Chapter

Introductory Chapter: Gyroscopes - Principles and Applications

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1. Origins of gyroscopes

In ancient China, dating back to 500 BC, an interesting toy called "bamboo dragonfly" was invented to emulate the dragonfly [1]. The toy was very popular among children. When they rubbed this toy between their hands, it went flying into the air. Children had great fun experimenting to see whose bamboo dragonflies would fly the farthest and the highest. Bamboo dragonfly is an early type of gyroscope owning a history longer than 2500 years. But the name "gyroscope" did not appear until in the middle of 19th century. Gyroscope was created by a French physicist, Jean-Bernard-Léon Foucault [2]. He named his experimental instrument for Earth's rotation observation by joining two Greek roots: gyros meaning "circle or rotation" and skopeein meaning "to see." During his experiment to demonstrate the Earth's rotation, he found gyroscopes could maintain their original orientations in space regardless of Earth's rotation. This unique merit made gyroscopes are the perfect sensors to detect and measure the angular velocity of a rotational object, the deviation of a vehicle from its desired orientation. Since then gyroscopes were widely used in autonomous navigation systems. According to Encyclopedia Britannica, the first workable gyrocompass was developed by German inventor H. Anschütz-Kaempfe in 1908 [3]. It was invented to be used in a submersible. Then, in 1909, the first auto-pilot was created by an American inventor Elmer A. Sperry. It consisted gyroscopes which used to measure the rotation speed of the airplane. By collecting this information, gyroscopes could help stabilize the flight of the aircraft. In 1916, gyroscopes were used for assistant steering in a Danish passenger ship of a German company. Since then, gyroscopes became more and more popular in attitude control and navigation systems.

2. Development process of gyroscopes

The prototypes of gyroscopes designed by Léon Foucault were mechanical gyroscopes. The typical type of this kind of gyroscope was made by suspending a spinning relatively massive rotor inside three rings called gimbals. The basic principle of mechanical gyroscopes was the law of conservation of angular momentum: the tendency for the spin of a system to remain constant unless subjected to external torque. Mechanical gyroscopes are the most common or familiar type of gyroscope. Bamboo dragonfly fits into this category, which includes any gyroscope that relies on a ball bearing to spin. These types of gyroscopes are often used in navigation of aeronautic devices and vessels. However, due to the friction in the support bearings, imbalances inherent in the construction of the rotor, mechanical gyroscopes are typically noisier than other forms of gyroscopes, and their performances prone to drift with time, needing to be maintained frequently.

With the progress of science and technology, new kinds of gyroscopes based on new principles continuously came forth in our eyeshot and found their applications in our daily lives. Optical gyroscopes are the most successful ones, including ring laser gyroscopes and fiber-optic gyroscopes [4]. These devices send two beams of light around a circular path in opposite directions. If the path spins, a "fringe interference" pattern (alternate bands of light and dark) was detected that depended on the precise rate of rotation. They first appeared in the 1960s, following the invention of the laser and the development of fiber optics. Optical gyroscopes have the advantages of excellent measurement accuracy and having no moving parts and thus, no friction. The first ring laser gyroscope (RLG) was built in 1963 by Mecek and Davis. Owing to their high level of accuracy, cheap cost, high reliability, and easy maintenance, RLGs are perfect for integration in Inertial Navigation Systems. Today, RLGs have largely replaced their mechanical gyroscope predecessors in autopilot systems in aircrafts and guided missiles through missions where GPS is not safe to use. The global ring laser gyroscopes market is anticipated to reach a market value of US$ 948.3 million by 2026, growing at a compound annual growth rate of 3.5% during the forecast period 2018–2026 [5].

Fiber-optic gyroscope (FOG) is another successful optical gyroscope [4]. It was first proposed and studied in 1970s and was initially considered to be devoted to medium-level applications. In 1978, McDonald Company developed the first practical FOGs, and in 1980, Bergh et al. devised the first all-fiber optic gyroscope. Since then, FOGs have experienced a period of rapid development, the angular velocity measurement accuracy has been improved to 0.001°/h, reaching the strategic level of performance and surpassing the ring laser gyroscope in terms of deviation noise and long-term stability. In addition to no moving and wearing parts, FOGs also have the advantages of small size, light weight, large dynamic range, and flexible design, which mean the performance of a fiber-optic gyroscope can be adjusted by altering the length and diameter of its coil. FOGs are now gradually evolving in the direction of low cost, high reliability, and long service life. FOGs are broadly used in inertial navigation systems in guided missiles, aircrafts, and vehicles for attitude measurement and navigation. The global market of FOGs is expected to worth US$ 948.3 million by 2022, growing at a compound annual growth rate of 3.61% during the period 2016–2022 [6].

