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Development of a 0.01-dph mode-matched MEMS gyroscope toward realizing a module-level gyrocompass with 1-mil accuracy

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Summary:

A gyrocompass, which measures the earth's rotation with a gyroscope, can detect north robustly. However, practical applications of gyrocompasses are limited due to the size of conventional gyroscopes. Micro-electro-mechanical systems (MEMS) gyroscopes have the potential to open up new markets; however, precision is a major challenge in MEMS gyroscopes. Here, we developed a novel high-precision MEMS gyroscope and demonstrated navigation-grade bias instability of <0.01 dph, which is the highest-level performance of a MEMS gyroscope. A gyrocompass using the developed gyroscope performed north finding with precision of <1 mil in a laboratory environment, and a precision of <10 mil was exhibited by our module-level gyrocompass, which is being refined toward realizing 1-mil accuracy.

Keywords: MEMS gyroscope gyrocompass

I. Introduction

A gyrocompass can detect north robustly even indoors and under magnetic fields by measuring components of the earth's rotation with a gyroscope. However, practical applications of gyrocompasses using such as ring laser, fiber optic, or mechanical gyroscopes are limited due to issues in terms of size, cost, and precision. Micro-electro-mechanical systems (MEMS) are a key technology for solving these challenges. Recently, many researchers have been focusing on MEMS gyroscopes, for which precision is a major challenge. Here, we developed a novel high-precision MEMS gyroscope and demonstrated navigation-grade bias instability of (BI) < 0.01 dph, which is the highest-level performance of a MEMS gyroscope. The gyrocompass using the developed gyroscope accomplished north finding with precision of 1 mil in a laboratory environment, and we will refine our prototype module-level gyrocompass with an eye toward realizing 1-mil accuracy.

II. Design and Experiments

A Gyroscope Design

Fig. 1 shows a schematic of our novel gyroscope, which we named "Kumo-no-su-Shaped Gyroscope" (KSG) (*kumo-no-su* is Japanese for spider web). KSG can be regarded as an improvement over the Boeing disk resonating gyroscope [1] for two reasons. The first reason is the lumped mass connected to the outermost ring, which decouples the effective mass from the ring width and therefore enables the effective mass to increase without widening the rings, thereby reducing mechanical noise [2]. The second reason is the combination of the in-phase-arranged spokes between the outer rings and the anti-phase-arranged spokes between the inner rings. The former works to make the outer rings vibrate with the same amplitude, which improves electrode sensitivity, while the latter works to maintain the wineglass vibrating mode by appropriately supporting the outer rings.

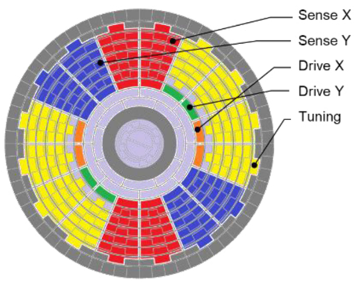

Fig. 1. Schematic view of KSG.

B Gyroscope Performance

Fig. 2 shows the experimental results of Allan deviation of KSG. The measurement was performed over 4 h without temperature control. The red and blue curves indicate the experimental values with and without temperature correction, respectively. The Allan deviation with temperature correction reached 0.01 dph at 3000 s, with BI < 0.01 dph, which corresponds to navigation-grade specification. The dotted line indicates the fitting curve proportional to $\tau^{-1/2}$, showing 0.0093 deg/$\sqrt{}$h of angle random walk.

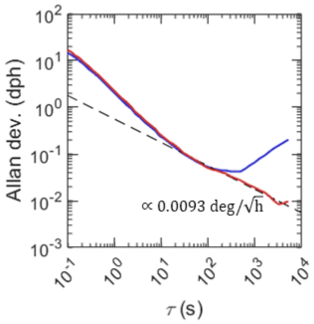

Fig. 2. Allan deviation of KSG with and without temperature correction (red and blue curves, respectively).

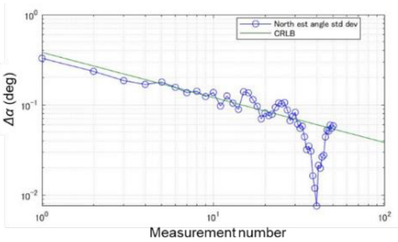

Fig. 3. Precision of azimuth angles measured by KSG using a turntable.

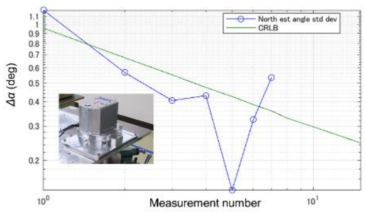

Fig. 4. Precision of azimuth angles measured by KSG using our prototype of module-level gyrocompass. Inset: Photograph of the prototype of module-level gyrocompass

C Gyrocompass

By measuring components of the earth's rotation with a single-axis gyroscope at various azimuths, the orientation of the earth's axis of rotation (i.e. north) can be detected. To demonstrate the specification of KSG, north finding was carried out based on this principle. The gyroscope was set on a turntable with its detection axis aligned horizontally, and the deviation of the reference angle from north was detected by measuring the magnitude of the earth's rotation component in four directions at 90-degree intervals, that is, by using the "maytagging" method. The azimuth angle α can be calculated as

$$\alpha = -\mathrm{atan2}(-\omega_2 + \omega_4, \omega_1 - \omega_3), \quad (1)$$

where ω_i is the angular velocity output in direction *i*. The measurement was performed in Kawasaki, Japan, where the component of the earth's rotation is 12 dph. The measurement time in one direction is 200 s and measurements of the four directions were repeated over 24 h. Fig. 3 shows the experimental values of standard deviation of azimuth angle $\Delta\alpha$ and the theoretical line of the Cramér–Rao lower bound (CRLB) [3] as

$$\Delta\alpha^2 = \frac{2{\sigma_N}^2}{\Omega_{\mathrm{in}}^2 N}, \quad (2)$$

where σ_N is the root mean square of the angular velocity output noise, Ω_{in} is the earth's rotation of 12 dph at Kawasaki, and *N* is the number of measurements. The experimental values of $\Delta\alpha$ decrease with CRLB as the measuring number increases and reach 0.056 deg, which corresponds to 1 mil according to the Japan/NATO definition. Fig. 4 shows our prototype module-level gyrocompass, which can detect an azimuth angle to the north using the maytagging method by performing manual rotation. The dimensions of the model are 18×18×16 cm^3. The azimuth precision using this module improves with CRLB and reaches 0.5 deg.

III. Concluding Remarks

Here, we developed a novel MEMS gyroscope, with BI < 0.01 dph. the azimuth angle precision of the gyrocompass using our developed gyroscope on a turntable was < 1 mil. Our prototype gyrocompass module, which is being refined with an eye toward commercialization, had an azimuth precision of 0.5 deg. In future work, we aim to realize a module-level gyrocompass with an azimuth accuracy of 1 mil, which is the same level as the gyrocompass using a turntable.

References

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