UDC: 681.586.3

V.V. Chikovani, doctor of engineering
(National Aviation University, Ukraine)
S.V. Golovach, Ph.D. (J.S. "Elmiz", Kyiv, Ukraine)

Multimode vibratory gyroscope adaptable to motion parameters and environmental conditions

Abstract. In a multimode vibratory gyroscope, each mode has its advantages. Combining these advantages results in adaptability to different motion parameters, such as high accuracy for small angle rates and low dynamic error for high angle rates. Moreover, it can adapt to changing environmental conditions, such as external vibrations, shocks, and permanent and variable magnetic fields.

Introduction

There are two known operating modes of a Coriolis vibratory gyroscope (CVG): first is a rate mode in which the Coriolis force due to rotation is compensated for by a negative feedback control loop, keeping the standing wave in a fixed position near the drive (excitation) electrode. In this case, the signal that compensates for the Coriolis force is proportional to the angle rate. This mode is called the rate mode. The rate mode provides high accuracy when measuring small and medium angle rates.

The second mode is the rate-integrating mode. The Coriolis force is not compensated for in this mode, causing a standing wave to rotate. The rotation angle of the standing wave is directly proportional to the rotation angle of the gyroscope relative to inertial space. The proportionality coefficient is called the Bryan coefficient and is the scale factor of the rate-integrating CVG. The first and second modes are described in detail in many works, for example, [1, 2]. These two modes were combined into a double-mode CVG, described in [3]. The rate-integrating mode has a large dynamic range, bandwidth, and a stable scale factor, ensuring a small dynamic error under measuring large angle rates.

Relatively recent investigations [4] carried out in Ukraine led to the development of a third, differential, mode, which complements the first two modes and can self-compensate for external disturbances when measuring angle rates.

In this paper, the differential mode of operation is briefly presented and its self-compensation properties are analyzed since the first and second modes are well known. It has been experimentally demonstrated that it reaches the considerable self-compensation coefficient of different external disturbances. It is proposed to combine three modes into one gyroscope, with automatic switching from one mode to another, increasing the CVG's versatility.

Differential mode of operation

In the differential mode of operation, the standing wave is located between the electrodes, (see Fig. 1), so that the angular position of the standing wave is $\theta \neq m\pi/4$, $m = 0, 1,\ldots 7$. In this mode of operation, the CVG control system is designed to hold the standing wave at any predetermined angular position that is not coincident with any of the 8 electrodes located equidistantly along the circle. Two measurement channels are formed in this case, which measure the same angle rate but with opposite signs, Ω and -Ω. Measurement equations can be written as follows [4]:

$$z_x = -2k\Omega D_y \sin 2\theta + d_{xx} D_x \cos 2\theta + d_{xy} D_y \sin 2\theta ;$$
$$z_y = 2k\Omega D_x \cos 2\theta + d_{yy} D_y \sin 2\theta + d_{xy} D_x \cos 2\theta, \quad (1)$$

where d_{xx}, d_{yy}, and d_{xy} are the resonator's dynamic parameters, z_x, z_y are the two *X* and *Y* measurement channel signals in volts, respectively, and D_x, D_y are total loop gains, including transformation coefficients of deformations into voltages of the *X* and *Y* electrodes, respectively.

As can be seen from the first equation (1), the angle rate Ω has a negative sign, and in the second one, it has a positive sign. Thus, the control system that holds the standing wave between the electrodes realizes the differential mode of operation. Under the subtraction of the *X* and *Y* channel signals, the useful components, containing angle rate, are increased, however, errors that have the same signs in both channels are compensated for.

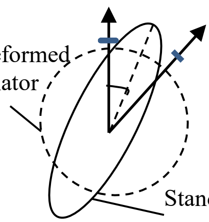

Fig. 1. A standing wave position in the differential CVG

To effectively implement the differential mode of operation, it is necessary to set the standing wave at an angle θ*, at which scale factors of both channels are equal to each other. It means, as follows from the expressions (1), the following condition should be met:

$$SF_x = 2kD_y \sin 2\theta = SF_y = 2kD_x \cos 2\theta . \quad (2)$$

From where the angle θ* can be obtained, as follows:

$$\theta^* = \frac{1}{2}\text{atan}\frac{SF_y^\theta}{SF_x^\theta}\tan 2\theta , \quad (3)$$

Where SF_y^θ and SF_x^θ are scale factors of the *X* and *Y* measurement channels at any standing wave angle $\theta \neq m\pi/4$.

