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4.2.7.4 Typical performance characteristics

Typical values for the significant error sources and performance parameters are given below:

g-Independent bias	1–50°/h
g-Dependent/mass unbalance bias	1–10°/h/g
Anisoelastic bias	0.05–0.25°/h/g^2
Scale-factor error (uncompensated temperature effects)	up to 400 ppm/°C
Scale-factor non-linearities (at high rotation rates)	0.01–0.1%
Bandwidth	up to 100 Hz
Maximum input rate	>500°/s

It can be seen that the error parameters are very similar to those quoted for the dynamically tuned gyroscope in Section 4.2.6.4. Typically, the drift performance of such a device is in the range 1–50°/h with the capability to capture rotation rates up to at least 500°/s. Additionally, the anisoelasticity is often slightly smaller, typically by a factor of 2–5.

4.3 Rate sensors

There is a class of mechanical sensors designed to sense angular rate using various physical phenomena which are suitable for use in some strapdown applications. Such devices resemble conventional gyroscopes in that they make use of the principles of gyroscopic inertia and precession described in Section 4.2.2. They are suitable for some lower accuracy strapdown applications, particularly those that do not require navigational data, but stabilisation. These devices tend to be rugged and to be capable of measuring rotation rates up to about 500°/s with typical drift accuracies of a few hundred degrees per hour. A number of devices of this type are discussed in the following sections.

4.3.1 Dual-axis rate transducer (DART)

4.3.1.1 Introductory remarks

Development of this type of gyroscope started in the United States during the 1960s. It has, as its name implies, the ability to sense angular rate about two orthogonal axes. Its basic performance is certainly sub-inertial, typically having a drift in the region of 0.5°/s or less. Its size is somewhat smaller than the rate-integrating gyroscope being about 18 mm in diameter and 40 mm in length.

4.3.1.2 Detailed description of sensor

The inertial element in this form of gyroscope is a sphere of heavy liquid, such as mercury, contained in a spherical cavity. This cavity is rotated at high speed about an axis along the case in order to give high angular momentum to the fluid sphere. There

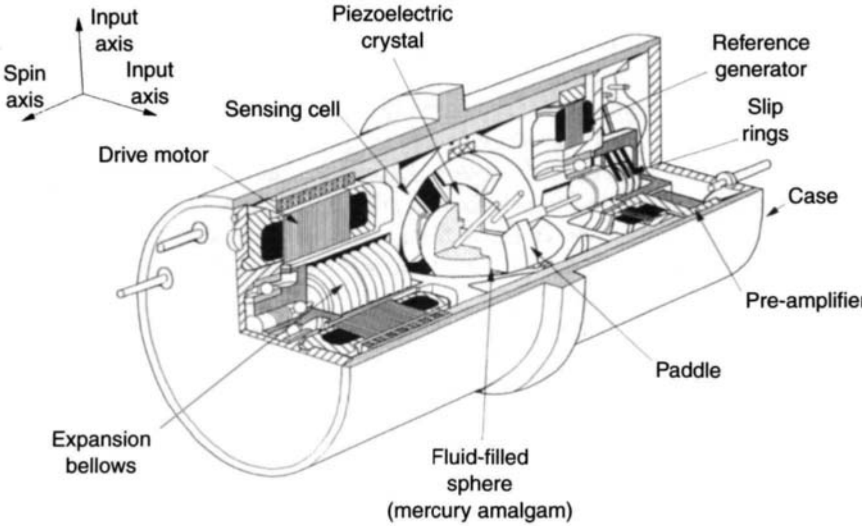


Figure 4.14 Dual-axis rate transducer

is an assembly of paddles, rigidly mounted to the inside of this spherical cavity. These paddles have piezoelectric crystals attached to them as shown in Figure 4.14. The instrument is sensitive to angular rates of the case about two orthogonal axes normal to the spin axis.

A simplified explanation of the operation of the complex dynamical interaction of this sensor is as follows. As the case of the sensor is rotated about either of its two sensitive axes, the spin axis of the mercury tends to lag behind that of the spherical cavity which moves with the rotation of the case. As a result of viscous coupling, a torque is applied to the rotating sphere of fluid in such a way as to make it precess at the input rate. This motion of the fluid causes a deflection of the paddles within the spherical cavity, bending the piezoelectric crystals and generating an a.c. electric signal which is proportional to the applied angular rate. The phase of this signal relative to the reference generator on the rotor shaft gives the axis of the applied rate.

