Theory of Gyroscopes

Chapter · May 2012

DOI: 10.1007/978-1-4614-3978-3_3

2 authors:

Jan Awrejcewicz
Lodz University of Technology

Zbigniew Koruba
Politechnika Świętokrzyska

Chapter 3
Theory of Gyroscopes

In this chapter, first a historical outline of the theory of gyroscopes is given. Elements of gyroscope classification are introduced, and then the evolution of the gyroscope concept is presented. In particular, the following gyroscope-type devices are considered: the directional gyroscope, the gyroscopic vertical, the stabilized gyroscopic platform, the laser gyroscope, the fiber-optic gyroscope, the piezoelectric gyroscope, the fork gyroscope, and the microgyroscope with a spinning disk and with a vibrating ring. Examples of devices for gyroscopic navigation and an observation device with a built-in gyroscope are provided. Finally, new challenges for gyroscopes are briefly summarized.

3.1 Elements of Gyroscope Classification

Presently, one can distinguish many types of gyroscope with regard to accepted criteria. Mostly, one classifies gyroscopes by the following criteria [1–3]:

1. Principle of operation:
   (a) Mechanical
   (b) Laser
   (c) Nuclear
2. Number of degrees of freedom of a gyroscope rotor:
   (a) One degree of freedom (one-step)
   (b) Two degrees of freedom (two-step)
   (c) Three degrees of freedom (three-step)
3. Type of suspension:
   (a) With Cardan suspension (external and internal)
   (b) Without Cardan suspension

J. Awrejcewicz and Z. Koruba, *Classical Mechanics*, Advances in Mechanics and Mathematics 30, DOI 10.1007/978-1-4614-3978-3_3,

4. Mutual position of intersection points of suspension axis (center of suspension) and center of rotor mass:
   (a) Astatic (center of suspension coincides with center of mass)
   (c) Non-static ("heavy")
5. Cardan-free (spherical mostly) gyroscopes with respect to suspension type:
   (a) Gasostatic
   (b) Gasodynamic
   (c) Floating
   (d) Electromagnetic
   (e) Electrodynamic
   (f) Cryogenic
6. Type of rotor:
   (a) With stiff rotor
   (b) With an elastic rotor
   (c) With liquid rotor
7. Constraints imposed on the rotor by the suspension:
   (a) Integrating
   (b) Differentiating
8. Dynamically tuned gyroscopes with respect to mutual ratio of centrifugal and elastic torques.

Generally, we can divide gyroscopes into three large classes (Fig. 3.1): (1) sensor, (2) navigation, (3) force.

Sensor gyroscopes are used as measuring devices and are located on a movable base. Navigation gyroscopes serve to determine a horizon plane and meridian. Force gyroscopes generate controlling torques in systems of angular stabilization and vibration damping (e.g., flatter types) and serve as stabilizing platforms in the targeting and tracking systems (e.g., cannons, missiles).

3.2 Evolution of Gyroscope Concept

In recent decades, the notion of the gyroscope has seen increasingly broader application. Presently, we call gyroscopes not only classical mechanical systems composed of a spinning rotor and elements of the rotor suspension, but also external devices that somewhat resemble the aforementioned mechanical system. In particular, in vibrating gyroscopes, the free motion of the rotor can take the form of translational or angular vibrations. A rotating or vibrating liquid can serve as a rotor in vibrating, hydrodynamical, or magnetohydrodynamical gyroscopes.

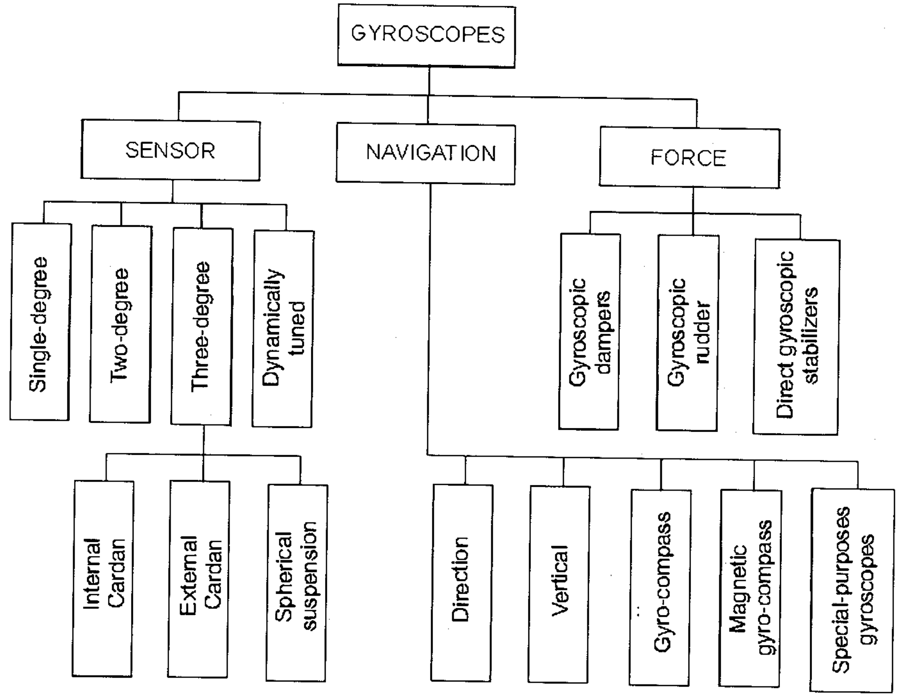


Fig. 3.1 Classification of gyroscopes

In molecular gyroscopes, carriers of angular momentum are particles—electrons, protons, neutrons, nuclei, or atoms. However, a general characteristic of gyroscopes, without regard to form, is that they contain angular momentum carriers.

The term "gyroscope" in recent decades has become increasingly broad. The word derives from the literal sense of an indicator of turns, rotation. Thus, by gyroscope we understand any device that allows one, e.g., without contact with the environment, to measure the rotation of a base relative to an inertial frame. Hence, we focus on gyroscopes such as optical, laser, and polarization gyroscopes and those based, e.g., on the interference of de Broglie waves of particles.

Initially, the concept of gyroscope was introduced by the French physicist Foucault as a name for a balanced, fast-spinning rotor in a uniaxial or biaxial Cardan suspension, incorporating the property of detection and measurement of rotations of a base. The name started to be applied as a general term for any device that had this property. In the literature, one can find nearly 100 physical phenomena that can be used to autonomously detect and measure turns, i.e., to build a gyroscope. In practical terms, just few of the physical phenomena are used. Until now, are applied the Foucault gyroscopes in a mechanical, stiff, fast-spinning rotor in a Cardan suspension. In order to unload bearings, one uses hydrostatic (floating) suspension.

Spherical gyroscopes with aerodynamic, electrostatic, and magnetic suspensions have gained widespread usage. The most modern solutions include gyroscopes with a cryogenic, magnetic suspension relying on superconductivity. A typical example of gyroscopes in the extended meaning of this notion, i.e., not having carriers of angular momentum, is a laser gyroscope. Nowadays, gyroscopic devices are used mainly on moveable objects such as airplanes, ships and submarines, rockets, and satellites. Their task is to navigate those objects and their orientation with respect to the assumed reference frame, stabilize the motion of an object relative to a given trajectory and automatically control this motion, and spatially stabilize devices located on-board a movable object.

