High-grade CVG for Stabilisation Control Systems and Tactical Grade Systems

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Abstract

INNALABS Ltd has developed a high-grade Coriolis Vibratory Gyroscope (CVG) for stabilisation control systems and tactical grade systems. Based on a very unique design, the CVG is successful in covering at very low cost a wide spectrum of performances from 0.1 to 10°/hr with an extremely low output noise better than 0.4 μrad up to 100 Hz, breaking with the trend driven by expensive and complex Fiber Optical Gyros (FOG) or Hemispherical Resonator Gyros (HRG).

After a quick description of the CVG basic principles and an overview of the CVG technical strengths in comparison to competing available technologies, this paper provides statistical results recorded on the INL-CVG-GU200, an INNALABS Ltd two-axis gyro Unit, CVG based, currently in full series production in Dublin for the stabilisation control market.

Some key performance parameters are presented, such as the bias temperature stability, the bias vibration sensitivity, the short-term bias stability and the scale factor temperature stability. This will also show the CVG as a breakthrough alternative to existing solutions for applications like heading reference systems, flight control, guidance systems and North-finders.

1. Introduction

1.1. About INNALABS Ltd

Innalabs was founded in 2003. After 8 years of R&D activities on inertial sensors, the Company transitioned its business model to an inertial sensors manufacturer and global supplier model headquartered in Dublin (Ireland):

Figure 1. Innalabs Ltd Headquarter – 5,700 m^2.

With 5,700 m^2 in total and a state of the art clean-room, Size 612 m^2 - Certified ISO Class7 or Class 10,000 equivalent, Innalabs Ltd operates a fully functional manufacturing line, capable of producing 12,000 tactical grade Coriolis gyros and 6,000 inertial/tactical grade fused quartz accelerometers for 2014. The setup of Innalabs' Headquarters in Ireland has been well assisted by local specialised research centres of excellence, the University of Limerick (Metrology, Material Engineering), Crann, Trinity College (Microscopy, Magnetism) and Tyndall Cork Institutes (Microelectronics).

1.2. Innalabs' Coriolis gyros

The basic principles of Coriolis gyroscope technology are well known with the first reported practical demonstration being the use of the Foucault pendulum to measure the earth's rotation in 1851. More recently, Coriolis gyros have become increasingly more common with a variety of resonator structures being utilised including tuning forks, planar rings, hemispherical and cylindrical structures. The first use of a cylinder structure was the START gyro [4], [5] which used a metal cylinder with drive and detection of vibration modes being performed using PZT structures bonded to the sides of the cylinder. All of these structures operate using the same basic principles with one mode (referred to as the excitation or primary mode) being excited to provide the linear momentum which is then coupled to a second mode (detection or secondary mode) by Coriolis forces induced by rotation of the structure about the appropriate axis. The operating principles and error mechanisms associated with this type of cylindrical structure are described in detail in numerous technical papers [6], [7] & [8].

Innalabs gyro technology uses a cylindrical resonator structure for the sensing element (SE) which is rigidly attached to the SE housing by means of a central stem. The cylinder is operated using two second order resonant modes as shown in Figure 2 below:

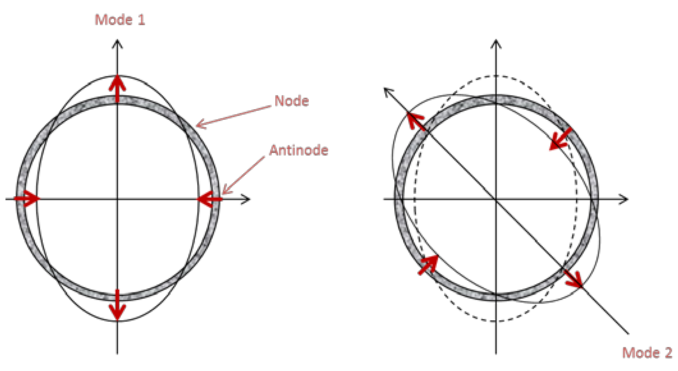

Figure 2. Primary mode (left) and the Secondary mode (right)

One of those two modes is driven at constant amplitude (Primary mode, mode 1) with the second mode being used to sense rotation (Secondary mode, mode 2). When the SE is rotated around the axis of the stem, Coriolis forces are induced which couple energy from mode 1 into mode 2, with the amplitude of motion being directly proportional to the applied rotation rate. The INL-CVG-GU-200 is operated in a closed-loop configuration which drives the mode 2 to zero. The force required to null this mode is then proportional to the input rotation rate. This control loop system is generally referred to as a 'force-rebalanced operating mode'.

