Module 12

Modern Navigation Systems

Inertial Navigation, Doppler, and Atomic Clocks

Module 12B

Practical Gyroscopes

Summary of Module 12

- The Keplerian equations from earlier modules are re-examined in terms of conservation of angular momentum, thus yielding expressions for the acceleration versus time of moving bodies. The Schuler frequency is introduced and analyzed in the context of a feedback control system, using as an example problem the inertial navigation of an aircraft flying from Dulles Airport to Beijing. Angular momentum is then re-examined in the context of circus acrobatic performances. (12A)
- **Sensors that can measure these accelerations are explored, including mechanical gyroscopes based on rotating flywheels, mechanical gyroscopes that use micro-electrical mechanical devices (MEMs), and optical gyroscopes that exploit the relativistic Sagnac effect (e.g., the ring-laser gyroscope). (12B)**
- Doppler techniques are introduced using the Cospas-SarSat system as a prototypical example. Students will watch a video that describes Cospas-Sarsat in detail. (12C)
- Atomic clocks and the Allan variance are introduced. A chip-scale atomic clock is described. (12D)
- Students will begin submitting and/or presenting their final projects. (12E)

Reading and Video

- Read about the Sagnac effect and ring laser and fiber optic gyroscopes in the primary text (Kayton & Fried chapter 7).
- If interested, go to the *ST Micro-Electronics* web site and other sites to read more about MEMs sensors
- View the various “mems” and mechanical gyroscopes videos posted to Module 12

The videos

- Gyro precess (12B)
    - This shows how a gyroscope precession changes direction when the direction of rotation of the gyroscope changes
- Gimble1 (12B)
    - This shows the effects of torque on the behavior of a gimbled gyroscope
- iNEMO demos 1, 2 and 3 (12B)
    - These show the operation of the ST Micro-electronics inertial measurement system via the use of a rotation platform and PC-based demo software.

Gyroscopes and accelerometers

- Accelerometers
  - These measure linear accelerations, and can be as simple as mass-spring systems or strain gauges
- Traditional rotating gyroscopes
  - These have rotating wheels, often with deliberately high moments of inertia, so that the angular momentum of the gyroscope stabilizes the system to which it is attached

Accelerometers – from the text

7.3.1 Accelerometers

Purpose An accelerometer is a device that measures the force required to accelerate a proof mass; thus, it measures the acceleration of the vehicle containing the accelerometer. Figure 7.3 shows a black-box accelerometer whose input axis is indicated. The instrument will supply an electrical output proportional to (or some other determinate function of) the component along its input axis of the inertial acceleration minus gravitation. If the instrument is mounted in a vehicle whose inertial acceleration is a and if the vehicle travels in a Newtonian gravitational field G, (Section 2.2), then the force acting on the proof mass m_p is

$$F = m_p a = F_R + m_p G + F_D$$

$$\frac{F_R}{m_p} = a - G - \frac{F_D}{m_p} = f \qquad \text{(accelerometer output)} \qquad (7.1)$$

Gyroscopes – from the text

7.3.2 Gyroscopes

Purpose The purpose of the gyroscopes ("gyros") in an inertial navigation system is to space-stabilize the accelerometers. In gimballed platforms, the gyros measure rotation of the platform, which is angularly isolated from the vehicle's motions. The gyros rotate at inertial angular rates from 0.005 deg/hr to 50 deg/hr, the maximum torquing rate on fast aircraft; a range of 10,000. The gyroscopes are used as error detectors to sense small rotations of the platform relative to the navigation coordinates. A gimbal servo-loop restores the error to near zero (see Figure 7.2 and Section 7.4.2).

In strapdown systems, the gyroscopes are fixed to the vehicle and follow its angular motion. A gyroscope on a military aircraft must sense angular rates as low as 0.005 deg/hr and as high as 400 deg/sec (1,440,000 deg/hr), a range of 8.5 orders of magnitude. Strapdown gyroscopes on civil aircraft need only sense an 8-order-of-magnitude range of angular rates.

Types of gyroscope systems

- Gimbal mounted
  - The gyroscope moves and rotates independently of the platform to which it is attached
- Strap-down
  - The rotation of the gyroscope is locked to the rotation of the body to which it is attached
- Examples of each are shown in the attached videos and in the slides that follow.