4.3.1.3 Typical performance characteristics

Typical values for the significant error sources and performance parameters are as follows:

g-Independent bias including temperature effects	0.1–0.4°/s
g-Dependent bias	0.03–0.05°/s/g
g^2-Dependent bias	~0.005°/s/g^2
Scale-factor temperature sensitivity over operating temperature	~5%
Scale-factor non-linearity	~0.5% of maximum rate
Bandwidth	>80 Hz
Maximum input rate	up to 800°/s

This form of sensor is very rugged owing to the form of its fabrication. Its error processes tend to be similar to those of the dynamically tuned gyroscope. The temperature sensitivity is quite a complex function and can be difficult to correct exactly. In general, accuracy is usually somewhat less than that of the rate-integrating and dynamically tuned gyroscopes, so it is not usually used for inertial navigation applications. However, it does have many applications such as seeker stabilisation and provision of signals for autopilot feedback.

Derivatives of this sensor have also been produced which do not use any liquid within the sphere. The accuracy of such devices is somewhat less than the mercury filled device.

4.3.2 Magnetohydrodynamic sensor

4.3.2.1 Introductory remarks

The development of this dual-axis rate sensor also has its origins in the United States and has taken place in parallel with the development of the dual-axis rate transducer described earlier. It is of similar size to the dual-axis rate transducer and has comparable performance capability, the g-insensitive bias being in the region of 0.05–0.5°/s.

4.3.2.2 Detailed description of sensor

This device does not rely upon the angular momentum of a spinning mass, but uses a rotating angular accelerometer to sense angular rates about two mutually perpendicular axes of the sensor. The rotating angular accelerometer acts as an integrator and provides an electrical signal directly proportional to the applied angular rate.

The sensor consists of the angular accelerometer and a synchronous motor, as illustrated in Figure 4.15. A slip ring assembly is required to access the electrical signals produced by the rotation of the angular accelerometer. The case is usually a high permeability alloy that provides the necessary magnetic shielding.

The principle by which the sensor operates is as follows. When an angular accelerometer is rotated at a constant rate (ω_a) about an axis perpendicular to its sensitive axis, and a steady rotation rate (ω_i) is applied about an axis perpendicular to this axis of rotation, then the instantaneous angular rate (ω_o) about the input axis of the angular accelerometer is given by:

$$\omega_o = \omega_i \sin \omega_a t$$

Hence, the angular acceleration is:

$$\dot{\omega}_o = \omega_a \omega_i \cos \omega_a t$$

Consequently, the input rate is changed to a time-varying angular acceleration. The rotating angular accelerometer produces an alternating signal, the amplitude of which is directly proportional to the applied angular rate whilst the frequency is equal to the rate of turn of the angular accelerometer. This output signal can be resolved to give the applied angular rate about two orthogonal axes, both of which are mutually perpendicular to the axis of rotation of the angular accelerometer.

