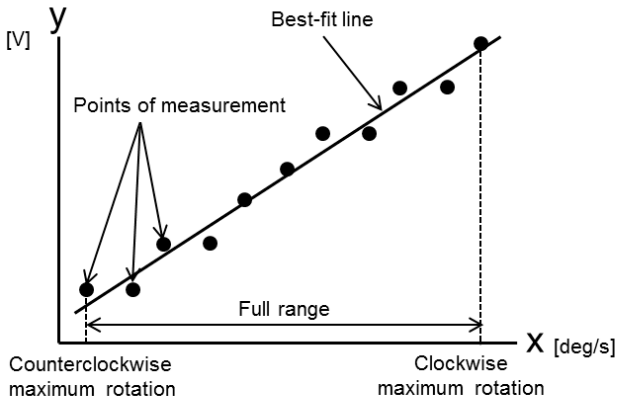

Figure 8. Example of angular velocity calibration of gyroscope.

The angular velocity is fixed at some value, and the constant output from DUT should be measured. This measurement should be repeated while changing angular velocity. It is recommended that number of measurement point should be greater than or equal 11. Then the input and output of gyroscope is fitted as linear relation by the least-square method. In detail, the output for the input angular velocity $V(\Omega)$ is expressed as

$$V(\Omega) = S \cdot \Omega + V_0 + \delta(\Omega).$$

Here Ω represents input angular velocity. V_0 and $\delta(\Omega)$ stands for the voltage offset and residual of fitting, respectively. The coefficient S is called scale factor. Its unit is $\mathrm{V/(deg/s)}$ or $\mathrm{digit/(deg/s)}$ for analog and digital output, respectively.

Calibration quantity II - Nonlinearity: Nonlinearity is also an important characteristic of gyroscope. This is defined as $\mathrm{MAX}|\delta(\Omega)|$ for all measurement points. Normally the nonlinearity is converted to the ratio to the full range of measurement, i.e.,

$$\mathrm{NL} = \frac{\mathrm{MAX}_{\Omega}|\delta(\Omega)|}{FS}.$$

In this paper nonlinearity and full scale is represented by the symbol NL and FS, respectively. This kind of nonlinearity is usually attached with the unit %FS for clarity of ratio to full scale; for example, "0.05 %FS".

Remarks on the calibration method: There are two remarks on calibration of gyroscopes. One is that highly-sensitive laser gyroscopes such as Ring Laser Gyroscope (RLG) or Fiber Optic Gyroscope (FOG) is sometimes calibrated using the rotation of the Earth as a reference angular velocity. This is a simple method, however, there is a problem that the Earth rotation, 4×10^{-3} deg/s, and full scale of these gyroscopes, usually 100 deg/s – 300 deg/s, are by far different. Therefore linearity of such a gyroscope is not validated in this method.

The second is that scale factor is also called sensitivity in vibration calibration. Note that linearity of response of accelerometer is premised. Thus, only in some cases such as shock calibration, linearity of accelerometer response should be questioned and examined.

5. ANGULAR VELOCITY STABILITY OF THE FACILITY

Stability of the facility: Considering the calibration method above, stable rotation is needed, i.e. angular velocity stability is an important parameter for angular velocity calibration facility. We measured angular velocity of the rotary table and evaluate its RMS amplitude and root Allan variance.

Time-domain stability of angular velocity was shown in Figure 9. The angular velocity was measured by the SelfA and compensated with extracted angular deviation at the nominal rotation rate of 300 deg/s. The signal from the SelfA is time-domain signal, that is, the time of rising edges of pulses are recorded. Taking time difference between adjacent two pulses, angular velocity between the two pulses is obtained. Then, to eliminate the effect of electric noise, 10 straight points of data are averaged.

In Figure 9, the bias about 0.03 deg/s, which is 0.01 % of the rotation rate, was seen. Fluctuation of angular velocity is also below 0.01 % of the rotation rate. The requirement of gyroscope on ESC testing system described in FMVSS 126 [8] is that nonlinearity should be less than 0.05 %FS. Compared with this result, it is suggested that the system satisfies the requirement for calibrating these gyroscopes.