The Innalabs cylinder design is excited and detected by means of PZT elements which are fixed to the base of the cylinder (Figure 3). This has a number of technical patented advantages such as a simplification of the PZT assembly as the surface is planar:

Figure 3. The resonator with PZT elements fixed to the base

Following on the footsteps of HRG [3] with silica's Q-factor of > 10^7 and demonstrated navigation grade performance by Northrop Grumman (< 0.01 °/hr drift error), INNALABS started early 2005 research on high Q-factor metallic resonator with the intention of achieving tactical grade performance (1~10 °/hr drift error) at very low cost. Research effort has been focused on material science, machining process, surface treatment and heat treatment, all this leading to Q-factors (under vacuum) of 10^4 in 2006 [9] to 10^5 today. Given those results, with a resonator frequency of F=6,000 Hz, corresponding damping time constant takes the form [3]:

$$\tau = \frac{Q}{\pi F} \approx 5.3 \text{ sec} \qquad ..(1)$$

With k the angular gain factor (0.8 in case of a cylinder), the force being applied to sustain the amplitude against damping losses is then:

$$f = \frac{1}{k.\tau} \approx 13\ °/\text{sec} \qquad ..(2)$$

The related drift error δb due to the electromechanical control loop errors (denoted ε) is then:

$$\delta b = f.\varepsilon \qquad ..(3)$$

As a consequence, in order to achieve a 1 °/hr drift error, electromechanical errors have to have less than 200 ppm instabilities, which is basically achievable with a conventional analogue electronics. That specific point gives another decisive competitive advantage to Innalabs over its competitors working with expensive digital components and complex embedded software.

Based on above technical/cost strengths, Innalabs has designed the INL-CVG-GU-200, a two-axis Coriolis Vibratory Gyroscope, land vehicle stabilisation oriented (turret, tracked vehicle) delivering high-grade performance as described below.

2. INNALABS two-axis gyro Unit: INL-CVG-GU200

The INL-CVG-GU200 is a circular 2 axis Unit which contains 2 sensitive elements and associated analogue control loop electronic, a compensation board, a power supply board, and a housing equipped with a MIL-C 38999-III user connector (Figure 4):

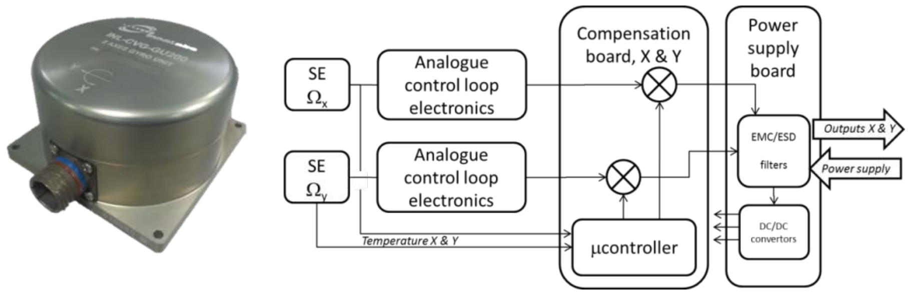

Figure 4. The INL-CVG-GU200 and corresponding architecture

The Unit senses rate rotations along its two perpendicular axes, X and Y as shown on Figure 4, up to ± 110 °/s as a baseline. The Unit can be powered with a voltage ranging from 12 V DC up to 36 V DC and whatever the input power voltage, the power consumption is less than 2 W (typical 1.85 W). Thanks to the very advantageous mechanical transfer function of the resonator, a bandwidth of 300Hz (-3dB) is achieved with -90º phase error at 130 Hz.

The compensation board hosts a microcontroller which operates out-of-loop simple corrections to format the 2 analogue output signals delivered to the user.

The Unit design is an EMI/EMC/ESD design, corrosion resistant, ruggedized to sustain high shock levels (tests performed up to 1,500 g with duration < 1 msec). The weight is 1 kg and the outline is mainly a 106 mm diameter and 68 mm height.

Given the material configuration of the Unit, some variants have been developed on the short term, as for example the 1 axis Units INL-CVG-GU100 X or Y. Further work is progressing for the release of customized variants in 2014 with digital output RS422 or RS485.

