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State-of-the-art MEMS Gyroscopes for Autonomous Cars

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ABSTRACT

A gyroscope is a sensor to measure the rotation (angular velocity or angle) of a system. Recently, MEMS gyroscopes are widely used for consumer electronics, but the performance is not sufficient for automatic driving application. This paper briefly reviews the recent research and development of high-performance MEMS gyroscopes. Two promising modes of gyroscope operation, “force-rebalance mode” and “whole angle mode”, are explained, and key points to achieve higher performance are described.

1. Introduction

MEMS (Micro Electro Mechanical Systems) gyroscopes are widely used for consumer electronics such as smart phones, digital cameras, camcorders, car navigation systems and vehicle stability controllers and drones [1]. On the other hand, optical fiber gyroscopes and ring laser gyroscopes, which have higher performance than MEMS gyroscopes, are used for industrial machines such as airplanes, ships and robots, as shown in Fig. 1. Autonomous cars also require a high-performance gyroscope, but the optical gyroscopes are too expensive for consumer cars. Drastic cost-cutting of the optical gyroscopes is difficult, and thus improvement in the performance of MEMS gyroscopes may be the most promising direction.

Bias stability (i.e. resolution) required for automatic driving is as small as 0.1 °/h, which is two orders of magnitude better than that of the present MEMS gyroscopes for consumer electronics. In other words, drastic performance improvement of MEMS gyroscopes at a reasonable cost is one of important challenges for the commercialization of autonomous consumer cars.

2. Principle of MEMS Gyroscope

A MEMS gyroscope uses Coriolis force. As shown in Fig. 2, a mass is suspended by springs orthogonally. One of the orthogonal axes is “drive axis” (x axis) and the other is “sense axis” (y axis). The mass is driven along the drive axis at the resonance frequency. When the system rotates, Coriolis force, which is proportional to the velocity of the mass along the drive axis and the angular velocity of the system, works along the sense axis. Therefore, the amplitude of forced vibration along the sense axis is proportional to the input angular velocity to be measured.

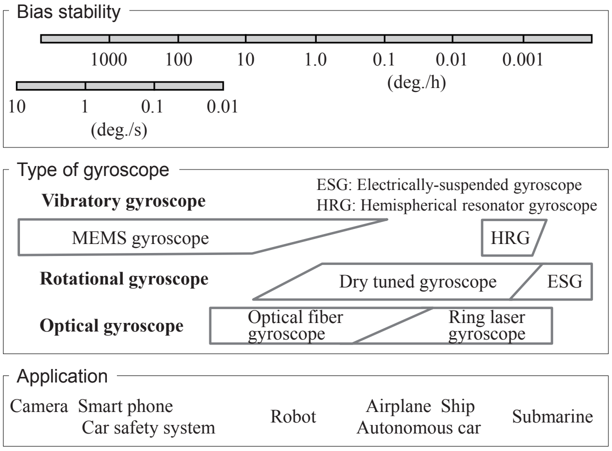

Fig. 1 Types, bias stability and typical applications of gyroscopes.

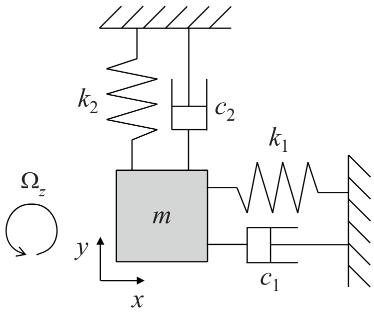

Fig. 2 Orthogonal vibration system of gyroscope.

As mechanical dynamics teaches, the amplitude of the sense axis is maximized, when the resonance frequencies of the sense axis is equal to that of the drive axis, and this situation is called “mode matching” [2]. Also, a higher Q factor is better in terms of sensitivity. As mentioned above, the performance of MEMS gyroscopes must be drastically improved for automatic driving application, and a high-Q mode-matched system is a natural choice.

3. Force-Rebalance Mode Gyroscope

A vibration system with natural angular frequency ω and Q factor Q has a response time of $2Q/\omega$. To make the bandwidth wider, the high-Q mode-matched gyroscope is generally feedback-controlled as the amplitude of the sense axis is always zero regardless of input angular velocity. This type of gyroscope is called “force-rebalance mode gyroscope”. The principle of MEMS gyroscopes is simple as explained in Section 2, but the actual high-Q mode-matched gyroscope suffers from a lot of difficulties. For example, a small shift of the resonance frequency, which is often caused by temperature change, results in a large difference of response. Therefore, the scale factor (i.e. sensitivity) is difficult to stabilize. Also, any small asymmetry of each axis deteriorates bias stability, because unnecessary in-phase vibration is generated not by Coriolis force but by the cross-coupling between the drive and sense axes. Such problems must be compensated by a well-designed

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control electronics [3], although the precise fabrication of the device structure is primarily important.

The best commercially-available high-end MEMS gyroscope (SGH03, Silicon Sensing Systems) has already achieved a bias stability of 0.1 °/h or better. It uses the fundamental wine glass mode of a ring resonator, and thus is immune to acceleration and mechanical shock. In Ref. [4] by Northrop Grumman and University of California, Irvine, one order of magnitude further better bias stability is predicted based on an experimental result under a medium vacuum level of packaging.