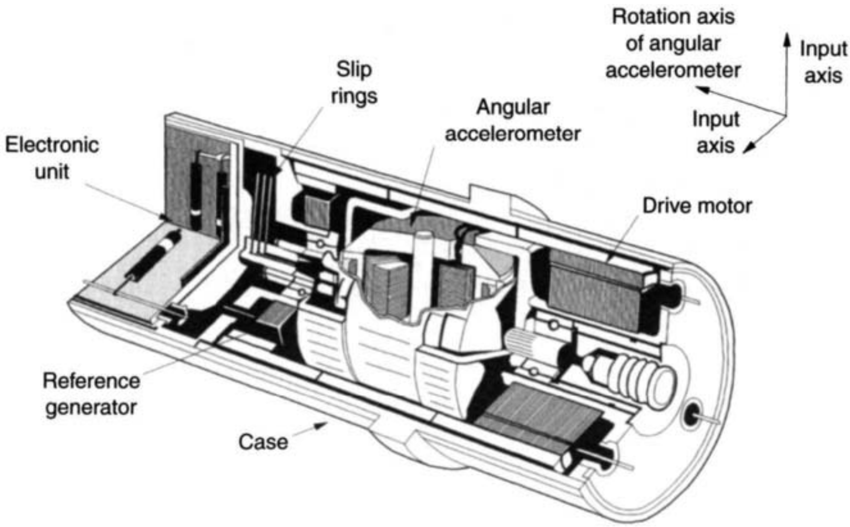


Figure 4.15 Magnetohydrodynamic sensor

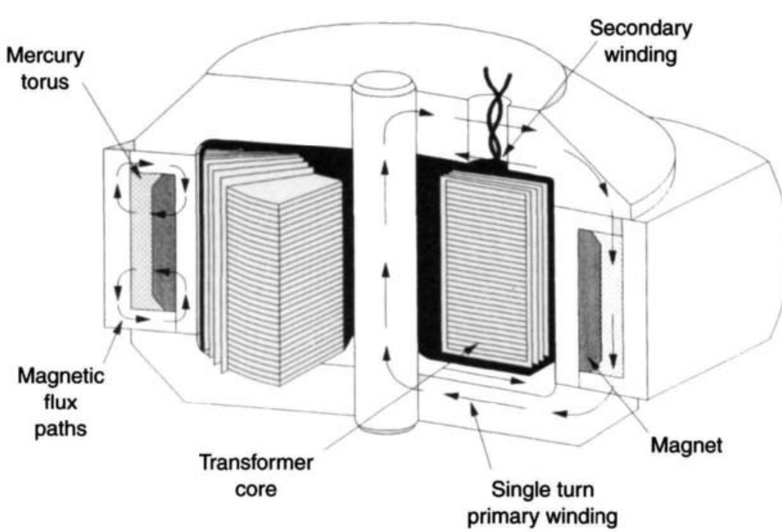


Figure 4.16 Magnetohydrodynamic active element

A diagrammatic representation of the angular accelerometer arrangement within the sensor is shown in Figure 4.16.

The angular accelerometer usually has an annular ring of mercury between the radially oriented permanent magnet and the magnetic case, which provides a path for the magnetic field. The presence of an input rate results in relative motion of the magnetic field with respect to the torus of mercury. As a result of the magnetodynamic effect, the motion of the magnetic field produces a voltage gradient across the mercury, mutually at right angles to the motion and the magnetic field. The presence of the transformer windings, as shown in Figure 4.16, results in a voltage appearing in the secondary winding.

4.3.2.3 *Typical performance characteristics*

The performance figures for the magnetohydrodynamic (MHD) sensor are typically as shown below:

g-Independent bias including temperature effects	0.05–0.5°/s
g-Dependent bias	~0.05°/s/g
g^2-Dependent bias	~0.001°/s/g^2
Scale-factor temperature sensitivity over operating temperature	~4%
Scale-factor non-linearity (at maximum rotation rate)	~0.1% maximum rate
Bandwidth	100 Hz
Maximum input rate	up to 400°/s

This sensor is very rugged and capable of surviving in very harsh environments. The performance capability appears to be that of a good rate sensor and is particularly suited for stabilisation applications. The error equation used to define performance may be expressed in a form similar to that used for the conventional mechanical gyroscopes as discussed in Section 4.2.

4.4 Vibratory gyroscopes

4.4.1 *Introduction*

The origins of this type of gyroscope may possibly be considered to be in the middle of the nineteenth century. Foucault demonstrated that a vibrating rod would maintain its plane of vibration whilst it was being rotated in a lathe. Later that century, Bryan [7] demonstrated that angular rate sensing, as well as linear acceleration sensing, could be achieved using this principle.

It was during the 1950s that work started to develop this principle of a vibrating element to sense angular rate, the majority of the effort being in the United States. The vibrating element has taken various forms such as a string, a hollow cylinder, a rod, a tuning fork, a beam and a hemispherical dome. This form of gyroscope occurs in nature as laterae in flying insects. One of the earliest forms of gyroscope using a vibrating element was produced by the Sperry Gyroscope Company. It was based on the tuning fork principle and was known as the gyrotron.

The basic principle of operation of such sensors is that the vibratory motion of part of the instrument creates an oscillatory linear velocity. If the sensor is rotated about an axis orthogonal to this velocity, a Coriolis acceleration is induced. This acceleration modifies the motion of the vibrating element and provided that this can be detected, it will indicate the magnitude of the applied rotation.

The most common design technology for these sensors has generally used a stable quartz resonator with piezoelectric driver circuits. Some designs have produced sensors with small biases, in the region of 0.01°/h. However, the smaller sensors have tended to produce biases in the region of 0.1–1°/s. Typical limitations for this type of technology for use in inertial navigation systems have been high drift rates, resonator time constants and sensitivity to environmental effects, particularly temperature changes and vibratory motion. However, these sensors can be made to be extremely rugged, including the capability of withstanding applied accelerations of many tens of thousands of '*g*'.

These sensors are usually quite small, usually with a diameter of somewhat less than 15 mm and a length of about 25 mm. Others are significantly smaller than this and are packaged in rectangular cases. These sensors have been used in many applications, particularly to provide feedback for stabilisation or angular position measurement tasks.

As there are many similarities in the performance characteristics of vibratory gyroscopes, such aspects are covered in a single section following general descriptions of the operating principles for different types of design.

