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Gyroscope Technologies: An Effective Role in the Mechanical & Optical Perspective

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ABSTRACT
In this work the discussion of current gyroscopes and their roles based on their industrial applications. Gyroscopic effect is ability of the rotating body to maintain a steady direction of its axis of rotation. The gyroscopes are rotating with respect to the axis of symmetry at high speed. The considered gyroscopes include mechanical gyroscopes and optical gyroscopes at macro- and micro-scale. Gyroscope technologies commercially available, such as Mechanical Gyroscopes, silicon MEMS (Micro-Electro-Mechanical System (MEMS) gyroscopes are motion sensors that detect and measure the angular motion of an object) they measure the rate of rotation of an object around a particular axis: 1-axis, 2-axis, and 3-axis). Gyroscopes, Ring Laser Gyroscopes (RLGs) and Fiber-Optic Gyroscopes (FOGs), are discussed. The main features of these gyroscopes and their technologies are linked to their relative performance. There are three basic types of gyroscope: Rotary (classical) gyroscopes: Vibrating Structure Gyroscope and Optical Gyroscopes.

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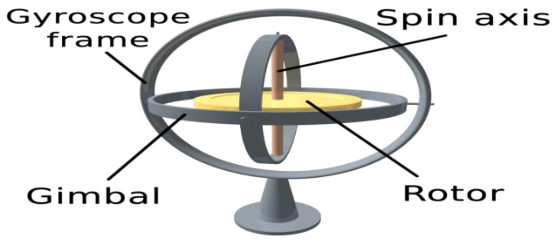
I. INTRODUCTION

A gyroscope is a device used for measuring or maintaining orientation and angular velocity. It is a spinning wheel or disc in which the axis of rotation (spin axis) is free to assume any orientation by itself. When rotating, the orientation of this axis is unaffected by tilting or rotation of the mounting, according to the conservation of angular momentum. The term “gyroscope”, conventionally referred to the mechanical class of gyroscopes, derives from the Ancient Greek language, being the Physics of the “precession motion”, a phenomenon also observed in ancient Greek society. Gyroscopes are devices mounted on a frame and able to sense an angular velocity if the frame is rotating. Many classes of gyroscopes exist, depending on the operating physical principle and the involved technology. Gyroscopes can be used alone or included in more complex systems, such as Gyrocompass, Inertial Measurement Unit, Inertial Navigation System and Attitude Heading Reference System. In this paper, a review of the more commercially diffused classes of gyroscopes is presented. In particular, mechanical gyroscopes optical gyroscopes, including Fiber Optic Gyroscopes (FOGs) and Ring Laser Gyroscopes (RLG) and Micro-electromechanical system (MEMS) gyroscopes have been considered by focusing attention on the operating principles and different improvements in commercial architectures in terms of performance. For all classes of gyroscopes, being angular velocity sensors, the major issues are related to the errors in measuring the angular velocity. For this reason, one of the more important merits is the stability of the scale-factor. Scale factor represents the sensitivity of the optical gyroscope, while the accuracy of the gyroscopes, which is inversely proportional to the sensitivity and takes into account the measurement errors due to the noise, can be expressed through the resolution, R, or, in the RLGs, by the Angle Random Walk (ARW), linking R with the bandwidth, B, of the measurement system through ARW = R/[60sqrt(B)]. Minimum scale-factor stability leads to small sensor errors and requires better instruments and improved accuracy, bringing higher cost of the system. Thus, gyroscope performance and costs are directly related to the application requirements

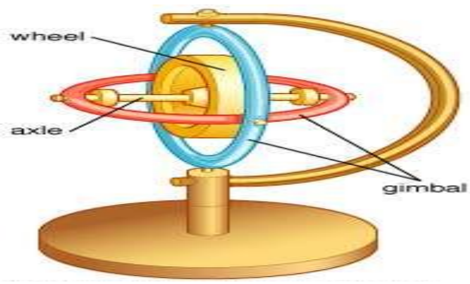


Scale factor stability (i.e., the accuracy of the gyroscope in monitoring the sensed angular velocity), expressed in parts per million (ppm), as a function of the bias stability (intrinsically dependent on the gyroscope technology) for Mechanical Gyroscopes, Ring Laser Gyroscopes (RLG), Interferometric Fiber-Optic gyroscopes (IFOG), Quartz, Dynamically Tuned Gyroscopes (DTG), Rate and Integrating Gyroscopes and MEMS.