3. Results and performance achieved with the INL-CVG-GU200

The INL-CVG-GU200 has been successfully tested through an exhaustive test plan based on the latest testing equipment, rate tables coupled with environmental chambers and shaker coupled with slip table (Figure 5). The paragraphs below provide an overview of the results:

Figure 5. Actidyn Rate table/Thermal Chamber (left), Spectral Dynamic Shaker (right)

3.1 Output noise

As a result of the force-rebalanced mode implemented for the control of the resonator, the white angular noise generated by op-amps working on the readout mode detection leads to an output noise with rate angular PSD with a +2 slope when units are $(°/sec)^2/Hz$, or +1 when units are $(°/sec)/\sqrt{Hz}$ (PSD: Power Spectrum Density). That noise with slope +2 appears to be the main output noise contributor under static conditions. This noise is very repeatable from gyro to gyro with a typical PSD shown in Figure 6 below:

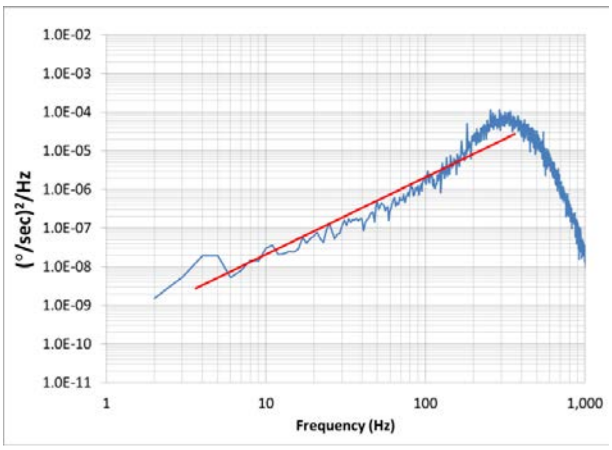

Figure 6. Output noise PSD with slope +2 below 200 Hz

Those who are familiar with output noise rate angular PSDs will appreciate from the data in Figure 6 that INNALABS' vibratory technology and FOG gyros are quite different in nature. As a matter of fact, the FOG's output noise is generally a white noise fully described by an Angular Random Walk (units (ARW, °/√Hz) while the INL-CVG-GU200's output noise is mainly an angular noise. This feature can also be observed on some other vibratory gyros [10]. As a consequence, the ARW cannot be used here to estimate the INL-CVG-GU200 noise performance and the relations below have to be considered. By denoting $PSD_{\dot{\theta}}$ the angular rate PSD (°/sec)^2/Hz, $\sigma_{\dot{\theta}}(\Delta F)$ the integral rate angular noise (°/sec rms) and $\sigma_{\theta}(\Delta F)$ the integral angular noise (µrad rms) within the frequency band $\Delta F = F2 - F1$ are given by the following equations:

$$\sigma_{\dot{\theta}}(\Delta F) = \sqrt{\int_{F1}^{F2} PSD_{\dot{\theta}}.\,df} \quad ..(4)$$

$$\sigma_{\theta}(\Delta F) = \frac{\pi}{180} 10^6 \sqrt{\int_{F1}^{F2} \frac{PSD_{\dot{\theta}}}{(2\pi f)^2}.\,df} \quad (5)$$

Figure 7 and Figure 8 below show typical integral rate angular noise and integral angular noise on INL-CVG-GU200:

