Advances in Gyroscope Technologies

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Preface

The gyroscope, which measures angular rotation around a fixed axis with respect to an inertial space, is a key sensor in modern navigation systems enabling to plan, record and control the movement of a vehicle from one place to another. This device has a wide spectrum of applications in space engineering, aeronautical and military industry, automotive, medicine and so on. For these reasons gyro architectures and technologies have been investigated by very important research groups in USA, Europe and Asia. National space agencies of a number of Countries have invested significant financial resources for developing innovative gyroscope technologies. Results of this intense research effort have been reported in a large number of scientific papers and patents.

The purpose of the book is to collect and critically review the main results obtained by the scientific community in advanced gyroscope technologies. Architectures, design techniques and fabrication technology of angular rate sensors proposed in literature are described. Future research trends aimed to cover special applications are also considered.

The book is intended for researchers and Ph.D. students interested in modelling, design and fabrication of gyros. It may be a useful education support in some university courses focused on gyro technologies.

In recent years the authors have spent an intense research effort on optical angular velocity sensors working on some specific projects supported by some space agencies. They use their deep know–how on different gyroscope technologies to offer to the readers a wide vision about the book subject.

The book includes seven chapters. First two chapters introduce the topic and briefly describe physical effects exploited in gyroscope technologies. Chapters 3, 4 and 5 are focused on optical gyros. State-of-the-art of ring laser gyros, fiber optic gyros and integrated optical gyros is accurately reviewed. Vibratory gyros and, in particular, MEMS gyros are the topic of Chap. 6, where MOEMS gyros are also introduced. Finally, the book topic is summarized in Chap. 7 that offers also an overview of the most innovative technologies for angular rate sensors with outstanding performance.

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Chapter 1
Introduction

Inertial sensors, which allow to measure linear acceleration and angular velocity, are emerging as a crucial class of sensors and their applications are continuously increasing. They were first developed for aerospace and military systems but currently are extensively used in a wide spectrum of applications, such as automotive, medicine, consumer electronics and so on.

Inertial Measurement Units (IMUs) enabling the measurement of acceleration along three axes and angular velocity around the same three axes are very sophisticated systems whose development in terms of cost reduction and performance improvement is considered an important task for naval, defense and aerospace industry. Innovative space-qualified IMUs having reduced weight, low power consumption, high sensitivity, and good reliability are needed for new space missions. IMU worldwide market, which is currently around 2 billion dollars, is expected to significantly grow up in the next few years.

Gyroscope (also named gyro) measures the angular rate around a fixed axis with respect to an inertial space. In the last four decades an intense research effort has been devoted to design, optimize and fabricate different kinds of gyros essentially based on angular momentum conservation, Sagnac and Coriolis effects. In the last few years development of innovative gyros has been focused on micro-photonics and micro-electro-mechanics technologies.

In this chapter main technologies and applications of angular rate sensors are briefly discussed. Performance parameters allowing the comparison of different gyros are defined, too.

1.1 Overview of Gyroscope Technologies

It is possible to recognize three different kinds of gyroscopes: spinning mass gyros, optical gyros and vibrating gyros. In the first category all the devices having a mass spinning steadily with respect to a free movable axis fall. Optical gyroscopes are based on Sagnac effect which states that phase shift between two waves counter-propagating in a rotating ring interferometer is proportional to the loop

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angular velocity. Vibrating gyros are based on Coriolis effect that induces a coupling between two resonant modes of a mechanical resonator.

The basic configuration of gyroscope exploits the inertial properties of a wheel (or rotor) spinning at high speed, which tends to keep the direction of its spin axis by virtue of the tendency of a body to resist to any change in the direction of its moment. In the 1960s Dynamically Tuned Gyroscope (DTG), which is based on this physical principle, was developed [1]. DTG was used for many years in aerospace and military industry and it was included in the IMU of the Space Shuttle.