It is convenient to take an angle θ equal to 22.5 deg. (in the middle between the *X* and *Y* electrodes. Then, scale factors $SF_y^{\pi/8}$ and $SF_x^{\pi/8}$ should be determined, and then calculate the angle θ* by the expression (3).

Due to the equality of scale factors of the two measuring channels, external disturbances acting on the gyroscope and having the same responses on the *X* and *Y* channels are compensated by subtracting the signals, z_y - z_x, in the differential channel.

Disturbances self-compensation in differential mode of operation

Fig. 2 shows the influence of five 100 g shocks and 2 ms duration on biases of *X*, *Y*, and differential channels. As can be seen from the fig. 2, the minimum self-compensation coefficient is 2.5/99≈40.

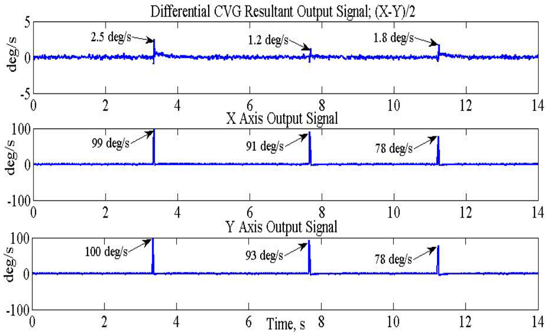

Fig. 2. Bias change after five 100 g shocks

Fig. 3 shows the influence of vibration on the X, Y, and differential channel biases. In these tests, we estimate the influence of g^2 (vibration rectification) on the biases of all three channels, for vibration amplitudes within the range of [1–3] g, and for the three vibration frequencies 50, 100, and 300 Hz.

The g^2 sensitivity of the differential channel to vibration at 300 Hz is 0.015 deg/s/g^2, and for the X and Y channels, they are -0.181 deg/s/g^2 and -0.239 deg/s/g^2, respectively. Thus, the g^2 sensitivity of the differential CVG to vibration is more than 10 times less than the rate CVG, which are represented by the X and Y channels.

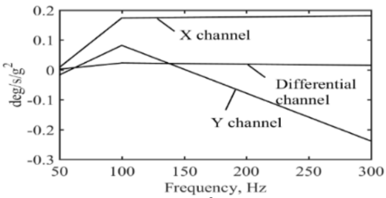

Fig. 3. A g^2 sensitivity to vibration frequency

Fig. 4 and 5 show the influence of the permanent of up to 480 mT and variable of 10 mT magnetic fields on the bias change for each of the three abovementioned channels.

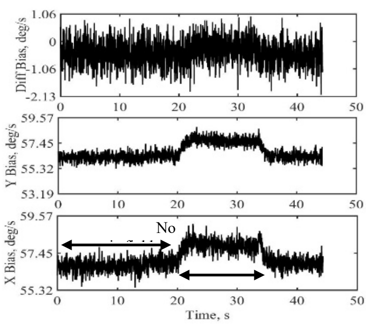

Fig. 4. Differential CVG signal responses to permanent

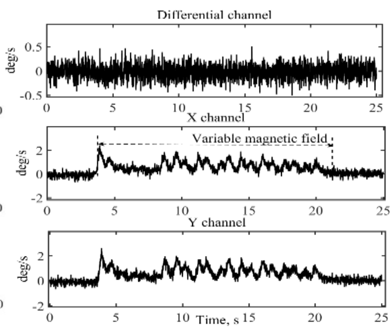

Fig. 5. Differential CVG signal responses to a variable magnetic

The X channel permanent magnetic field sensitivity is about 4.54×10^{-3} deg/s/mT; the Y channel sensitivity is about 4.2×10^{-3} deg/s/mT, and the differential channel sensitivity is about 1.7×10^{-4} deg/s/mT. Hence, the differential CVG self-compensation coefficient of the magnetic field is about $4.2\times10^{-3}/1.7\times10^{-4} \approx 25$.

The responses of the differential CVG signals to a variable magnetic field with an amplitude 10 mT shown in Fig. 5, demonstrate, that the differential channel does not reveal a change in bias.