3.3 Fundamental Stages of Gyroscope Development

The phenomenon of preserving the position in inertial space of a fast-spinning body around its symmetry axis was known in ancient times. For a long time, amazing feature (which seems at first glance to contradict the fundamental laws of nature) of a spinning body has not found its practical application. This feature was used only to build simple toys known as "humming tops." A humming top attracted the attention not only of children but of many outstanding scientists as well. It was Newton (1642–1727) who analyzed the behavior of a humming top for the first time. The theory of the gyroscope is based on a branch of mechanics dealing with the rotational motion of a rigid body around a fixed point. For this reason, the fundamentals of the theory of gyroscopes were studied along with the development of celestial mechanics. In the initial stages of the history of mechanics, was observed that spinning bodies were simply huge humming tops, having all the specific properties of spinning bodies. Research in the field of celestial mechanics was performed by L. Euler (1707–1783) (who created the theory of nutation of the Earth's axis and the theory of lunar libration), and his derivation of equations of the rotational motion of a rigid body around a fixed pivot point in the work *Theory of the Motion of Rigid Bodies*, published in 1765, became a fundamental contribution to the contemporary theory of gyroscopes. Further development of the theory of spinning bodies ensued in the works of Lagrange (1736–1813), Poinsot (1777–1859), and other brilliant scientists such as D'Alembert and Laplace, Kovalevskaya, Somov, Bobyliev, and Zhukovski [4–6].

The applied theory of gyroscopes, i.e., the theory of devices and gyroscopic systems, emerged mainly in the twentieth century; however, the first attempts at practical application of gyroscopes had been made much earlier.

In 1752 *Serson* suggested making use of a spinning body to obtain an "artificial horizon" on a ship [2]. Unfortunately, the attempt to apply this invention on the frigate *Victory* had a tragic end not only for the ship (which sank) but also the inventor himself. Thus, no attempt was made to apply a similar invention for the next hundred years, and the humming top remains merely a toy.

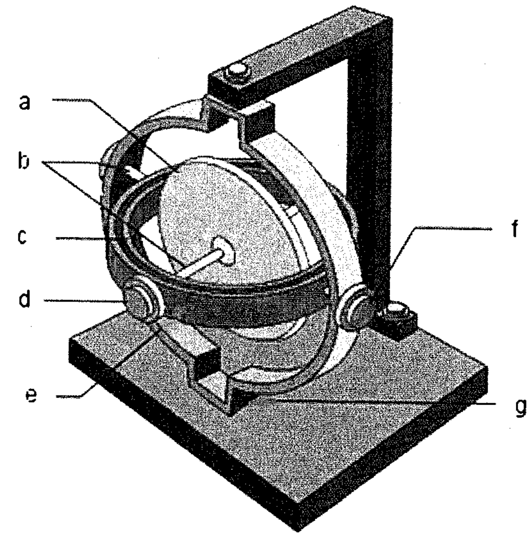


Fig. 3.2 Foucault gyroscope: (**a**) Rotor. (**b**) Spin axes. (**c**) Internal frame. (**d**) Internal joint. (**e**) External frame. (**f**) External joint. (**g**) Base

In the nineteenth century, *L. Foucault* decided to prove experimentally the existence of the Earth's rotation. To this end, he put a fast-spinning, axially symmetric body in a Cardan joint. He first presented the device (Fig. 3.2) at the meeting of the Paris Academy of Sciences in 1752 and called it a *gyroscope* (from the Greek *giros*, spinning, and *skopeo*, observe).

The French physicist investigated a gyroscope (gyro). However, not all the results were convincing due to technical difficulties, which were not overcome before the turn of the twentieth century. The main difficulties concerned the considerable friction in the bearings of the Cardan suspension rings and others related to the rotor drive's not allowing for a high and constant angular velocity to be maintained.

In those days an urgent need arose to build a device that could replace the magnetic compass because the operating conditions of the compass got worse on ships with steam engines and steal frames compared to the compass's operation on wooden sailboats. Foucault demonstrated the possibility of using a gyroscope to determine a meridional line at a given latitude [4]. Thus, the idea of a gyrocompass was presented for the first time. However, due to incorrect calculations on the value of period of free vibrations of the device and to technical difficulties, a gyrocompass that would be useful in practical applications could not be built sooner than in the early twentieth century. Since Foucault's experiments, the history of the development of gyroscopes has involved the continuous pursuit of lower disturbing torques that affect rotors and an increase in the angular velocity of gyroscopes.

In 1898, a lieutenant of the Austrian army, *Obri* [3], started using a gyroscope in practical applications. He built one with three degrees of freedom whose rotor was set in motion by means of the energy of compressed air. Slight friction in the Cardan suspension bearings was achieved with the application of ball bearings. Such a device was applied to stabilize a torpedo.

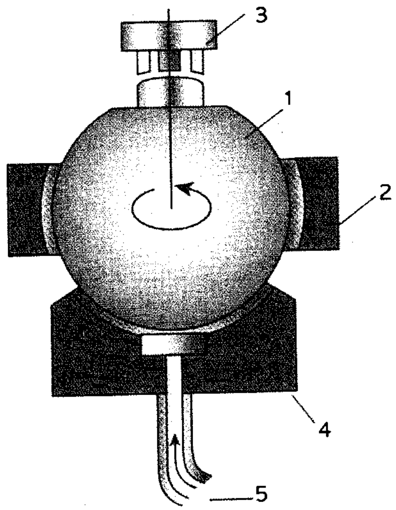


Fig. 3.3 Sperrs gyroscope: 1—steal rotor; 2—stator producing a rotational magnetic field; 3—sensor whose signals enable one to follow the ball axis on a swinging base (ship); 4—bronze bowl separated from rotor by layer of air of micrometer width; 5—inflow of compressed air suspending gyroscope

In 1905, the German engineer *Herman Anschütz Kaempfe* patented a gyrocompass, which was tested in practice. A few years later, in 1911, an American, *Elmer Sperry*, built another type of gyrocompass (Fig. 3.3). Thanks to continual improvements in these types of compass, they have been used on warships for many years [5, 6].

When *Zhukovski*'s works were published in 1912, new possibilities in the application of gyroscopic devices appeared [4, 6]. Zhukovski proposed mounting a gyroscope in an airplane in order to improve stability of flight. In that case, a gyroscope served as an actuator, by means of which controlling and damping torques were produced. In the 1920s, Soviet inventor *S.A. Nozdrovskiy* worked out a system for a gyroscopic stabilizer. Presently, gyroscopic actuators are widely applied in systems of angular stabilization of spaceships.

Gyroscopic tachometers were initially used in aeronautics as indicators of turn, and then in artillery of naval guns to determine the angle of shot lead. They found very wide applications in control systems of flying objects (automatic pilot), in gyroscopic stabilizers, and in systems of indirect stabilization. As aviation developed, vertical gyroscopes and course gyroscopes were commonly used as pilotage instruments, necessary for blind flights, i.e., flights without any visual external reference on the ground.

Integrating gyroscopes have been widely applied since no earlier than the second half of the twentieth century in the form of floating-integrating gyroscopes, which allowed one to obtain small drifts of the gyroscope axis.

In 1963, *E.W. Howe* worked out a gyroscope called a *dynamically tuned gyro*, or a gyroscope with an elastic suspension [7, 8].

The rotor of such a gyroscope is suspended on a Cardan joint (Fig. 3.4), where there is no bearing of the frame joint, which is made of elastic elements [9–11], e.g., torsion bars (Fig. 3.5).