A traditional gimbal-mounted mechanical gyroscope

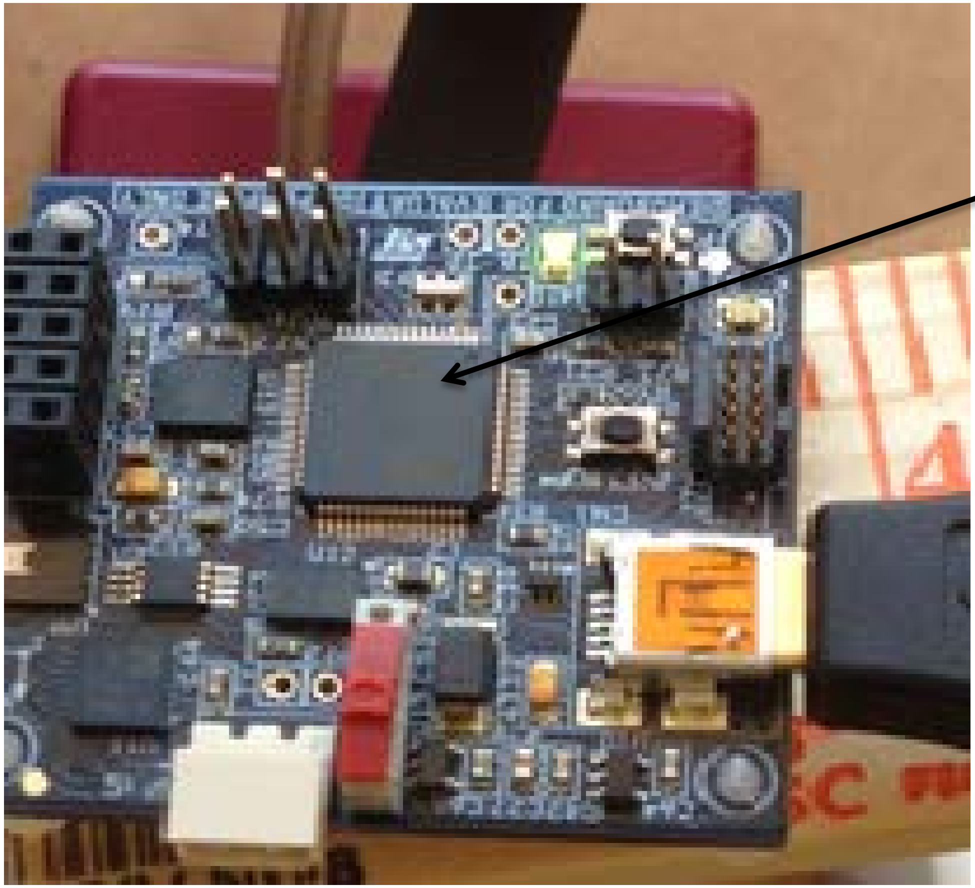
The gyroscope has teflon bearings, and rotates quite well.

The gimbals permit easy observations of the effects of torque in changing the angular momentum as the base platform is tilted.

MEMs-based devices

- Micro-electronic mechnical devices are based on the use of integrated circuit fabrication techniques to produce chips that have moving electrodes inside
- These are configured as capacitors whose electrodes move when the chip is tilted, accelerates, or is rotated.
  - The resulting changes the inter-electrode capacitance are readily measured
- These devices are used as the tilt sensors in iPads, smart phones, Nintendo remotes, etc.
- They are also used in automobiles as pressure sensors

ST Micro-electronics MKI062 3-axis MEMs Navigation Unit



The MEMs integrated navigation chip. The other chips are for power regulation, interface control, etc.

See, for example, https://www.mems-exchange.org/MEMS/what-is.html

Screen shot of the demo software for the ST Micro-electronics 3-axis inertial measurement module

The three graphs indicate inertial forces
in the x, y, and z, directions,
including the 1000 mg earth's gravitational field

From the text, chapter 7

In the 1980s, optical angular sensors were perfected after 30 years of development. They are the mainstay of aircraft inertial navigators in the 1990s and are described in Section 7.3.3. These instruments are called *gyroscopes* to emphasize their function. Research efforts on new gyros are described in Section 7.3.5.

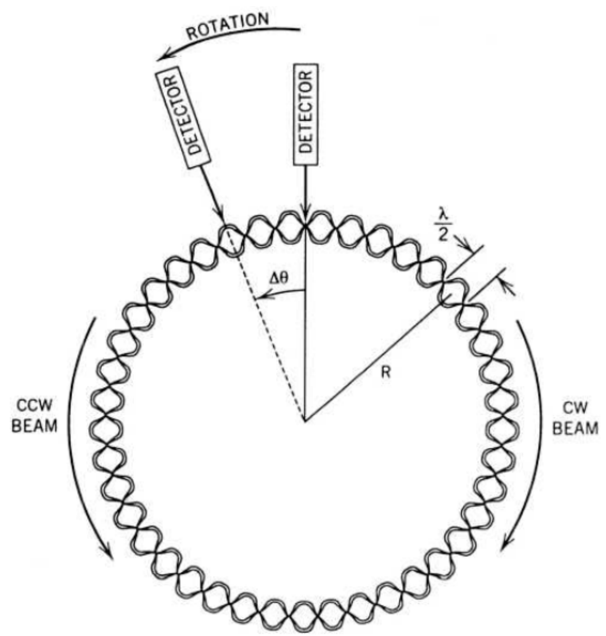
The Sagnac effect

The Sagnac Effect The Sagnac effect [43] is a general relativistic phenomenon relating to the propagation of light in a rotating reference system. When laser beams circulate in a closed path that is rotating in inertial space, the optical length seen by the co-rotating beam appears longer than that seen by the counter-rotating beam. The Sagnac effect permits observation of rotation in one of two different ways.