4. Whole Angle Mode Gyroscope

In general, the force-rebalance mode gyroscope can achieve good bias stability, but suffers from bandwidth limitation and scale factor inaccuracy. This section introduces another mode of gyroscope operation, “whole angle mode” [5]. Let us consider again the vibration system shown in Fig. 2. The drive and sense axes are orthogonal, and thus vibration in each axis is independent. If the system rotates along *z* axis at angular velocity Ω_z, however, the drive and sense axes are coupled via Coriolis force, as shown in the following equations of motion;

$$\ddot{x} + \frac{c_1}{m}\dot{x} + \left(\frac{k_1}{m} - \Omega_z^2\right)x = 2\Omega_z\dot{y},$$

$$\ddot{y} + \frac{c_2}{m}\dot{y} + \left(\frac{k_2}{m} - \Omega_z^2\right)y = 2\Omega_z\dot{x}\cdot$$

The two-degree-of-freedom system has two eigenmodes. Assuming that the system is completely symmetric, i.e. $k_1 = k_2 = k$ and $c_1 = c_2 \sim 0$, the eigenmodes are CCW and CW modes, at different natural angular frequencies, $\omega - \Omega_z$ and $\omega + \Omega_z$, respectively ($\omega = (k/m)^{1/2}$). If these eigenmodes are superimposed, the mass vibrates linearly, and the trajectory (i.e. direction) of the vibration rotates at $\alpha\Omega_z$, where is α is a constant. This is exactly the same as Foucault pendulum. For the ideal Foucault pendulum, $\alpha = 1$, but generally α is determined by the structure of the system.

The gyroscope based on the principle of Foucault pendulum is the whole angel mode gyroscope. Rotation angle, which is finally needed for inertial navigation, is directly obtained by from the direction of linear vibration without the integration of Ω_z, which also integrates bias instability. α is actually a scale factor and inherently stable, because it is determined only by the structure of a gyroscope. In addition, there is no limitation of bandwidth theoretically. Therefore, the force-rebalance mode and the whole angle mode are complementary each other. Importantly, the two mode can share the same structure of a high-Q mode-matched gyroscope, and be switched by electronics [4].

To obtain high performance, the precise fabrication is again important, and residual errors must be electronically compensated, because the symmetry of the structure is highly important. The two orthogonal axes must have the same resonance frequency and the same dumping coefficient (i.e. Q factor). On the other hand, any symmetric orthogonal vibration systems including lumped mass-spring systems [5], rings [6], disks [7] and hemispherical shells [8] potentially work as the whole angle mode gyroscope as well as the force-rebalance mode gyroscope.

5. Conclusion

The principle of MEMS gyroscopes is simple, but the implementation of a high-performance gyroscope is not so easy. First of all, precise fabrication of MEMS structures is essential. The critical dimension of MEMS is much larger than that of the state-of-the-art CMOS circuits, but other types of accuracy, e.g. <±0.1° verticality of etched side walls, are required for the next-generation MEMS gyroscopes. The designs of the structure and electronics also have a great impact on the performance.

The development of MEMS gyroscopes with a bias stability better than 0.1 °/h in actual use cases is a great challenge. Once it becomes available at a reasonable cost, however, the application is not limited to autonomous cars, extending to advanced robots for home uses, autonomous drones for consumer services, accurate personal navigation systems, compact personal vehicles and other not-yet-imagined systems.

In this paper, the state-of-the-art MEMS gyroscopes were briefly introduced. Unfortunately, it is not so easy to understand MEMS gyroscopes, although the principle is simple. For more details, please do not hesitate to make a contact with the author.

References

[1] Dunzhu Xia, Cheng Yu, Lun Kong, *Sensors*, 14 (2014) 1394–1473.

[2] Mohammad Faisal Zaman, Ajit Sharma, Zhili Hao, Farrokh Ayazi, *J. Microelectromech. Syst.*, 17, 6 (2008) 1526–1536.

[3] A.A. Trusov, I.P. Prikhodko, D.M. Rozelle, A.D. Meyer, A.M. Shkel, *Proc. Transducers 2013*, Barcelona, Spain, 16–20 June, 2013, 2531–2534.

[4] A.A. Trusov, D.M. Rozelle, G. Atikyan, S.A. Zotov, B.R. Simon, A.M. Shkel, A.D. Meyer, *Proc. Solid-State Sensors, Actuators and Microsystems Workshop*, Hilton Head Island, USA, 8–12 June, 2014, 419–422.

[5] Igor P. Prikhodko, Sergei A. Zotov, Alexander A. Trusov, Andrei M. Shkel, *Sens. Actuators A*, 177 (2012) 67–78.

[6] D. Senkal, S. Askari, M.J. Ahamed, E.J. Ng, V. Hong, Y. Yang, C.H. Ahn, T.W. Kenny, A.M. Shkel, *Proc. IEEE MEMS 2014*, San Francisco, USA, 26–30 January, 2014, 24–27.

[7] Houri Johari, Farrokh Ayazi, *Proc. IEEE MEMS 2007*, Kobe, Japan, 21–25 January, 2007, 47–50.

[8] Jae Yoong Cho, Jong-Kwan Woo, Jialiang Yan, Rebecca L. Peterson, Khalil Najafi, *J. Microelectromech. Syst.*, 23, 1 (2014) 66–77.