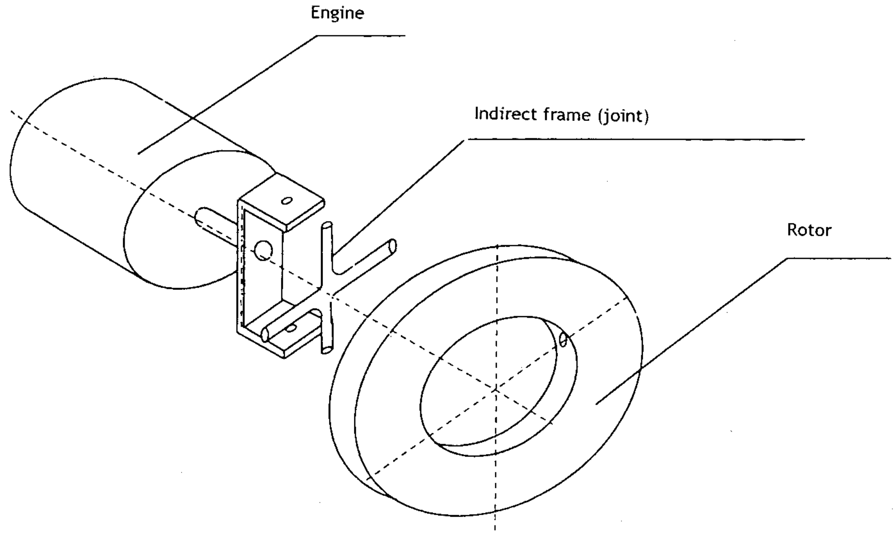
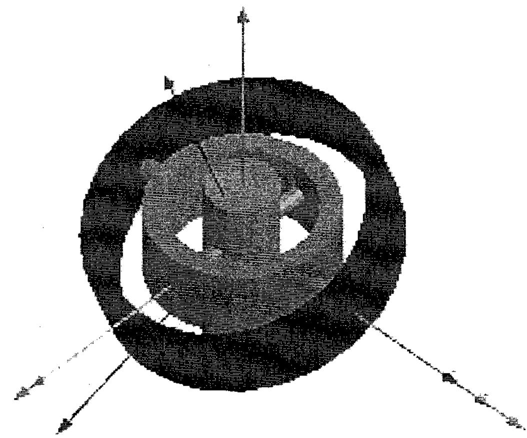


Fig. 3.4 Gyroscope with a rotor suspended on a Cardan (Hooke) joint

Fig. 3.5 Dynamically tuned gyroscope



However, in his gyroscope, Zhukovski made use of the dynamical effects of inertia of a Cardan suspension frame to eliminate the elastic torques of torsion bars. It has become one of the most commonly produced velocity gyroscopes. It finds application mainly as a sensor in autonomous orientation referencing systems, inertial navigation, and stabilization of various objects such as aerial, marine, and land objects.

Presently, a free gyroscope enjoys the most common usage in navigation instruments.

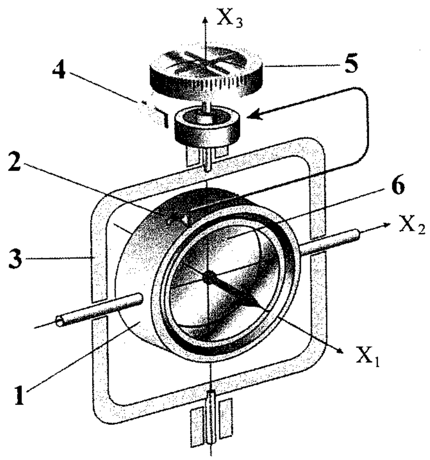


Fig. 3.6 Schematic diagram of a course gyroscope [8]: 1—internal frame; 2—gravitational sensor; 3—external frame; 4—pointer; 5—course disk; 6—gyroscope rotor

3.3.1 Directional Gyroscope

This is an on-board instrument used to determine the course of a flying object (FO). A fundamental element of the device is a gyroscope of three degrees of freedom with a main axis lying in the plane of horizon (Fig. 3.6). The axis of the external frame is perpendicular to the plane of the FO board. A directional gyro does not determine a constant direction (e.g., northern), but it can maintain an arbitrarily chosen direction, which can be regarded as a reference direction.

A correction system for the device is composed of a gravitational sensor and a corrective engine. Its objective is to maintain the rotor axis in the horizontal plane. As the course of the FO changes, the external frame moves relative to the gyroscope body. A disk with an angular scale on it allows one to read the change in the FO's course relative to the fixed stroke in the case window. In early solutions (despite the corrective systems), deviation of the gyroscope axis off the given position was even 15° per hour. Nowadays, this deviation can be only 0.5° per hour in improved systems.

3.3.2 Gyroscopic Vertical

This is an on-board device to measure the deviation of the FO off the horizontal and vertical planes. Its main element is a gyroscope of three degrees of freedom whose rotor axis is set vertically and suspension-frame axes are placed according to the tilt and inclination axes of the FO (Fig. 3.7).

Gravitational sensors, located on the gyroscope body (internal frame), measure the angular deviation of the angular momentum axis off the vertical and make the

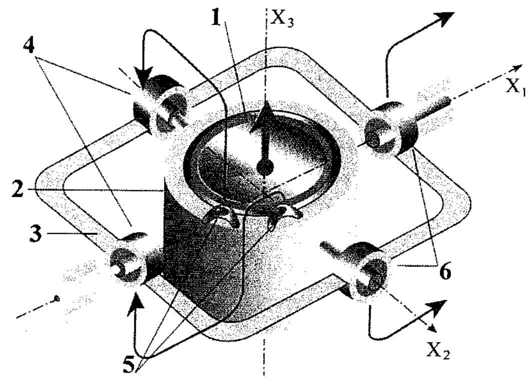


Fig. 3.7 Scheme of gyroscopic vertical [8]: 1—rotor; 2—internal frame; 3—external frame; 4—torque engines; 5—gravity sensors; 6—selsyns (angular position sensors)

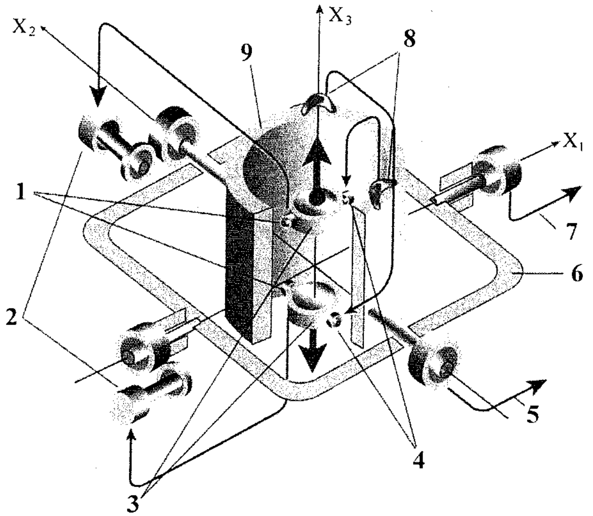


Fig. 3.8 Schematic diagram of a biaxial stabilized gyroscopic platform [8]: 1—angular position sensors; 2—correction engines; 3—internal frames; 4—torque engines; 5—inclination angle signal; 6—external frame; 7—tilt angle signal; 8—gravitational sensors; 9—stabilized element (platform)

correcting engines operate. The engines make the gyroscope move in precession, which eliminates deviations. Changes in the angular position of the FO are measured by selsyns or other sensors placed on the axes of both frames.