4.4.2 Vibrating wine glass sensor

This sensor is synonymous with the vibrating cylinder and vibrating dome gyroscopes. These devices usually have three basic components inside a sealed case:

(i) A resonant body in the shape of a hemisphere or a cylinder with a high Q factor to maintain a stable resonance. It is often made from ceramic, quartz or steel.
(ii) A forcing or driving mechanism, commonly made from a piezoelectric material.
(iii) A pick-off device to sense the modified motion, also usually a piezoelectric device.

These components are shown schematically in Figure 4.17a together with the resonant vibration patterns in the static and rotating cases in Figure 4.17b.

The resonant body, usually a hemisphere or cylinder, is forced to vibrate at its resonant frequency by four equally spaced piezoelectric 'driving crystals' that are firmly attached to its circumference. One 'opposite' pair of crystals is driven with an oscillatory signal to distort the resonant body so that modes appear in the distortion pattern on its circumference. The other pair of crystals are used as feedback sensors to control the nodes in the induced motion. When the cylinder is stationary, the nodes in the vibratory motion are positioned exactly between the driving crystals, the anti-node axes A and B being shown in the figure. If the resonant body is rotated at an angular rate about an axis orthogonal to the plane containing the vibratory motion of this body, the pattern of vibration is modified by the Coriolis acceleration.

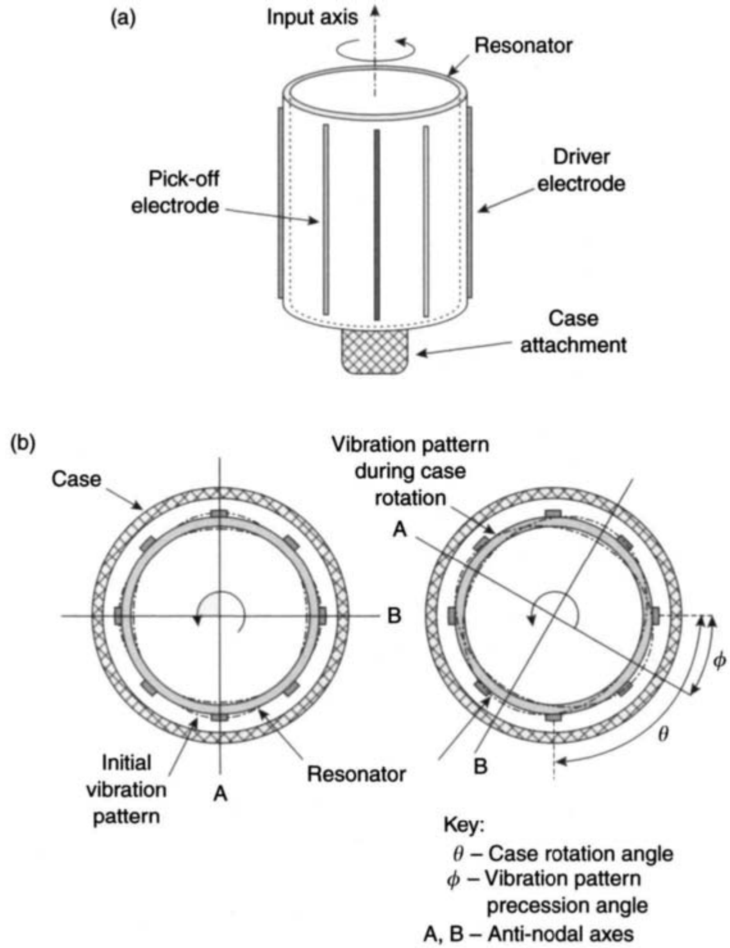


Figure 4.17 (a) Vibratory gyroscope schematic diagram. (b) Resonator vibration patterns

The effect is to add a tangential force to the vibratory force along the diameter of the resonant body. Consequently, there is a change in the motion at the points mid-way between the 'driving crystals' as the vibration pattern has moved through an angle ϕ relative to the case. Hence, the pick-off transducer crystals now sense movement of the resonant body, the amplitude of displacement being directly proportional to the applied rotation rate.

By demodulating the signal from the pick-off transducers, with respect to the waveform used to power the driving crystals that vibrate the cylinder, a d.c. signal is produced. Its magnitude is proportional to the applied rotation rate and its sign indicates the sense of rotation. The second pair of piezoelectric crystals, which are nominally at the nodal positions, can be used to modify the vibration characteristics of the cylinder in order to enhance the bandwidth of this sensor. These crystals are driven by a feedback signal derived from the signal produced by the pick-off transducers.