- In a *resonator* (such as an RLG), the counterpropagating beams form resonant modes within the cavity. These create an electromagnetic standing wave that remains fixed in inertial space [1] . When the housing of the gyro rotates, a detector can count nodes of the standing wave, each of which represents a fixed increment of angle (see Figure 7.7).
- In an *interferometer*, counterpropagating beams are launched into an optical path and recombined as they exit. The interference generated by the recombination depends on the optical phase difference (proportional to the optical path difference) between the two beams and therefore provides a measure of rotation. In 1996 most fiber optic gyros were configured as interferometers. Fiber-optic gyros may also be constructed as resonators but the absence of a gain medium and the relatively high losses of the fiber rendered this type of device impractical in 1996.

From the text

The Sagnac Effect



- Interference between CW and CCW beams creates standing wave pattern
- Standing wave pattern stays fixed in inertial space
- As gyro case rotates, detector moves around ring and counts minima
- Scale factor correspondence:

$\lambda/2$ circumferential displacement $= 2\pi$rad optical phase shift

$\Delta\theta$ mechanical rotation $= (4\pi R/\lambda)\ \Delta\theta$ optical phase shift

Figure 7.7 Circular ring laser gyro.

An illustration of the Sagnac effect from the primary text (Kayton and Fried).

A ring-laser gyroscope

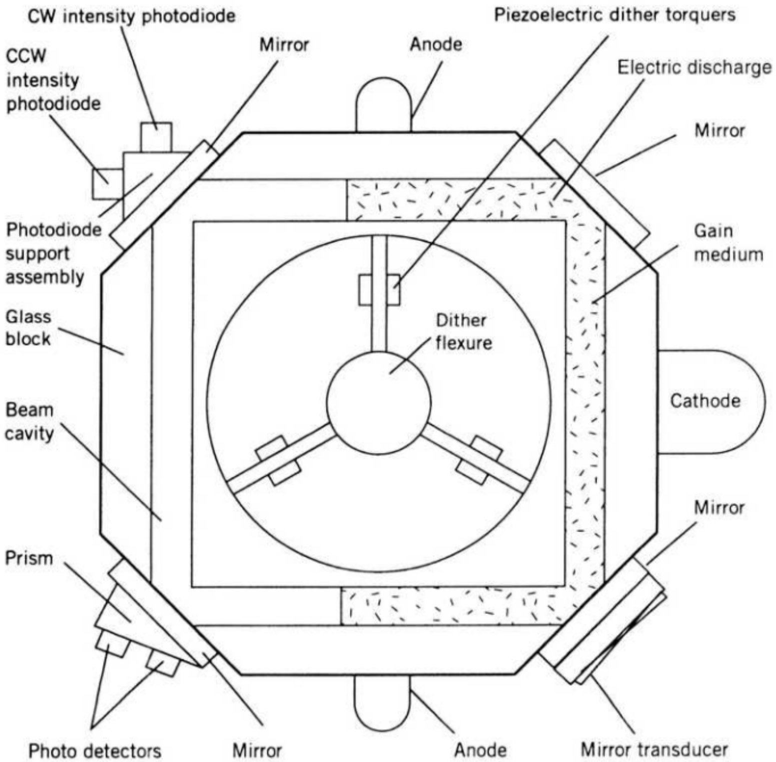


Figure 7.6 Two-mode ring laser gyro (courtesy of Litton Guidance and Control Systems).

Light waves from a laser travel in opposite directions from mirror to mirror, thus setting up a standing wave that has easily detectable Interference fringes.

The Sagnac effect causes these fringes to remain stationary as the body of the gyroscope rotates.

Light detectors count and "time" the fringes as they pass the sensors when the body of the gyroscope rotates.

Assignment 12-2

1. Explain succinctly the relationship between medical MRI, microwave YIG filters, mechanical gyroscopes, and the precession of the orbit of a planet (including earth) around the sun. In particular, why is it that GHA♈ implies a vector that points to the constellation Aries, when in fact it currently does not. (Hint, read the very end of the *Measure* article from the earlier module).
2. Give an example where a gyroscope is used as a sensor, and an example where the angular momentum of the gyroscope actually serves to stabilize a platform.

End of Mod 12B