3.3.3 Stabilized Gyroscopic Platform

This is an on-deck device to precisely measure the vertical and course or simultaneously to measure the vertical and course of an Flying Object (FO). A biaxial stabilized, gyroscopic platform (Fig. 3.8) acts as a gyroscopic vertical. Two gyroscopes of two degrees of freedom are placed such that the axes of their suspension frames are mutually perpendicular and parallel to the axis of the platform and external frame of the platform suspension, respectively, while the axes of the

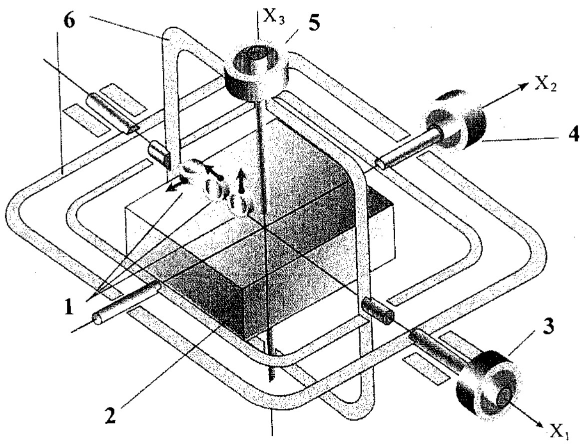


Fig. 3.9 Schematic diagram of four-axial stabilized gyroscopic platform [12] (www.docstoc.com/docs/19589480/Gyroscope.htm): 1—gyroscopes of two degrees of freedom; 2—stabilized elelement (platform); 3—tilt sensor; 4—inclination sensor; 5—course angle sensor; 6—suspension frames

gyroscope's rotors coincide with the vertical axis of the system. Maintaining the axes of rotors in the vertical position is ensured by a corrective device composed of a gravitational sensor and correcting engine. Precession of the gyroscopes generated by disturbing torques on the suspension axes is compensated by torques generated by sensors of inclination connected with corrective engines. Selsyns (or another sensor of angular position) placed on the axes of the platform and external frame produce output signals of tilt and inclination angles.

One can obtain complete information about the spatial position of the FO without angular limitations by means of a four-axial stabilized gyroscopic platform (Fig. 3.9).

The FO can rotate without disturbing the position of the stabilized element, in which there are three gyroscopes of two degrees of freedom such that their measuring axes are parallel to the axes X_1, X_2, X_3 of the system. Sensors of angular position on the axes X_1, X_2, X_3 generate tilt and inclination signals of the course, respectively.

3.3.4 *Laser Gyroscope*

The most modern solutions include an optical gyroscope, which makes use of the phenomenon of change in the propagating light wave. With regard to the lack of mechanical systems, optical gyroscopes are insensitive to rapid maneuvres and experience neither precession nor blocking. In early constructions of optical gyroscopes, there was a blurring of the fiber-optic block, which made the system life shorter, to about a year. Presently produced optical gyroscopes have a service life of about 60,000 h. They are able to measure angular velocities from 0.1°perhour to several hundreds of degrees per second.

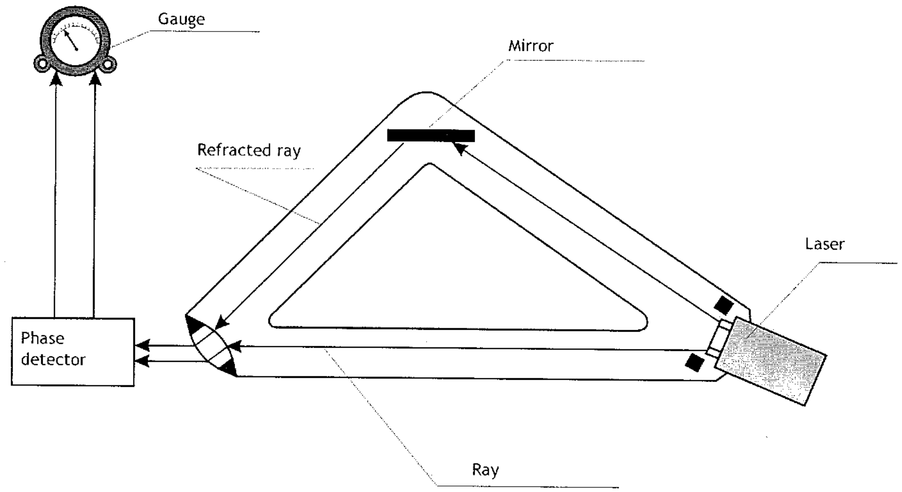


Fig. 3.10 Principle of operation of a laser gyroscope (www.meos.com/Laser_Metrology/laser_gyroscope.htm)

Optical gyroscopes can be classified as (1) laser and (2) fiber optic (www.alphapiezo.com/ring_laser_gyroscope.htm). The most typical example is the *laser gyroscope*, in which coherent light beams from a laser circulate a toroidal resonator in opposite directions. A rotation of the device in the resonator plane makes the frequency in both beams change in accordance with the Doppler effect. The frequency of the beam circulating the resonator in the direction coincident with the rotation decreases and increases in the opposite direction. The sensitivity difference is proportional to the angular velocity. In a photodetector, placed in the output of the system, one obtains a difference signal as a result of the coincidence of both bands. This signal can be used for navigation purposes.

In a laser gyroscope, one applies the method of comparing phases of laser rays running in a triangular fiber optic (Fig. 3.10). The phases of a linear and refracted ray are compared by a detector, transmitting a signal that is proportional to the difference of these phases. When the base of a gyro does not change its position, then the phases of both rays are identical and the pointer points to zero. At the moment of position change, rays of distinct phases reach the detector and the gauge shows the angular velocity of this change.

3.4 Fiber-Optic Gyroscope

Another example of an optical gyroscope is a fiber-optic one, which contains long optical fibers, wound in a coil, that make the instrument more sensitive [8] (www.alphapiezo.com/ring_laser_gyroscope.htm).

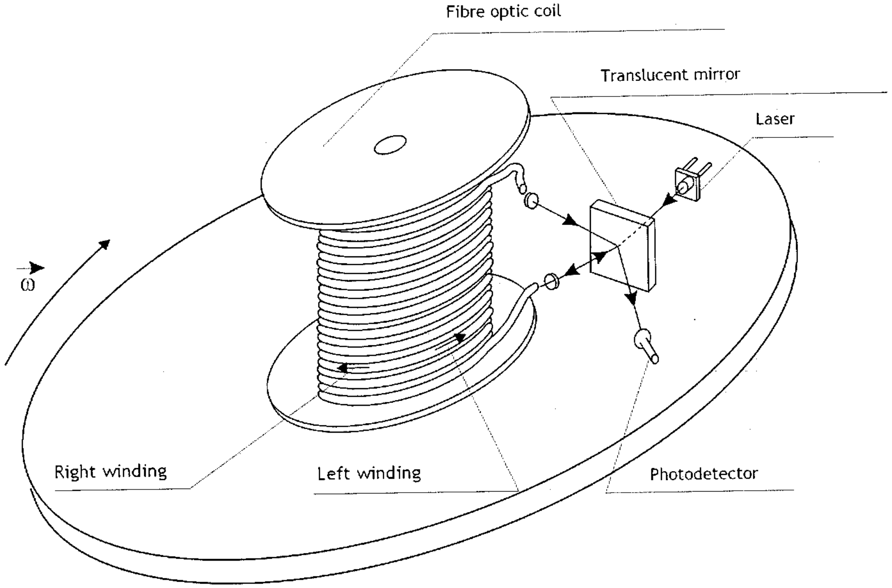


Fig. 3.11 Fiber-optic gyroscope scheme

In a fiber-optic gyroscope (Fig. 3.11), the sensitivity limit is lowered due to resonance phenomena. One measures the difference between the distances traveled by the ray in the left and right fiberglass. During coil rotation, a phase shift appears between the light rays, and when they are superposed on a half-transparent mirror, the resultant force of light follows changes in the angular velocity. The larger the coil area, the larger the phase shift, and sensitivity grows as the number of coils increases. This method is passive since an independent laser source is used. This device allows one to measure angular velocities up to 10^{-8}rad/s.