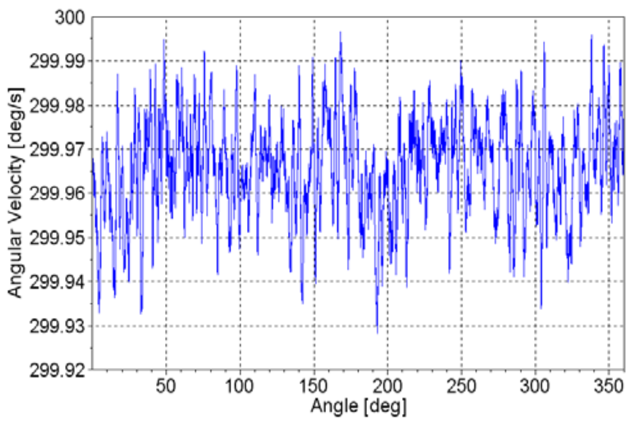

Figure 9 Example of an angular velocity compensated with extracted angular deviation with the SelfA.

Evaluation using root Allan variance: We also use relative root Allan variance to evaluate performance of the system. We calculate root Allan variance of the angular velocity stability as follows. The angle data from the zero points measured by the SelfA at index i is shown as θ_i. Then angular velocity in the time range τ is calculated as

$$\omega_i = \frac{\theta_{i+k} - \theta_i}{k\Delta t}$$

Here $\tau = k\Delta t$. Then, Allan variance for angular velocity ω is defined as

$$\sigma^2(\tau) = \frac{1}{2}\langle(\omega_{i+k} - \omega_i)^2\rangle.$$

Ideally the bracket means ensemble average, but practically we take sampling average for the bracket. Then taking the square root, root Allan variance is obtained. In addition, using the relation of ω_{m} and ϕ to the time τ,

$$\tau = \frac{\phi}{\omega_{\mathrm{m}}}$$

we convert the root Allan variance to the function of rotating angle ϕ for clarity,

$$s(\phi) = \frac{\sqrt{\sigma^2\left(\frac{\phi}{\omega_{\mathrm{m}}}\right)}}{\omega_{\mathrm{m}}}.$$

Here we also divided it by mean angular velocity in the revolution (i.e. 300 deg/s) to convert it to relative value. The result is shown in Figure 10.

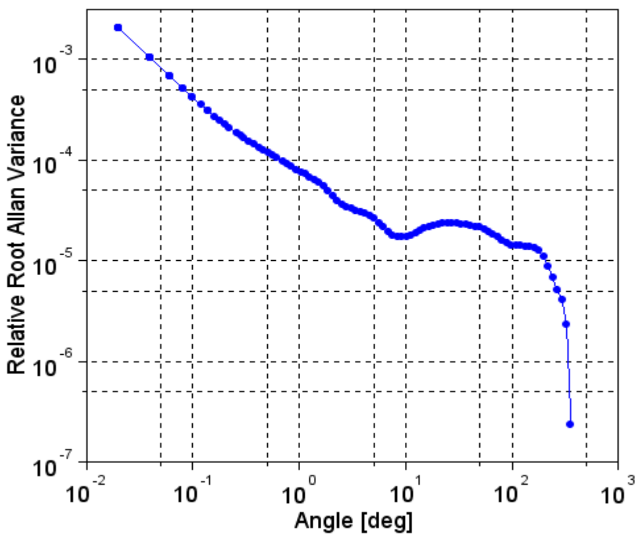

Figure 10 Relative root Allan variance of angular velocity at $\omega_{\mathrm{m}} = 300$ deg/s

Due to the trivial 360-degree symmetry of the encoder scale, root Allan variance around 360 deg is smaller than other angles. In contrast, the curve shows the dependency of θ^{-1} below several degrees. We consider that this is induced by the nearly-white electronic noise in the encoder output signals.

The performance of this system is better than those of ordinary commercial rotary tables used by gyroscope manufacturers. Thus this facility is suitable for standard calibration system, which provide angular velocity standard to such kind of commercial rotary tables.

Note that we compare two differently-defined quantities: the root Allan variance and the rate stability. According to the rate stability test procedure of the commercial rate table, rate stability is measured by comparing the elapsed time to rotate through a known angle. Thus rate stability is generally smaller than root Allan variance due to angular velocity fluctuations. Therefore we can consider that the facility has good performance.

6. CONCLUSION

As more and more MEMS gyroscopes become equipped in automobiles, there are growing demands for angular velocity traceability in industry, especially in ESC testing. To deal with these demands, novel type of angular velocity standard is in development at NMIJ. The system is equipped with SelfA, which is a same apparatus of national angular standard in Japan. SelfA is cheaper but more accurate than conventional rotary encoders. In addition, SelfA also enables the angular traceability in a robust way. Considering the calibration method for gyroscope, stability of the angular velocity generated by the system is examined. As a result, 0.01 % stability in time-domain and 0.002 % in root Allan variance at 10-deg range is confirmed. This performance satisfies the requirement for calibration of 0.05-% nonlinearity of gyroscope. Further system improvements are in progress.

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