One of the most successful spinning mass gyroscope is the Control Moment Gyroscope (CMG) [2] which is widely used for satellites stabilization [3]. It consists of a spinning rotor and one or more motorized gimbals that tilt the rotor angular moment. As the rotor tilts, the changing angular moment causes a gyroscopic torque that rotates the spacecraft. CMGs were used for decades in large spacecraft, including Skylab, Mir Space Station and the International Space Station.

Miniaturization of spinning mass gyros is very difficult and their consequent decline has created interesting business opportunities for vibrating and optical gyros that can be effectively miniaturized by MEMS and integrated optical technologies, respectively.

In the 1980s, a highly performing vibrating gyro, the Hemispherical Resonator Gyro (HRG), was developed. HRG sensing element is a fused silica hemispherical shell (diameter around 30 mm) covered by a thin metal film [4]. This device is a very sensitive and expansive gyro and it was used in some space missions, including the Near Earth Asteroid Rendezvous and the Cassini ones.

Silicon and quartz MEMS gyros are innovative miniaturized vibrating angular rate sensors. They assure low cost and performance which is constantly increasing. MEMS gyros market is quickly growing up and is reaching 800 millions dollars in 2010 [5].

Since 1963 when the first Ring Laser Gyroscope (RLG) based on Sagnac effect was fabricated [6], a number of photonic gyroscopes have been proposed and demonstrated, including Fiber Optic Gyroscopes (FOGs) and integrated-optics gyroscopes [7, 8]. In the 1990s, the first FOG in space was used in X-ray Timing Explorer mission [9].

Recently, other very sophisticated technologies for future gyros have been demonstrated, including the nuclear magnetic resonance gyro [10] and the superfluid gyro [11].

Some reviews on gyro technology are reported in literature [12–15], while the most recent advances are in this book.

1.2 Gyro Performance Parameters

Different gyro technologies are usually compared in terms of cost, power consumption, reliability, weight, volume, thermal stability, immunity to external disturbance and other very important performance parameters describing the gyro behavior when it is set up in a more complex system.

Starting from gyroscope static input–output characteristic a number of gyro performance parameters can be defined such as scale factor, bias, input and output range, full range, resolution, dynamic range and dead band [16].

Gyro scale factor is defined as the ratio between the change in sensor output and the relevant angular velocity variation. It is usually evaluated as the slope of the straight line that can be obtained by linear fitting input–output data.

Bias is defined as the average, over a specified time interval, of gyro output that has no correlation with either input rotation or acceleration. Bias is measured in °/h or °/s.

Input range is the range of input values in which the gyro performance matches a specified accuracy. Output range is the product between input range and scale factor. The algebraic difference between the upper and lower values of the input range is called full range.

Minimal detectable angular rate or resolution (expressed in °/h or °/s) is the minimum angular velocity that can be detected by a gyroscope. The ratio between full range and resolution is called dynamic range (dimensionless quantity).

Finally, dead band is a range between the input limits within which variations in the input produce output changes less than 10% of those expected.

Gyro frequency response or step response allow to calculate gyroscope bandwidth and response time.

Main noise contributions in gyroscope are:

- quantization noise,
- bias instability (or bias drift),
- angle random walk.

Quantization noise is mainly due to analog-to-digital conversion of the gyro output signal whereas the cause of other noise contributions depends on the gyro operating principle.

Bias instability is the peak-to-peak amplitude of the bias long term drift. It is expressed in °/s or °/h.

Angle random walk (ARW) is a noise contribution to the rotation angle value obtainable by integrating the angular velocity. Standard deviation of noise observed in rotation angle estimation can be written as:

$$\sigma_{\mathrm{rw}} = W_{\mathrm{ARW}}\sqrt{t} \tag{1.1}$$

where W_{ARW} is the angle random walk coefficient, usually expressed in $°/\sqrt{\mathrm{h}}$ or $°/\sqrt{\mathrm{s}}$.