3.5 Piezoelectric Gyroscope

A modern vibrating piezoelectric gyroscope is designed and produced on a quartz crystal. The principle of operation is based on making use of vibrations, which increase the thickness of piezoelectric materials. Trihydrate lead acetate is a fundamental compound used to produce these gyroscopes. A thin layer of this compound is coated on the substrate Pt/Ti/SiO_2/Si.

The final steps in assembling a piezoelectric gyroscope are depicted in Fig. 3.12. A thin layer of Lead Zirconate Titanate (LZT) is coated on the substrate by means of a sol-gel method. PZT is coated layer by layer, by rotating at high velocity, on a titanium/platinum electrode at 3, 500°C for 20 s. Next, it is annealed at a temperature of 700°C for 3 h to increase strength and crack toughness. After this process, on the

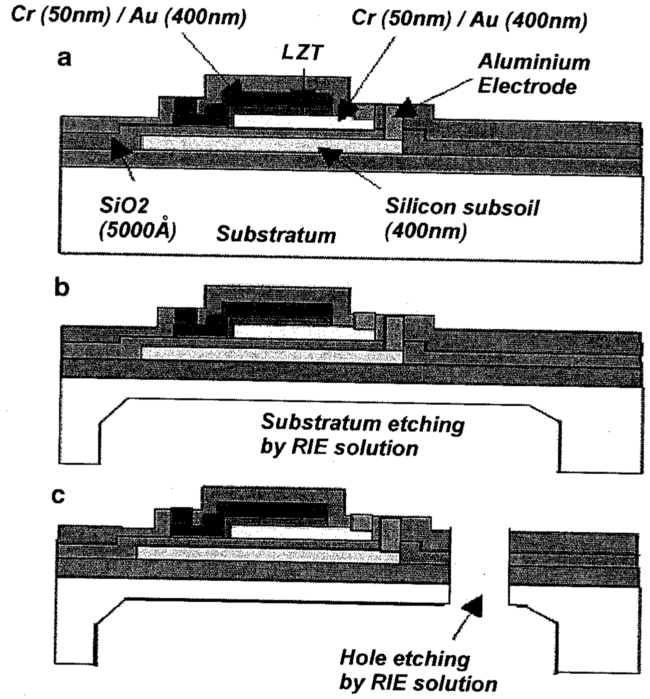


Fig. 3.12 Manufacturing a piezoelectric gyroscope (www.microstrain.com/3dm-gx1.aspx.)

layer LZT is sprayed layer of chromium/silver. It is the top electrode. The whole structure undergoes oxidization and pickling to obtain a suitable structure so that the gyroscope can operate.

The top view of four sensors of a piezogyroscope is shown in Fig. 3.13, where F_1 denotes the force caused by vibrations of the central mass and F_2 is the Coriolis force. Each sensor of dimension $388 \times 800\mu$m possesses a middle layer of a piezoelectric material, PZT, and top and bottom electrodes.

If we apply a signal of a particular frequency to the IN port, we obtain the piezoelectric effect. Sensors 1 and 3 start to vibrate at a frequency that is equal to the frequency of the input signal and make the central mass vibrate. The frequency of its vibrations is the same as that of elements 1 and 3.

A gyroscope is situated parallel to the X_1X_3 plane and set in rotational motion around the X_3 axis. Then, piezoelectric elements 2 and 4 experience cyclic changes in velocity in the X_2 direction. The Coriolis force, acting in the X_1 direction, is generated as a result of changes in the vibrations and angular velocity and has the form

$$\mathbf{F}_C = 2m\mathbf{V}_{X_1} \times \boldsymbol{\Omega}. \tag{3.1}$$

In (3.1) m is the mass of the central element. The Coriolis force can be regarded as a shear force in sensors plates 2 and 4, acting in the X_1X_3 plane and in the

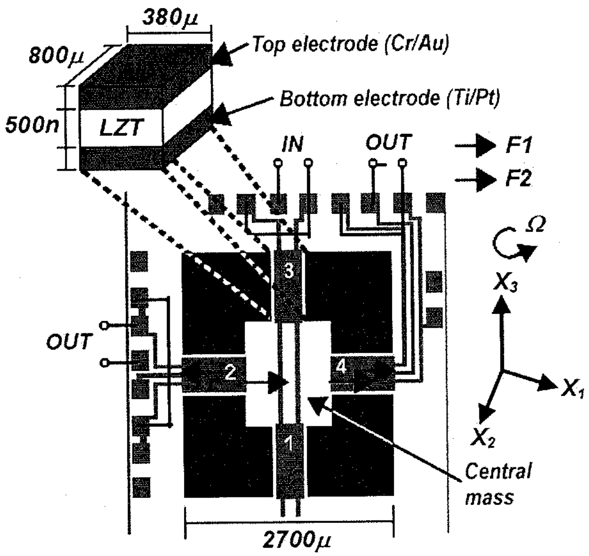


Fig. 3.13 Principle of operation of a piezoelectric gyroscope (www.microstrain.com/3dm-gx1.aspx.)

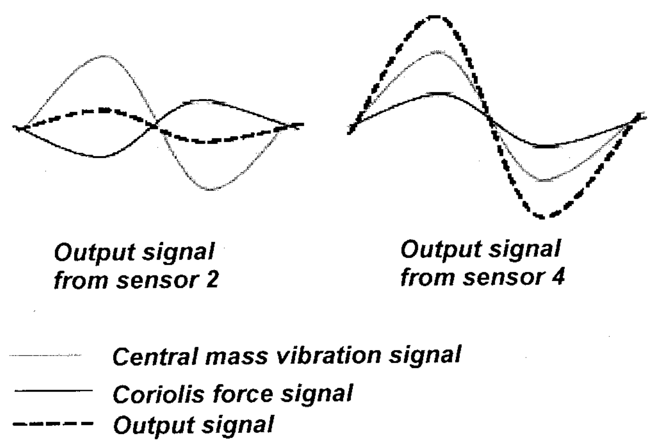


Fig. 3.14 Principle of operation of a piezoelectric gyroscope (www.microstrain.com/3dm-gx1.aspx.)

X_1 direction. It cause the emergence of an electric field that acts in the X_2 direction. Thus, a voltage appears on electrodes of elements 2 and 4. Since the output signal is a consequence of the Coriolis force, its frequency is exactly the same as the frequency of vibrations of a central mass, which is equal to the frequency of the output signal.

Two output sensors give two different signals, depending on the value of the angular velocity. The Coriolis force is generated in sensor 2 (Fig. 3.14) in the positive direction and in sensor 4 in the opposite direction. Two output signals, generated in sensors 2 and 4 are depicted in the Fig. 3.14.

The output signal, generated by vibrations of sensor 2, is in the same phase as the signal coming from the vibrating mass. While the amplitude of the output signal decreases as the angular velocity increases, the amplitude of the output signal in sensor 4 increases as the angular velocity grows.

3.6 Fork Gyroscope

These are electromechanic gyroscopes assembled on a silicon crystal with vibrating forks. They are driven by electrostatic force, while the Coriolis force is read as a change in the capacitance of the microcapacitors. Additionally, the module contains capacitors that measure feedback forces and for voltage application fix the resonance frequency of the forks.

