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Angular velocity calibration system with a self-calibratable rotary encoder

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ABSTRACT

Gyroscopes are essential components of electronic stability control systems (ESC), which are currently incorporated in automobiles to reduce car accidents. To meet the traceability requirements of gyroscopes in ESC testing system, a novel type of angular velocity calibration system was developed at the National Metrology Institute of Japan. The system is equipped with a self-calibratable rotary encoder (SelfA), operating on the same self-calibration principle as the national angle standard in Japan. To evaluate the performance of the system, the stability of the measured angular velocity was examined in both time domain and in terms of Allan variance. The noise effect from the slip ring was also measured. The calibration procedure was demonstrated by monitoring the response of a fiber-optic gyroscope from $-180°/s$ to $180°/s$ at $30°/s$ intervals. The results confirmed that the system performance satisfies the requirements for angular velocity calibration of mid-performance MEMS gyroscopes.

1. Introduction

Owing to recent advances in microelectromechanical systems (MEMS) technology, many types of high-performance MEMS gyroscopes have become available in the market at reasonable cost. Consequently, the automobile industry has begun applying gyroscopes in car-embedded electronics, particularly to active safety systems, such as electronic stability control (ESC) and rollover detection systems. ESC monitors the yaw rate of a car by an on-board gyroscope and compares it with the steering angle to detect hazardous car slipping.

Because ESC has proven to be effective at reducing the number of traffic accidents, it is now required by regulations in many countries and regions, including Japan [1]. Thus, performance regulations have been established for ESC testing systems in some countries. For example, FMVSS 126 [2] issued by the U.S. department of transportation requires that gyroscopes be accurate to within 0.05% of full scale, as shown in Table 1. Thus, angular velocity standards for the calibration of general-purpose MEMS gyroscopes are demanded. In the automobile industry, gyroscopes are calibrated by measuring their electric output signal at an input angular velocity. The important parameters are the scale factor, bias, and linearity. In addition, the Japanese industry requests that these parameters be traceable to SI units.

To date, several national metrology institutes have established angular acceleration calibration systems compliant with ISO 16063-15 [3], which describes a primary method for calibration of angular vibration transducers with sinusoidal angular vibration. The angular acceleration calibration system at Physikalisch-Technische Bundesanstalt (PTB, Germany) is based on an electro-dynamic angular vibration exciter and laser interferometer measurements [4]. Korea Research Institute of Standards and

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Table 1
Gyroscope requirements stipulated by FMVSS 126.

Measurement range	±100°/s
Resolution	<0.004°/s
Accuracy	<0.05% full scale

Science (KRISS, Korea) has developed an angular acceleration calibration system by the same approach [5]. The calibration ranges of both systems include 0.4 Hz–1 kHz. Changcheng Institute of Metrology and Measurement (CIMM, China) has also developed an angular acceleration calibration system [6].

Different from these systems, we are developing a novel type of angular velocity calibration system using a self-calibratable rotary encoder (SelfA) [7–10]. The target angular velocity range for MEMS gyroscopes is 5–300°/s; the reasons are explained in Section 2.

The remainder of this paper describes our calibration system and evaluates its capability. The configuration and principle of the system are detailed in Section 2. The angular velocity calibration is described and evaluated in Sections 3 and 4, respectively. Section 5 evaluates the stability of the angular velocity calibration in the time domain and in root Allan variance. Discussions can be found in Section 5. Conclusions are presented in Section 6.

2. Calibration system

2.1. System configuration

To meet the traceability requirements of gyroscopes in ESC testing system, we have developed an angular velocity calibration system based on a rotary table equipped with a SelfA. Most MEMS gyroscope manufacturers apply rotary tables to the before-shipping inspection of the sensors. These calibration systems detect rotation angle by a normal rotary encoder. Our calibration system differs from ordinary rotary tables by its use of a SelfA, which enables precise, robust measurements of rotation angle.

An overview of the calibration system is shown in Fig. 1. The tested device, i.e., a gyroscope, is set on the table of the angular velocity generator. The angular velocity of the table is controlled by a commercial servo control module installed in the FPGA interface box (center of Fig. 1). The rotation rate of the table is measured by a SelfA installed beneath it. The signal from the SelfA is recorded by FPGA with our original algorithms. The analog output from the gyroscope is measured with a high-speed digitizer (NI PCI-6250, 16 bit, 1 MS/s, National Instruments, Inc., U.S. A.) simultaneously. The data acquired from the SelfA and digitizer are sent to a personal computer for analysis.

The angular velocity generator of this system is based on a brushless direct drive servo motor. The generator comprises a rotary table supported by an air bearing, a SelfA, a brushless electric motor, a slip ring for transmitting signals, an FPGA-based motion controller, and a PC-based data acquisition unit. A schematic of the generator is shown in Fig. 2. The generator is attached to a brushless electric servo motor, and its angular velocity output (1–1080°/s) meets the calibration requirements of the system. Its construction with four coils and nine magnets imparts a 36-fold mechanical symmetry, which affects the angular velocity stability as discussed later.

In this system, output signals are transferred from the gyroscope to electronic measuring instruments via a slip ring (SRC100; Kyoei Denki, Japan). The signal disturbance from the slip ring was evaluated from the variability in the series resistance measured by the four-terminal method. As shown in Fig. 3, the series resistance varied by less than 5 mΩ. Considering the input impedance of the electronic measuring instruments (i.e., the 1 MΩ impedance of the oscilloscope probes), we inferred that the slip ring does not affect the gyroscope output signals. Note that EMI noise is excluded from this measurement.

We set the calibration range of our system to 5–300°/s to meet calibration requirements. The maximum angular

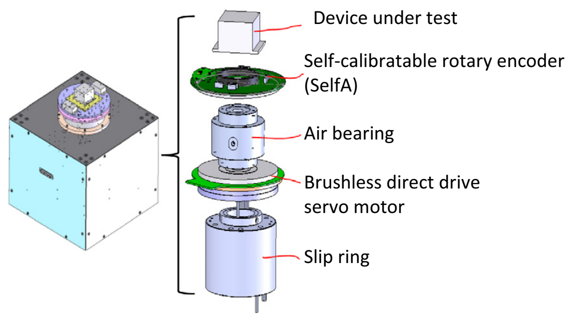

Fig. 2. Exploded view of the angular velocity generator installed with the SelfA.

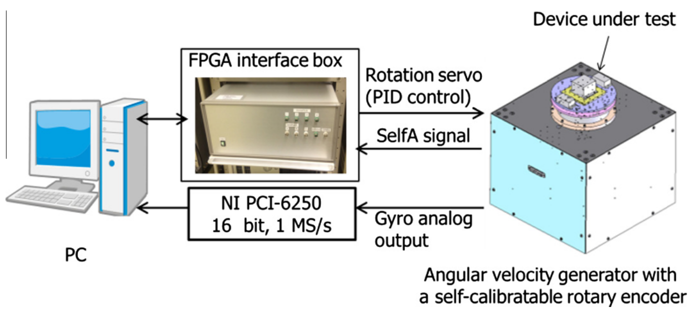

Fig. 1. Overview of the calibration system.