Mechanical gyroscopes, classified as displacement gyroscopes and rate gyroscopes, are the historical ones consisting in a toroid-shaped rotor that rotates around its axis while, since the 20th century, optical gyroscopes operate by sensing the difference in propagation time between counter-propagating laser beams traveling in opposite directions in closed or open optical path. The main diffused types of optical gyroscopes are IFOG and RLG, which both exploit the physics of the Sagnac interference. For applications requiring very high performance, the ring laser gyroscope is currently more diffused and has the bigger market share. Micro-Electro-Mechanical System (MEMS) gyroscopes are motion sensors that detect and measure the angular motion of an object. They measure the rate of rotation of an object around a particular axis: 1-axis, 2-axis, and 3-axis. Although initially used for expensive military applications, now they are also adopted for low cost commercial applications of consumer electronics for Automotive, Defense, Industrial and Medical applications. The increased demand for mobile devices is also responsible for the growth of the MEMS gyroscopes market. The cost of MEMS gyroscopes is expected to reduce drastically in the next years, leading to an increment in the use of these devices. The MEMS and optical gyroscopes, in particular Interferometric Fiber-Optic gyroscopes (IFOG), are replacing many of the current systems using Ring Laser Gyros (RLGs) and mechanical gyroscopes. However, among the optical gyroscopes, applications requiring extremely high scale factor stability continue to be achieved only with RLG. The scale factor stability (i.e., the accuracy of the gyroscope in monitoring the sensed angular velocity), expressed in parts per million (ppm), as function of the bias stability (a parameter that is intrinsically dependent from the gyroscope technology), is reported. Depending on the scale stability, an extensive range of applications is considered with reference to the gyroscope technology (i.e., Mechanical, RLG, IFOG, Quartz, Dynamically Tuned Gyroscopes (DTG), Rate and Integrating Gyroscopes, and MEMS), and the performance in terms of Scale Factor Stability vs. Bias Stability.

II. MECHANICAL GYROSCOPES

A mechanical gyroscope essentially consists of a spinning mass that rotates around its axis. In particular, when the mass is rotating on its axis, it tends to remain parallel to itself and to oppose any attempt to change its orientation. If a gyroscope is installed on gimbals that allow the mass to navigate freely in the three directions of space, its spinning axis will remain oriented in the same direction, even if it changes direction. A mechanical gyroscope shows a number of physical phenomena, including precession and notation. In the following sections, the main operating principles of the mechanical gyroscopes are reported, with reference to the Inertial Navigation Systems.



III. PRINCIPLE OF MECHANICAL GYROSCOPES

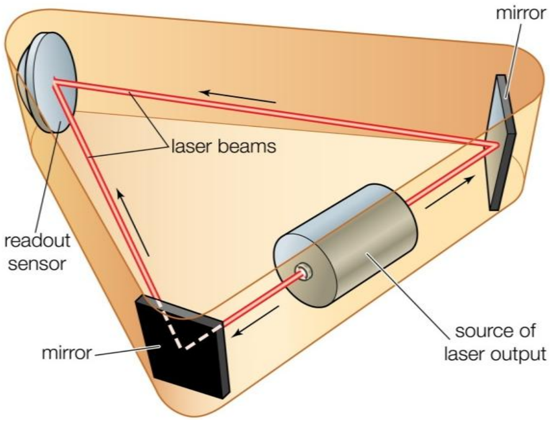
Gyroscopic Effects The basic effect upon which a gyroscope relies is that an isolated spinning mass tends to keep its angular position with respect to an inertial reference frame, and, when a constant external torque (respectively, a constant angular speed) is applied to the mass, its rotation axis undergoes a precession motion at a constant angular speed (respectively, with a constant output torque), in a direction that is normal to the direction of the applied torque (respectively, to the constant angular speed). External forces acting on the center of mass of the rotating part do not affect the angular position of the rotation axis.

Mechanical Displacement Gyroscopes The primary application of gyroscopic effects consists in the measurement of the angular position of a moving vehicle. The spinning mass is mounted upon a gimbaled frame, allowing rotation along two perpendicular axes. The gimbaled frame of the gyroscope is attached to the vehicle and it is free to rotate, while the rotation axis of the spinning mass keeps its angular position during the motion of the vehicle. The variation of the absolute angle of the vehicle can be simply associated to the relative variation of the angle between the rotation axis of the mass and a fixed direction on the frame of the gyroscope.