Two separate masses A and B (Fig. 3.15), connected with the frame, will be excited by an electrostatic force after voltage is applied to electrode C, and they will in the X_1 direction. Their motion is guided by combs. The angular velocity in the X_2 direction will force the plate to vibrate, and the vibrations will be detected. The forks are affixed to supports D and E. The external electrodes F and G are used to control the amplitude and phase of mechanical vibrations. Three plates of the capacitor are located in the masses A and B to measure the Coriolis force (signal of the gyroscope effect) for the feedback force and for voltage application to fix the twisting resonance frequency.

A rotation relative to the axis perpendicular to the gyroscope generates the Coriolis force, which is perpendicular to the plane of the fork module. This force makes the masses move in the X_1 direction (Fig. 3.16). It causes changes in volume

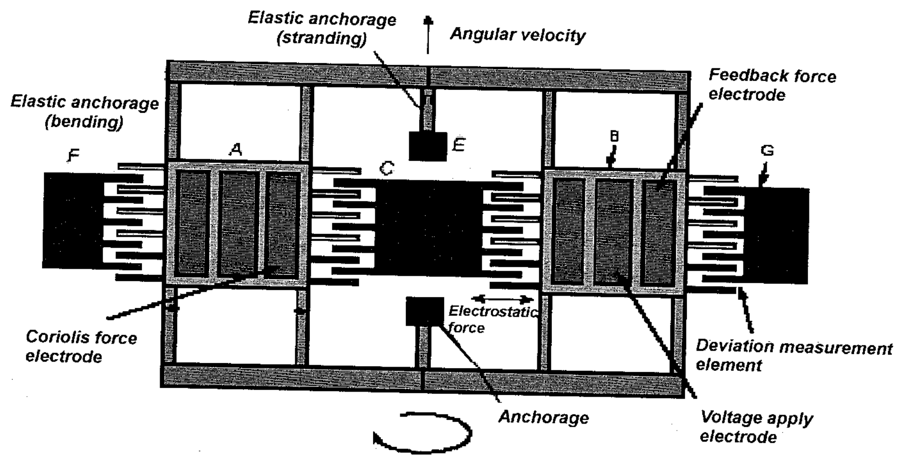


Fig. 3.15 Principle of operation of a fork gyroscope [8] (www.microstrain.com/3dm-gx1.aspx.)

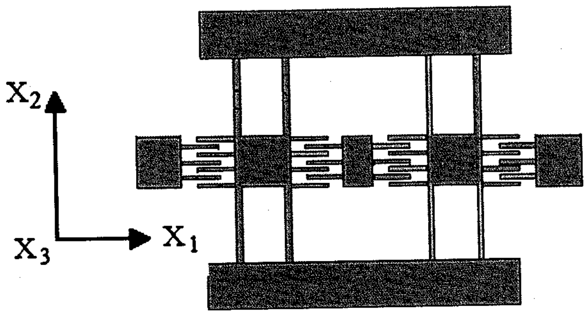


Fig. 3.16 Coriolis force in a fork gyroscope [8] (www.microstrain.com/3dm-gx1.aspx.)

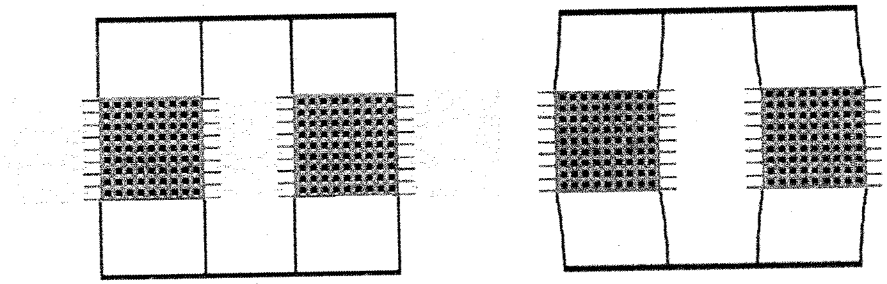


Fig. 3.17 Generation of the gyroscope effect [8] (www.microstrain.com/3dm-gx1.aspx.)

between the forks of mass and the frame. Thus, the amplitude of the vibrating-fork displacements is a basis for determining of the gyroscopic effect (Fig. 3.17).

3.7 Microgyroscope with a Spinning Disk

These gyroscopes possess a thin, magnetic levitating disk that spins at very high angular velocity. This high spinning velocity allows it to attain the gyroscope effect. When a sensor rotates at constant angular velocity with respect to an arbitrary axis, levitation forces make the disk move in precession, and it inclines at some angle. The inclination is proportional to the speed of rotation of the gyroscope (Fig. 3.18).

3.8 Microgyroscope with Vibrating Ring

A microgyroscope with a vibrating ring is composed of a ring, eight semicircular spring supports, and leading, detecting, and controlling electrodes (Figs. 3.19 and 3.20).

The symmetric structure of the gyroscope requires applying at least eight elastic supports to keep the ring in equilibrium. The ring is subject to the action of two elliptically shaped bending waves. The vibration ring is excited electrostatically.

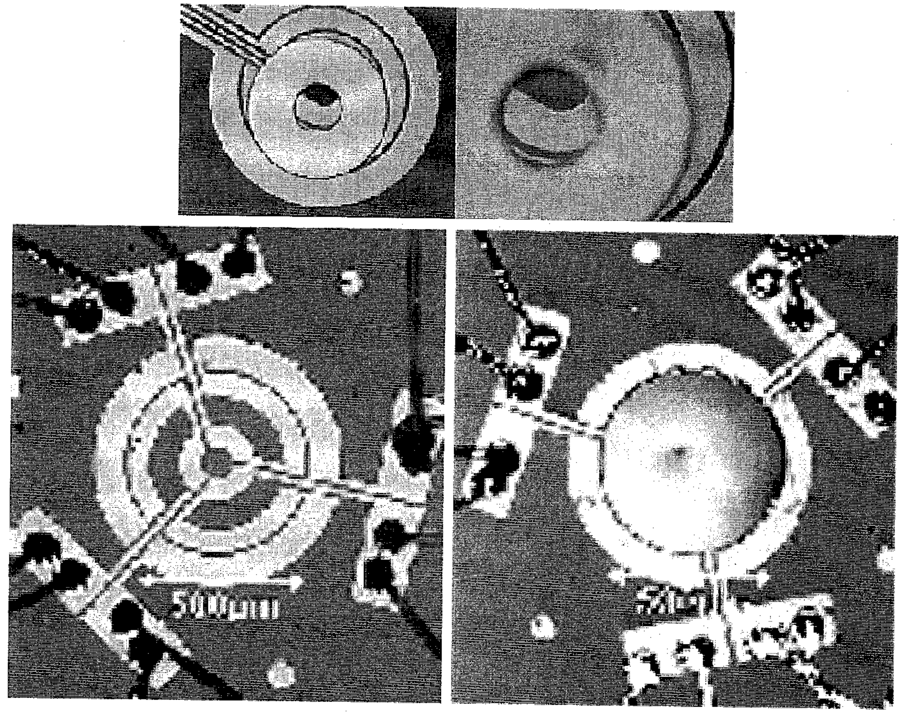


Fig. 3.18 Microgyroscope with spinning disk [8] (www.microstrain.com/3dm-gx1.aspx.)

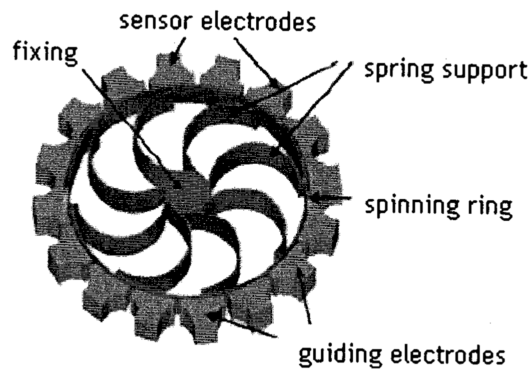


Fig. 3.19 Microgyroscope with vibrating disk [8] (www.microstrain.com/3dm-gx1.aspx.)