Different noise contributions can be estimated by modeling the noise in angular rate measurement by a stochastic process [17]. A stochastic process $u(t)$ consists of a family of time dependent real functions $u(t,r)$, each of them associated to an element r of a probability space $\Re$. The real function $u(t,r)$ (also denoted as $u(t)$) is called trajectory of the stochastic process. If we consider a stationary stochastic process, its autocorrelation is given by:

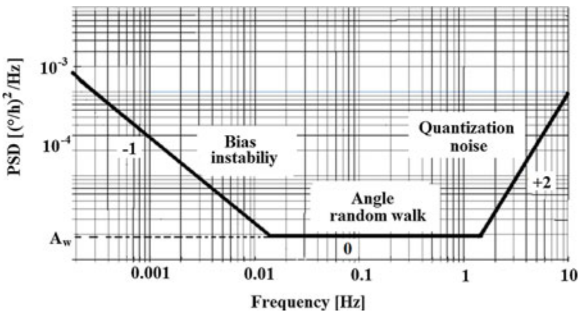

Fig. 1.1 Piecewise representation of noise PSD in the angle rate measurements

$$\phi_u(\tau) = E[u(t+\tau)u(t)] \tag{1.2}$$

where E is the expectation operator. If the stochastic process is ergodic, autocorrelation can be calculated by any trajectory $u(t)$ as:

$$\phi_u(\tau) = \int_{+\infty}^{+\infty} u(t+\tau)u(t)\mathrm{d}t. \tag{1.3}$$

Power spectral density (PSD) of a stationary stochastic process is defined as:

$$\Phi_u(f) = \Im[\phi_u(\tau)] \tag{1.4}$$

where $\Im$ is the Fourier transform operator.

For an ergodic stochastic process, PSD is given by:

$$\Phi_u(f) = |U(f)|^2 \tag{1.5}$$

with

$$U(f) = \Im[u(t)]. \tag{1.6}$$

From Eq. 1.6 it is clear that PSD can be estimated by the Fourier transform of any realization if the stochastic process is ergodic and stationary.

Integrating a stochastic process $u(t)$, we obtain another stochastic process $v(t)$ whose PSD is given by

$$\Phi_v(f) = \frac{1}{(2\pi f)^2}\Phi_u(f). \tag{1.7}$$

When a white noise stochastic process is integrated, a random walk stochastic process (also called Winer-Lévy stochastic process) is obtained [17]. The main feature of the random walk stochastic process is that its variance is proportional to time. A random walk stochastic process models very well the measurement noise on estimation of the rotation angle.

In the PSD log–log plot of data obtained by measuring a constant angular rate (Fig. 1.1), we can distinguish three regions having different slope. The region

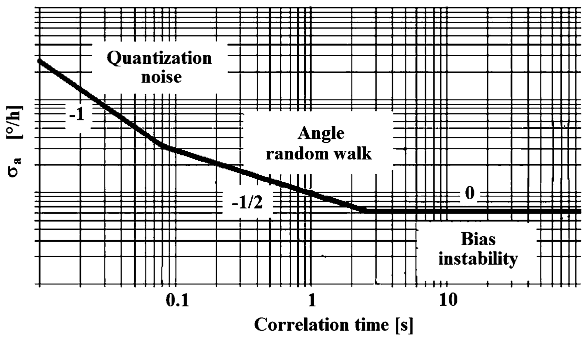

Fig. 1.2 Allen standard deviation of data obtained by measuring a constant angular rate (piecewise representation)

having slope equal to 0 is relevant to angle random walk. This means that the random walk noise is a white noise contribution to the angular velocity estimation. This can be explained observing that the rotation angle can be calculated by integrating the angular rate and, as previously explained, a random walk stochastic process is obtained by integrating a white noise stochastic process.

The region with −1 slope is relevant to bias instability and the region related to quantization noise has a slope equal to +2.

Gyroscope angle random walk coefficient W_{ARW} in °/$\sqrt{}$h is given by [18, 19]:

$$W_{ARW} = \frac{1}{60}\sqrt{\frac{A_w}{2}} \tag{1.8}$$

where A_w is the white noise level of the gyroscope expressed in (°/h)^2/Hz.