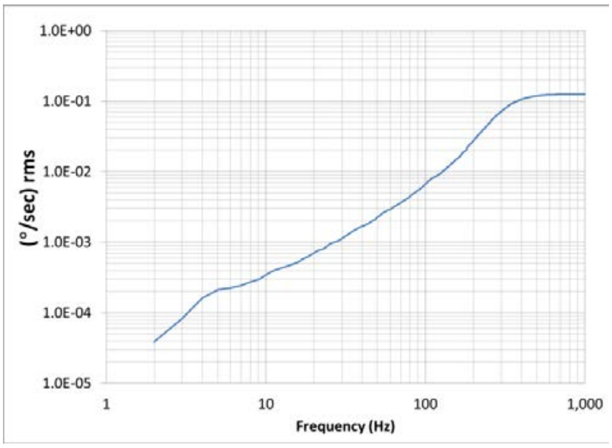

Figure 7. Integral rate angular noise with 0.006 °/sec rms @ 100 Hz

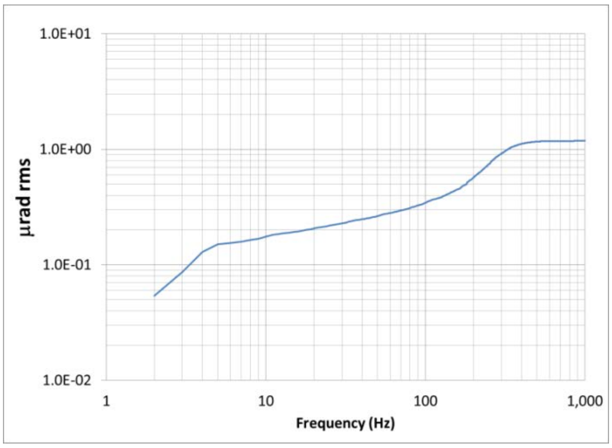

Figure 8. Integral rate angular noise with 0.35 μrad rms @ 100 Hz

Thus, the INL-CVG-GU200 achieves a typical 0.3~0.4 μrad rms over a 100 Hz band, equivalent to better than 0.4 mm at 1 km. The corresponding rate angular noise is 0.006~0.008 °/s rms. With a phase error of -90° @ 130 Hz (-3dB @ 300 Hz), the INL-CVG-GU200 technology provides a low cost and high-grade solution for top of the range stabilisation or optical sights systems.

2.2 Short-term bias stability

The short-term bias stability analysis is performed by use of an ALLAN variance method [10]. The following chart shows a typical result achieved by the INL-CVG-GU200 tested over 32 days under a non-controlled 25°C ±5°C:

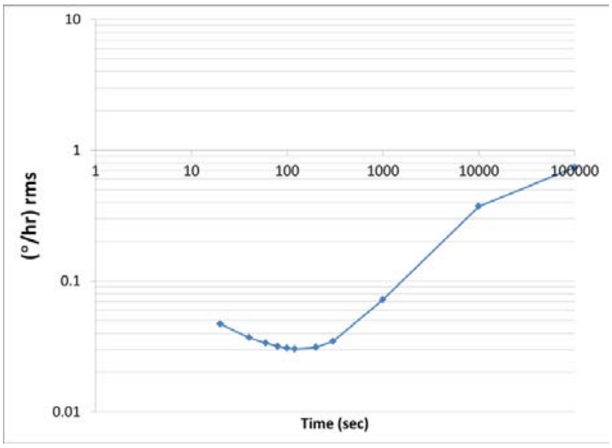

Figure 9. Allan variance chart over 1 month with 0.03 °/h rms at 150 sec

The lowest point is 0.03 °/h rms at 150 sec and the 1 day bias stability is 0.7 °/h rms. The estimated angular random walk is 0.004 °/√h which categorizes the INL-CVG-GU200 technology as a pertinent candidate for low cost North-Finders.

2.3 Bias and scale factor temperature sensitivity

The following chart shows a typical bias temperature sensitivity achieved in the full temperature range [-45°C, +90°C] with +/- 2°C/min temperature slope. Peak values are better generally than 10 °/h with standard deviation of 4.3 °/h (1σ) and short term stability of 0.4°/h/min (1 σ) over 5 minutes for this test.

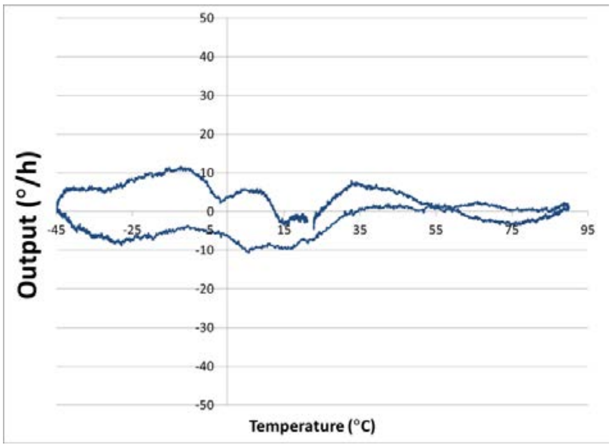

Figure 10. Bias temperature sensitivity, [-45°C, +90°C],

with standard deviation of 4.3 °/h (1σ)

By increasing the sample size to 50 units randomly chosen, the distribution function of the bias temperature sensitivity takes the following form:

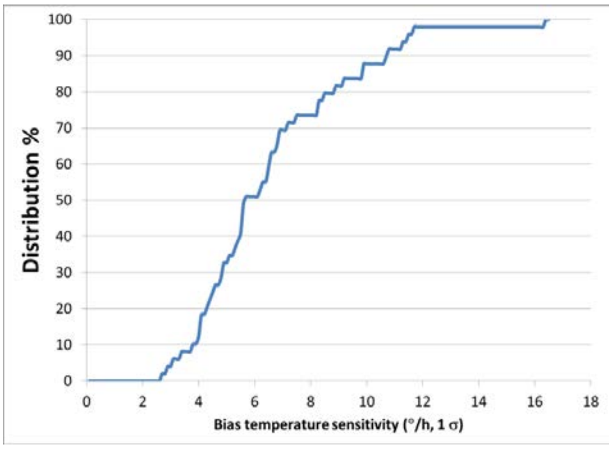

Figure 11. Bias distribution – 50% of the population better than 5 º/h (1σ)