When the gyroscope is at rest (does not spin), the ring vibrates in the first mode of bending at a fixed amplitude. When the gyroscope is set in motion in the rotational motion about the normal axis, the Coriolis force makes a transition from the first bending mode to the other. Then the nodes and maxima are displaced at 45° (Fig. 3.21). The amplitude change is then detected by the electrodes as the capacitance changes. Finally, the signal is transmitted to the reading instruments.

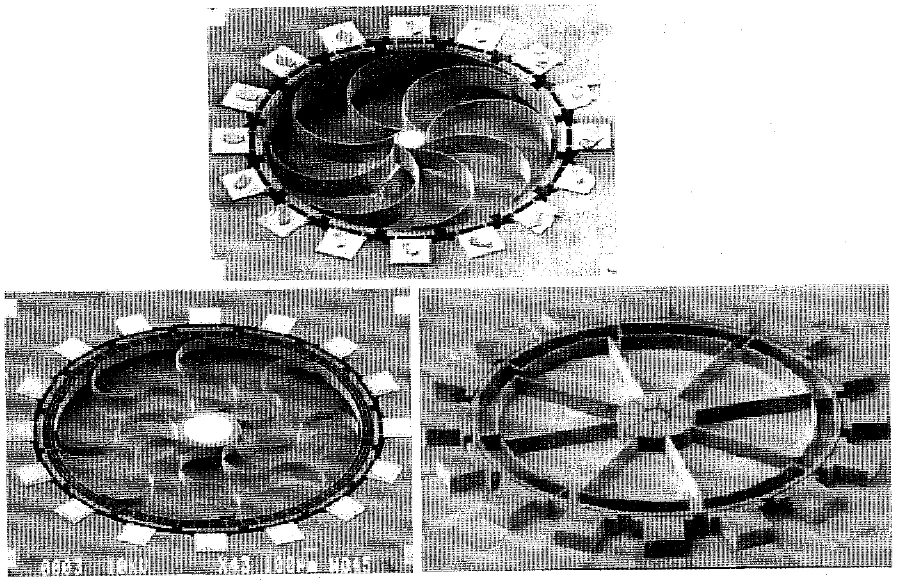


Fig. 3.20 Types of gyroscopes with a vibrating ring

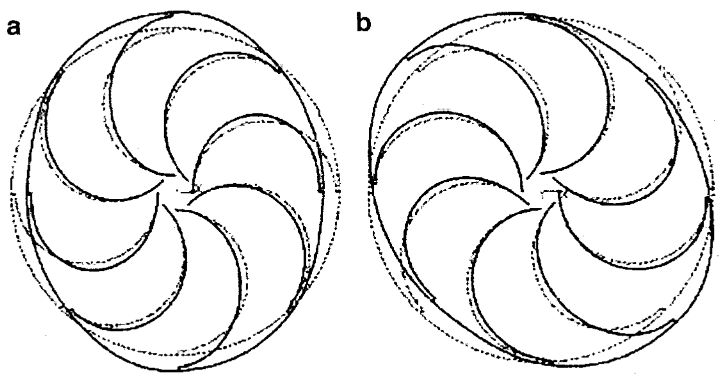


Fig. 3.21 Principle of operation of a gyroscope with a vibrating ring [8] (www.microstrain.com/3dm-gx1.aspx). (**a**) First bending wave. (**b**) Second bending wave shifted at 45° relative to first one

3.9 Examples of Gyroscopic Pilotage Devices

A *gyrocompass* is an on-board device pointing in the geographic northern direction (Fig. 3.22). It makes use of a basic feature of gyroscopes, namely, it maintains an unchanged position in the space of eigenrotations. A gyrocompass is independent of the magnetic field and declination of the object in which it is located.

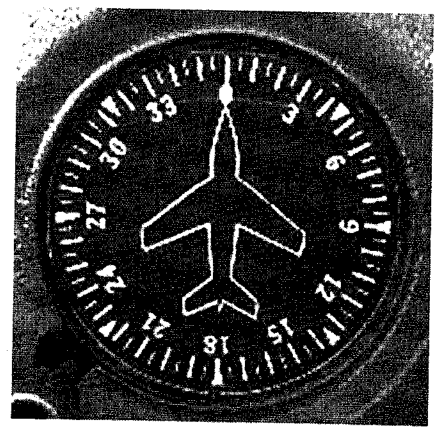


Fig. 3.22 Gyrocompass (www.imar-navigation.de/englishside/dat_engl/ifog_e.htm)

A gyrocompass is the oldest aeronautic gyroscopic instrument. It was initially designed by Elmer Sperry for ships but as its size has been reduced, it is used in aviation. Its operation is based on that of a gyroscope, namely, when it spins, it maintains the position of its axis. A vertically placed gyroscopic disk is suspended on a Cardan joint, so that the orientation of the disk in space is unchanged. A rotation of an airplane about the gyroscope is transmitted on a 360-degree scale.

A Cardan system with a gyroscope can be placed inside or outside the device. In the latter case a gyrocompass is placed in a hermetic thermostat, and an indicator on the instrument panel (electromechanic or electronic) is electrically coupled with it.

In order to periodically update a gyrocompass one uses a compass. Such a system is called a gyromagnetic compass. The accurate so-called distant reading compass is located away from magnetic field sources (steal elements, electric energy receivers, cables), mostly placed in wing tips, and is electrically coupled with other systems.

A *turn indicator* allows for perfect turns without skidding or sideslipping (a so-called coordinated turn). The shape of the plane fixed to the gyroscope represents turn depth (angular velocity) (Fig. 3.23). A ball indicates the direction of the centrifugal force; it must stay in the marked area. A turn indicator can be made as a turn coordinator or a turn indicator with a vertical hand instead of an airplane shape.

An *artificial horizon* points indicates the position of an aircraft (horizontal flight, climb, descend, and tilt) relative to the real horizon plane (Fig. 3.24). The real horizon is called a plane that is perpendicular to the vertical at the observation point. The real horizon plane is parallel to the plane of visible horizon—it is specified by the rotor plane of a gyroscope. The real distance of the visible horizon depends on the curvature of the Earth's altitude and optical refraction (refraction of the track visible light rays in the atmosphere). As a result of refraction, an observer sees below something like a huge hollow; objects seem to be much farther away than they really are. Optical refraction depends on air temperature, humidity, pressure, pollination, and other factors.

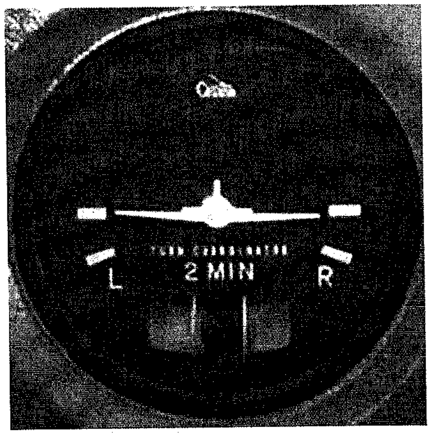


Fig. 3.23 Turn indicator (www.imar-navigation.de/englishside/dat_engl/ifog_e.htm)

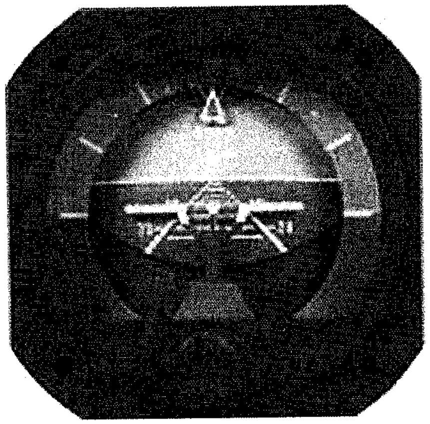


Fig. 3.24 Artificial horizon (www.imar-navigation.de/englishside/dat_engl/ifog_e.htm)

An artificial horizon is a base of flight without visibility. The artificial horizon indicates the real orientation of an airplane in space. The suspension of a gyroscope in an artificial horizon has three degrees of freedom. Therefore, the artificial horizon can rotate without limitations.