Alternatively the amount of noise contributions can be estimated by the Allan variance σ_a^2 [20] of data obtained by measuring a constant angular velocity [20, 22].

Let us denote with Ω_ξ ($h = 1,\ldots, N$) the angular rate data taken at a rate of f_s samples per second. From these N data we can form $K = N/M$ clusters (M is the number of samples per cluster). We can calculate the average for each cluster:

$$\bar{\Omega}_j(M) = \frac{1}{M}\sum_{\sigma=1}^{M}\Omega_{(j-1)M+\sigma} \quad (j = 1,\ldots,K) \tag{1.9}$$

and the Allan variance of angular rate data:

$$\sigma_a^2(\tau_a) = \frac{1}{2(K-1)}\sum_{j=1}^{K-1}\left[\bar{\Omega}_{j+1}(M) - \bar{\Omega}_j(M)\right]^2 \tag{1.10}$$

where $\tau_a = M/f_s$ is the correlation time.

In the log–log plot of $\sigma_a(\tau)$ versus τ_a (see Fig. 1.2), the ARW can be estimated by the plot section having slope equal to −1/2, bias instability by the plot section having slope equal to 0 and quantization can be estimated by the plot section having slope equal to −1.

Table 1.1 Performance requirements for different classes of gyroscopes

Parameter	Rate grade	Tactical grade	Inertial grade
Angle random walk ($°/\sqrt{h}$)	>0.5	0.5–0.05	<0.001
Bias drift (°/h)	10–1000	0.1–10	<0.01
Scale factor accuracy (%)	0.1–1	0.01–0.1	<0.001
Full range (°/h)	1.5×10^5 to 3.6×10^6	$>1.8 \times 10^6$	$>1.4 \times 10^6$
Bandwidth (Hz)	>70	~100	~100

Based on the performance, we can distinguish three different classes of gyroscopes. So we classify inertial-grade, tactical-grade, and rate-grade gyros. Table 1.1 summarizes the gyro performance for each of these categories [23].

Obviously different applications require specific gyro performance. For instance, gyroscopes used in automotive applications requires a full range of at least 1.8×10^5 °/h (=50 °/s), a resolution of about 360 °/h (=0.1 °/s) and a bandwidth of 50 Hz, whereas other applications as autonomous navigation require better performance. Strategic missiles navigation requires a scale factor stability around 10 ppm and a bias stability around 1×10^{-4} °/h. Autonomous navigation of submarines requires a scale factor stability around 1 ppm and a bias stability around 1×10^{-3} °/h.

1.3 Gyro Applications

The fundamental application of gyros is within strapdown inertial navigation systems, used for navigation of ships, submarines, aircraft, guided missiles and other military vehicles. These navigation systems are directly mounted on the vehicle and allow its position and velocity estimation without the support of any signal generated by positioning systems, e.g. GPS (Global Positioning System).

Two basic building blocks of a strapdown inertial navigation system are the IMU and the navigation micro-computer. The IMU, including high performance gyros and accelerometers, measures vehicle angular rate and acceleration. The micro-computer processes data provided by the IMU and estimates vehicle position and velocity.

Satellites orientation is controlled by Attitude and Orbit Control Systems (AOCSs) including different attitude sensors such as gyros, sun sensors, earth sensors, star trackers, magnetometers and so on. Main space application of angular rate sensors is within AOCSs but recently gyros have been successfully exploited for navigation of rover vehicles, too. In particular, rovers developed by NASA and Jet Propulsion Laboratory for Mars exploration were equipped with FOGs [24]. Space applications require gyros having a resolution in the range 0.01–10 °/h.

Antijitter platforms in high quality digital cameras, GPS backup systems, virtual reality devices and gaming consoles are some typical examples of consumer electronics products using low cost gyros having quite limited performance. Usually gyros for consumer electronics are MEMS devices.