A similar analysis carried out on the scale factor gives:

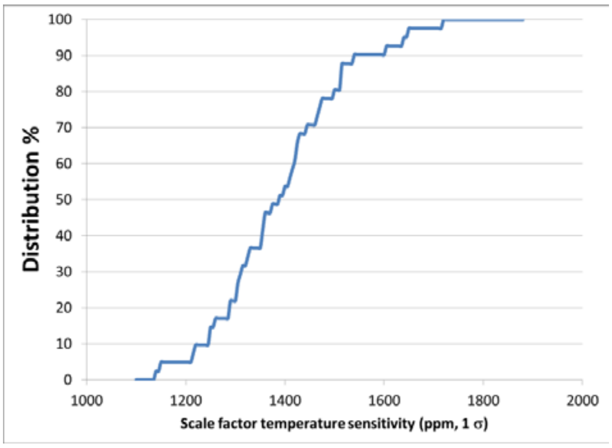

Figure 12. SF distribution – 50% of the population better than 1350 ppm (1σ)

The above results are showing nearly 85% of the population is ranging between 2.5 °/h (1σ) and 10.0 °/h (1σ) under [-45°C, +90°C] with +/- 2°C/min temperature slope, and between 1200 ppm (1σ) and 1500 ppm (1σ) in regard to the scale factor.

As a consequence, the INL-CVG-GU200 technology is also a solid candidate for low cost IMU for medium/short range missile applications and/or low cost AHRS.

2.4 Bias vibration sensitivity

One of the primary target markets for the INL-CVG-GU200 is in land vehicle stabilisation applications. Three randomly selected units have therefore been tested under 3.56 g rms random vibrations, over a [5 Hz, 2000 Hz] band (DEF STAN 00-35, Material installed in Turret or/and Tracked Vehicle). A typical result is shown here below:

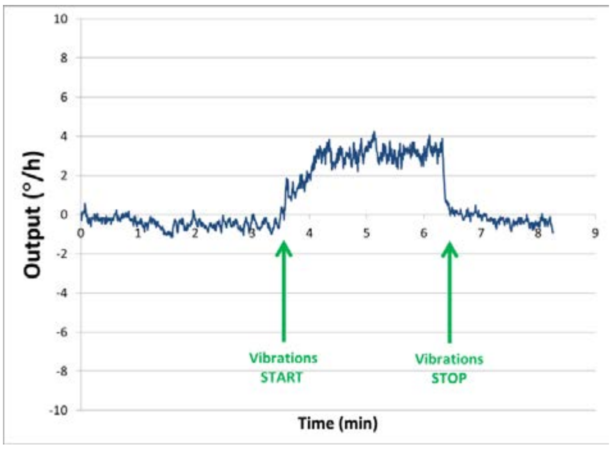

Figure 13. Bias rectification of 3 °/h under 3.56 g rms random vibrations

Whatever the input acceleration orientation in regards to units' axes, the bias rectification error before/under or under/after vibrations is less than 6.6 °/h. No significant change is observed on the output noise.

In order to further characterise the INL-CVG-GU200 behaviour under hardened conditions, a 12 g rms [5 Hz, 2000 Hz] test has been carried out on the same 3 units. The bias rectification ranges up to 30 °/h which confirms the technology is suitable for medium/short range missile applications.

3. Conclusion

INNALABS Ltd has developed a low cost tactical-grade Coriolis Vibratory Gyroscope with very low output noise (0.4 μrad rms @ 100 Hz) and excellent short term bias stability (0.03°/h rms @ 150 sec with ARW of 0.004 °/√h). An exhaustive test plan has been carried out on serialised units and INNALABS Ltd is today mass producing the INL-CVG-GU200 2 axis gyro unit in Dublin for the stabilisation control market. High production volume and productivity are achieved through a best in class manufacturing line, capable of producing 12,000 tactical grade Coriolis gyros a year.

Given the performance spectrum shown by the INL-CVG-GU200, INNALABS Ltd CVG technology appears to be also a promising technology for terrestrial low cost North-finders and aerospace applications such as heading reference systems (AHRS), flight control, guidance systems.

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