The first autopilot devices emerged from the gyrocompass and artificial horizon. Gyroscopic instruments controlled the actuators employed in airplane control systems by stabilizing the position in two planes. Previous autopilots were hydropneumatic devices without no electronics on-board.

Tachometer sights belong to a group of sight systems dealing with the problem of analytically determining the target hit by projectile.

The name refers to the fact that in sights of this kind, one measures the angular velocity of the vector radius determined between a target and a shooter. A typical solution of tachometer sights is coupling of the sight with a barrel of the canon.

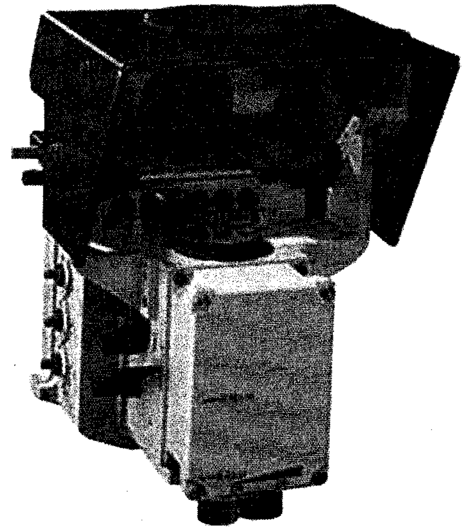


Fig. 3.25 Tachometer sight (www.imar-navigation.de/englishside/dat_engl/ifog_e.htm)

The structure of a tachometer sight depends on the method of measuring the angular velocity, the method of determining the flight duration of a projectile, and the multiplying system. One uses gyroscopes or generators to determine the angular velocity.

When a gyroscope is used in a sight, it is mounted on the barrel lift unit in such a way that the main axis is parallel to the axis of a barrel under no external influence. An optical system is connected with the internal frame of a gyroscope. With an internal gyroscope frame is related to the optical system (sight) which optical axis is parallel to the axis of the gyroscope.

An example of a tachometer sight is the GP-02MR (Fig. 3.25), designed to manage gunfire and the naval cannon ZU-23-2M, which uses electromechanical equipment, the naval cannon ZU-23-2M. The sight is designed to shoot with antiaircraft short-range 9K32M missiles and ammo of various ballistics. During target tracking, it automatically determines the advanced and sight angles. The sight enables attacking targets on land or sea that are at rest or in motion.

3.10 Example of an Observation Instrument with a Built-in Gyroscope

Gyroscopic tracking systems represent a great improvement over binoculars in the observation of moving objects.

Modern binoculars, an example of which is the Stabiscope S1240 D/N (Fig. 3.26), are characterized by an internal built-in stabilizing system, so that the observed object remains motionless regardless of the vibrations of the holder's

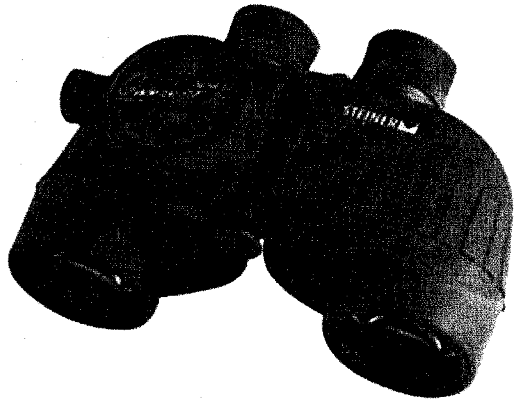


Fig. 3.26 Binocular with a built-in gyroscopic stabilization system

hands or shaking generated by a car, helicopter, or ship. The stabilizing system consists of a fast-spinning gyroscope, coupled with a prism system suspended in a Cardan joint and placed in the optical axis between the lenses. When after a few seconds after it is turned on the rotating mass of the gyroscope is at full speed, and the suspension system is released—the binoculars are ready to work. The gyroscope ensures that the prism will maintain a fixed position independent of vibrations of the binoculars, so that an observer can see the object steadily.

3.11 New Challenges for a Gyroscope

An especially notable contribution to the development of gyroscopic devices came from the emergence and rapid growth of missile and spaceship technology. Gyroscopic devices were classified into two groups: seaborne and airborne. The former were characterized by relatively high accuracy, but they were large and massive. The latter, in contrast, had low accuracy but were of simple construction and small dimensions. The necessity of applying a gyroscope as a drive of an optoelectronic target coordinator in self-guided missiles forced the construction of gyroscopic devices of high accuracy and small overall dimensions, mass, and minimal energy consumption [8]. It should be emphasized that the high accuracy of a gyroscope needs to be maintained in hard, dynamic (overloads, vibrations), and climatic (large amplitudes of temperature and pressure) operating conditions. Thus the development of gyroscopic devices and their applications in missiles and spaceships has been revived. Scientists and engineers started new investigations into the causes of error generation and techniques of minimizing errors, construction improvements, inventing new materials of required properties providing high accuracy at small sizes and masses.

The development and improvement of precise and small gyroscopic instruments, working in complex conditions, has not ended and remains a scientific-engineering problem.

References

1. M. Davidson, *Gyroscope and Its Application* (Hutchinsons Scientific and Technical Publications, London, New York, 1946)
2. E.L. Nikolay, *Theory of the Gyroscopes* (OGIZ, Moscow, 1948), in Russian
3. R.F. Deimel, *Mechanics of the Gyroscope: The Dynamics of Rotation* (Dover, New York, 1950)
4. J.B. Scarborough, *The Gyroscope: Theory and Application* (Interscience Publishers, New York, 1958)
5. N.F. Babaeva, *Gyroscopes* (Mashinostroeniye, Leningrad, 1973), in Russian
6. V.A. Pavlov, *Aviational Giroscopic Devices* (GOSIZDAT of Defense Industry, Moscow, 1954), in Russian
7. L.Z. Novikov, M.Iu. Shatalov, *Mechanics of Dynamically Tunable Gyroscopes* (Nauka, Moscow, 1985), in Russian
8. Z. Koruba, *Elements of the Theory and Applications of Gyro-Controlled.* Monographs, Studies, Dissertation No. 25 (Kielce University of Technology, Kielce, 2008), in Polish
9. P.A. Abramov, *Errors of Dynamically Controlled Giroscopes* (Mashinostroeniye, Moscow, 1985), in Russian
10. M.A. Pavlovskiy, *Theory of the Gyroscopes* (Vyshaya Shkola, Kiev, 1986), in Russian
11. S. Popowski, *Methods to Improve the Metrological Characteristics of Dynamically Tuned Gyroscopes* (Military University of Technology, Warsaw, 1997), in Polish
12. A.A. Odintsov, *Theory and Computation of Gyroscopic Systems* (Vyshaya Shkola, Kiev, 1985), in Russian.