A multimode CVG

The CVG differs from other modern gyros, like ring lasers and fiber optics, in that all three modes of operation discussed above could be realized in one CVG with automatic switching from one mode to another. This can provide the best accuracy for different motions and environmental conditions. For instance, it is advisable to use rate mode to measure small and medium angle rates. It is because the measurement errors are mainly determined by the gyro noise and bias drift, which can be lower than those of the rate-integrating modes of operation.

Under measuring a high angle rate, it is advisable to use the rate-integrating mode since the measurement errors in this mode are mainly determined by a dynamic error $\Delta\Omega$ caused by the scale factor instability (ΔSF), $\Delta\Omega=\Delta SF\cdot\Omega$. The scale factor for the rate-integrating mode of operation is a stable constant k (Bryan coefficient) depending on resonator size and vibration mode number n (usually n=2).

When measuring should be produced in stringent environmental conditions, for example, under the acting of high shocks, vibrations, and permanent or variable magnetic fields, the differential mode of CVG operation can be used.

Fig. 6 shows the simulation result of three modes of the CVG operation with automatic switching from one mode to another. The first mode is rate one, which measures the angle rate of 100 deg/s. Then, it switches to the differential mode of operation with $\theta=\theta^*$. We can see two output signals, z_x=-100 deg/s, and z_y=100 deg/s. The difference between these signals, z_y-z_x, offers the benefits mentioned above.

Then, it switches to the rate-integrating mode without changing the angle rate. The deviation from a straight line in this mode of operation is due to the resonator manufacturing imperfections.

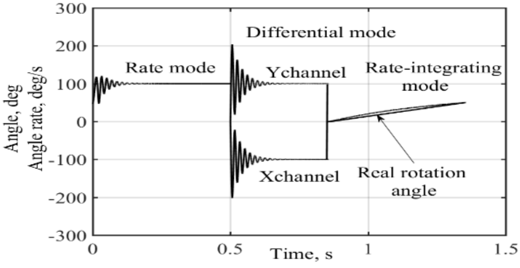

Fig. 6. Example of the multimode CVG measurements

Based on the abovementioned discussion, one of the switching logic variants can be proposed. This variant is presented in Fig. 7.

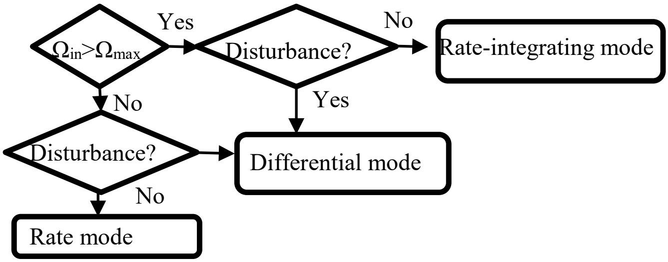

Fig. 7. Example of modes' switching logic

Conclusions

The differential CVG can consider as the third mode of operation for vibratory gyroscopes along with two well-known rate and rate-integrating ones.

The differential mode of operation can be built in the single gyro together with the two others, rate and rate-integrating modes, to implement multimode CVG. The multimode CVG can be implemented both for MEMS and non-MEMS vibratory gyros.

The differential mode of operation can effectively self-compensate for external disturbances and can be used when motion occurs in harsh environmental conditions. Implementing the multimode CVG gives it the highest "versatility" compared with competitive gyro technologies like ring laser and fiber optic gyros.

Combining the advantages of the three modes results in adaptability to different motion parameters, such as high accuracy for small angle rates and low dynamic error for high angle rates. Moreover, it can adapt to the changing environmental conditions.

References

1. D. D. Lynch: Coriolis Vibratory Gyroscope, IEEE Standard Specification Format Guide and Test Procedure for Coriolis Vibratory Gyros, IEEE std. 1431TM, Annex B, pp.56-66, Dec. 2004.
2. J.A. Gregory "Characterization Control and compensation of MEMS rate and rate-integrating gyroscopes", Ph.D. Dissertation, Michigan University, 2012, P. 198.
3. D.D. Lynch, A. Matthews: Dual Mode Hemispherical Resonator Gyro Operating Characteristics, 3-rd S. Petersburg Int. Conf. on Integrated Navigation Systems, part 1, pp. 37-44, May 1996.
4. Valeri V. Chikovani "Vibratory Gyroscopes Based on Micro-Electro-Mechanical and non-Micro-Electro-Mechanical Systems", Cambridge Scholar Publishing, 2023, P. 375. (Monography).