MEMS gyroscope is the most successful commercial modal for angular velocity sensors [7]. MEMS gyroscopes are based on micro electrical mechanical systems (MEMS) technology and are very suitable to mass production. Benefiting from the advancements in MEMS technology, MEMS gyroscopes own their most prominent advantages: cheap, small, and light. The common type of MEMS gyroscope is made of silicon, with a massive object suspended in the air by an anchor or some springs. When a gyroscope is in operation, the suspended structure keeps vibrating. As the gyroscope experiences a rotation relative to its reference, a force called Coriolis force will act on the suspended structure and causes it to move in a direction perpendicular to its vibrating direction. This movement is proportional to the rotation speed and converts into electrical signals that can be amplified and read by a microcontroller, the angular velocity is then ascertained. Once the accuracy of MEMS gyroscopes was much lower than that of their competitors, such as optical gyroscopes and mechanical gyroscopes. So, their applications were restricted to low-end. In the last 10–15 years, the precision of MEMS gyroscope improves drastically and achieves the tactical grade level (0.1°/h). On the benefits of the small size, low costs, and light weight and due to its improved precision and environmental stability, MEMS gyro is applied in more and more areas, such as consumer electronic devices, wearable devices, automotive safety, personal and vehicle navigation systems, robots controlling, stability controlling system, video games, and toys. MEMS gyroscope is also entering markets that were previously dominated by optical gyroscopes, now they have been the successful mass-produced commercial productions. The MEMS gyroscope market is growing rapidly and is expected to witness a CAGR of 9.48% during the period between 2020 and 2025 [8].

Gyroscope is now showing an encouraging momentum of accelerated development. New gyroscopes based on new principles, new fabrication process, and new materials are spring up like mushrooms, such as microscale hemispherical resonator gyroscopes, surface acoustic wave (SAW) gyroscopes, electrostatic (suspended) gyroscopes, integrated optic gyroscopes, superfluid gyroscopes, diamond gyroscopes, atomic gyroscopes, etc. [9–12]. The application field of gyroscope is also expanding rapidly, and it has covered almost every aspect of human lives, from aircrafts to vehicles, to wearable medical devices, to our smartphones, and to children's toys. Gyroscopes have been the most powerful tools of human beings to explore our living environment (ocean exploration, space exploration, planetary exploration, and even exoplanet exploration in the future) to improve the quality of our daily lives. Gyroscope is old, but also is young. With the efforts of researchers and scientists, gyroscopes are becoming more and more prosperous and benefit all humankind.

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References

[1] Toys Invented in Ancient China. Classroom. Available from: https://classroom.synonym.com/toys-invented-ancient-china-10930.html [Accessed: 18 March 2020]

[2] Gyroscope. Available from: http://physics.kenyon.edu/EarlyApparatus/Mechanics/Gyroscope/Gyroscope.html [Accessed: 18 March 2020]

[3] Gyroscopes have a huge variety of uses, find out how they work in our latest Tech Explained. Tech Explained: Gyroscopes. Available from: https://www.springwise.com/tech-explained-gyroscopes/ [Accessed: 20 November 2018]

[4] Shamir A. An Overview of Optical Gyroscopes Theory, Practical Aspects, Applications and Future Trends: Technical paper: Adi Shammir; 2006

[5] Ring Laser Gyroscope Market-Snapshot. Transparency Market Research. available from: https://www.transparencymarketresearch.com/ring-laser-gyroscope-market.html [Accessed: 15 March 2020]

[6] Fiber Optics Gyroscope Market. Markets and Markets. Available from: https://www.marketsandmarkets.com/Market-Reports/fiber-optic-gyroscope-market-99825571.html [Accessed: 14 March 2020]

[7] Trusov AA. Overview of MEMS Gyroscopes: History, Principles of Operations, Types of Measurements. Irvine, USA: University of California; 2011

[8] MEMS Gyroscope Market - Growth, Trends and Forecast (2020-2025). Mordor Telligence. Available from: https://www.mordorintelligence.com/industry-reports/mems-gyroscope-market [Accessed: 15 March 2020]

[9] Fang J, Qin J. Advances in atomic gyroscopes: A view from inertial navigation applications. Sensors. 2012;**12**(5):6331-6346

[10] Zhuang X, Chen B, Wang X, et al. Microscale polysilicon hemispherical shell resonating gyroscopes with integrated three-dimensional curved electrodes. Journal of Physics: Conference Series. 2018;**986**:012022

[11] Oh H, Lee KJ, Lee K, et al. Gyroscopes based on surface acoustic waves. Micro and Nano Systems Letters. 2015;**3**(1):1

[12] Armenise MN. Emerging gyroscope technologies. In: Advances in Gyroscope Technologies. Berlin, Heidelberg: Springer; 2010. pp. 103-108