Another useful application of this physical effect is that exploited in gyrocompasses: when external torques is not applied to the frame, the gyrocompass keeps the angular position of a pointer to North direction, independently of the path followed by the vehicle. The advantage of such a mechanical system is that it is immune to magnetic fields that can cause deviations on the pointer angle.

IV. OPTICAL GYROSCOPES

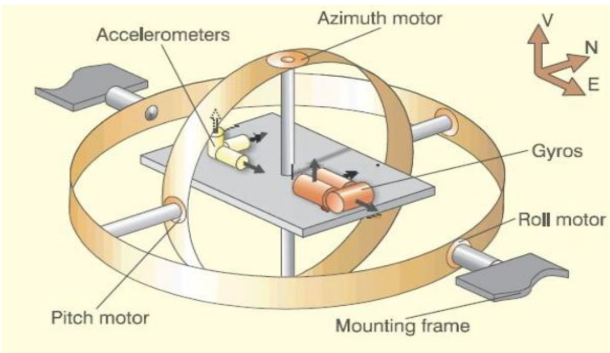
Optical gyroscopes operate by sensing the difference in propagation time between counter-propagating beams travelling in opposite directions in closed or open optical paths. A rotation-induced change in the path lengths generates a phase difference between the counter-propagating light beams. This rotation-induced phase difference physically consists in the Sagnac interference, being the basic operating principle of all optical gyroscopes.



Based on the measurement technique of the Sagnac interference, it is possible to classify the optical gyroscopes. The two main different typologies of optical gyroscopes consist in active and passive architectures. In the active configurations, the closed-loop optical path (i.e., the ring cavity) contains the optical source, forming a ring laser. The active configurations can be built in Bulk Optics or in Integrated Optics technology, although only the Bulk Optics solutions have achieved commercial maturity. Among the Ring laser gyros, there are different categories depending on the method employed to overcome the lock-in effect (i.e., a condition for which the active gyroscope response results insensitive to low rotation rates) which occurs at low rotational rates (tens of degrees/hour). Lock-in can be reduced by introducing a mechanical dither, a magneto-optic biasing, or by using of multiple optic frequencies configuration. Differently, in passive architectures, the optical source is external to the closed optical loop (i.e., a fiber coil) as in the Inter ferometric Fiber Optic Gyroscope. Ring Laser Gyroscopes and Inter ferometric Fiber Optic Gyroscopes, whose features differ in terms of size, weight, power requirements, performance, and cost, are the more diffused optical gyroscope technology.

V. RING LASER GYROSCOPES (RLGS)

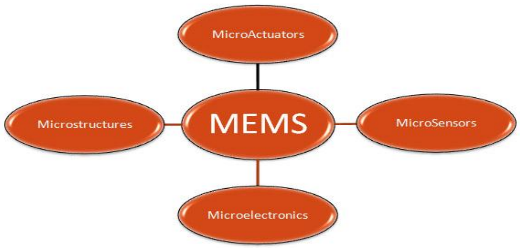
The ring laser gyroscopes (RLGs) are based on a ring laser (i.e., a annular cavity) where, due to the Sagnac interference , two independent counter-propagating resonant modes, intrinsically generated within the cavity through a gain medium, show of a frequency shift if the cavity undergoes a rotation. The ring laser can be realized in bulk solid-state optics or in integrated optics, although the integrated optics solutions (e.g., semiconductor ring laser gyroscopes) are not commercially mature.



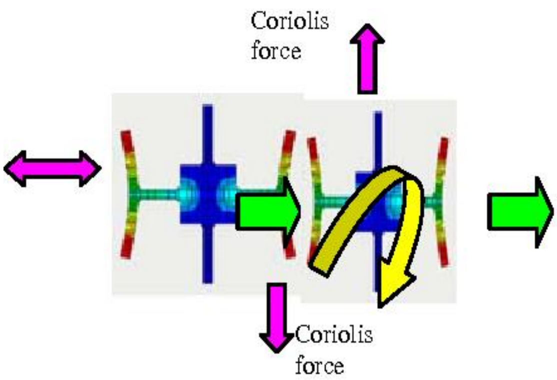
In one of the most diffused architectures, the RLG body is made from a triangular glass block. Three air channels are drilled in the glass body and three mirrors are placed at each corner to create a triangular optical resonator. A low pressure He-Ne gas mix fills the three tubes. A high voltage electrical discharge is applied through the two anodes and the cathode for electrically pumping the optical cavity. Due to the action of the electrical pump, two independent counter-propagating laser beams (i.e., clockwise CW and counter-clockwise CCW), resonating at the same frequency, are generated inside the optical cavity. By making a partially reflecting mirror, it is possible to detect the angular velocity of the rotating system by reading the frequency change of the resonant behavior of the device or the interference pattern generated by the interaction of the CW and CCW laser beams, leading to a standing wave. The two read-out techniques are covered by the physics of the Sagnac interference. At very low rotation rates, the mirrors, being imperfect, produce backscattered light, which couples energy from a CW to a CCW. The backscattered light acts as a mechanism of frequency synchronization—lock-in of the two resonant beams at low rates of rotation.

VI. MICRO-ELECTRO-MECHANICAL SYSTEM (MEMS) GYROSCOPES

MEMS gyroscopes generally use a vibrating mechanical element as a sensing element for detecting the angular velocity. They do not have rotating parts that require bearings and this allows an easy miniaturization and the use of the manufacturing techniques typical of MEMS devices. All MEMS gyroscopes with vibrating element are based on the transfer of energy between two vibration modes caused by the acceleration of Coriolis. The Coriolis acceleration, proportional to the angular velocity, is an apparent acceleration that is observed in a rotating frame of reference.



Further development followed since the late 1990s, thanks to the fact that silicon technology became more mature, so it was possible to integrate control and processing electronic components into MEMS.



Studies aiming at improving MEMS gyroscopes increased, being already known the main aspects of theory and operation; the availability of more sophisticate test equipment to characterize prototypes, more powerful design tools and industrial interest in other application fields contributed to the progress of this technology. Georgia Institute of Technology also put great efforts in the research of MEMS gyroscopes. It used an electrostatic comb drive to move the proof-masses in x-axis and a capacitive detecting in y-axis to sense rotation in z-axis. Drive and sense mode were electro statically balanced to achieve perfect mode matching; this design improved sensitivity, bias stability and noise floor. Sharma, through further research on the M2-TFG, designed the closed-loop circuit based on a trans impedance amplifier with a dynamic range of 104 dB, capable to keep the matched-mode. Experimental data showed a capacitive resolution of 0.02 aF/√Hz at 15 kHz. Zaman in 2008 reported an improvement of the M2-TFG using two high-quality factor resonant modes. The open-loop rate sensitivity of the new design was 83 mV/°/s in vacuum while the bias instability was 0.15°/h. These structures forced an anti-phase drive-mode and a linearly-coupled dynamically-balanced anti-phase sense-mode, that prioritizes sense-mode quality factor. The prototypes were characterized in a vacuum chamber, demonstrating a quality factor drive-mode of 67,000 and of 125,000 for the sense-mode. Meanwhile, the joined forces of Old Dominion University and University of Utah led to the improvement of the M2-TFG architecture. In fact, Wang et al. presented a multiple beam tuning fork gyroscope that reached a measured Q-factor of 255,000 for drive-mode and 103,000 for sense-mode at 15.7 kHz. Further measurements pointed out a rate resolution of 0.37°/h/√Hz, a rate sensitivity of 80 VPP/°/s while ARW and bias instability were 6.67°/√h and 95°/h, respectively. Other researches were performed towards enabling a wider bandwidth to expand flexibility and ease of use.

VII. CONCLUSIONS

In this part it discussed the currently more expanded gyroscope technologies. The considered gyroscopes include mechanical gyroscopes and optical gyroscopes at macro- and micro-scale. In particular, commercially available gyroscope technologies, such as Mechanical Gyroscopes, silicon MEMS Gyroscopes, Ring Laser Gyroscopes (RLGs) and Fiber-Optic Gyroscopes (FOGs) are discussed effectively, focusing attention on the main features, performances, technologies, applications. Gyroscopic action is the rotation of a spinning body's axis. The understanding of gyroscopic action is crucial for vehicle and aircraft engineering design. Stabilizing a system like an automobile or a plane requires awareness of gyroscopic effects that may alter the stability of the system. Consequently, the focus of this paper is to study the gyroscopic couple, angular velocity of the rotor, and the precession velocity.

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