An alternative configuration of this form of sensor is to fabricate the resonant body from a ceramic material and then deposit metal electrodes on to the ceramic. This design has some advantages in terms of reliability as the wires can be attached at points of zero movement. An alternative method of making the cylinder vibrate is to use a magnetically driven ferromagnetic cylinder. Capacitive pick-offs can be used thus reducing the damping of the resonance produced by attaching leads to the resonator.

It is very important that the vibrating shape, such as the shell of the hemispherical resonator gyroscope, is machined to have a wall thickness that is as uniform as possible and that it is then dynamically balanced to compensate for material inhomogenities and machining errors. A non-uniform shell is not sensitive to small rotations as the nodes do not move when the case is rotated at low rates about the input axis.

Sensors of this type can be very rugged and have been demonstrated to withstand accelerations or shocks well in excess of 20,000g. Additionally, these devices can be activated very rapidly, but great care is required in the choice of resonant material to achieve a form of temperature sensitivity that does not mask its rate sensitivity. This form of device generally does not show any significant acceleration sensitivity as such a response only results from deformation of the resonant body.

Vibrating wine glass sensors can be operated as either open-loop or closed loop devices. In the open-loop configuration, the electric signal merely increases as the angular rate increases. When used in a closed loop configuration, the second set of crystals are used to null any displacement sensed by the pick-off crystals, this secondary drive signal being proportional to the detected rate. This latter technique leads to a far more linear relationship between the output signal and the input stimulus.

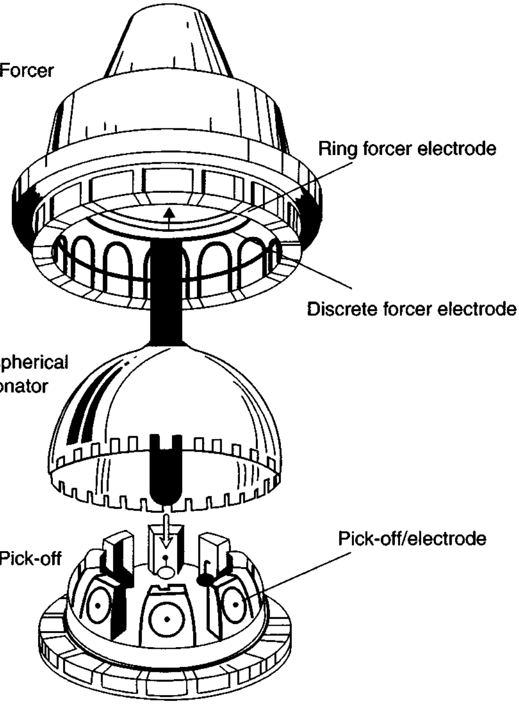
4.4.3 Hemispherical resonator gyroscope

Whilst most vibrating wine glass gyroscopes sensors are relatively low accuracy devices having biases in the region of 0.1–1°/s, an exception to this is the hemispherical resonator gyroscope (HRG). An inertial grade HRG was developed originally by Delco (now the Northrop Grumman Corporation, Litton Systems) in the 1980s, primarily for space applications, incorporating a 58 mm resonator. This sensor has a bias stability in the region of 0.01°/h. In addition, the device is characterised by its excellent scale-factor accuracy (less than 1 ppm uncertainty) and low random walk (0.0008°/$\sqrt{\text{h}}$) [8].

The base material used in the construction of the HRG is quartz. As with other sensors of this type, it comprises three main elements:

- a quartz forcer to induce and sustain a standing wave in the resonator;
- a quartz resonator with a high Q factor ($\sim 10^7$);
- a quartz pick-off which senses the locations of nodes and anti-nodes in the standing wave pattern of the resonator.

(a)



(b)

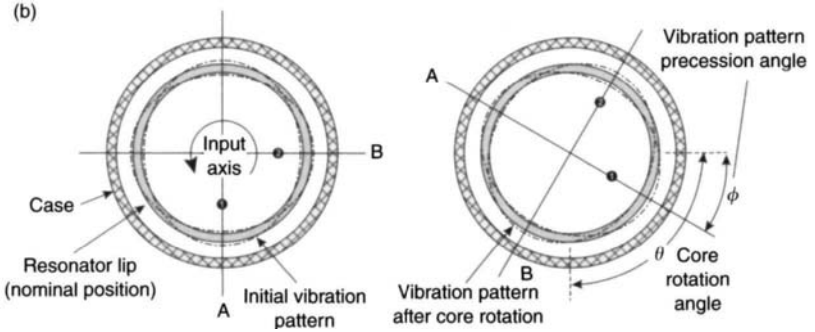


Figure 4.18 (a) Major components of a hemispherical resonator gyroscope. (b) Principle of operation
(Published courtesy of Northrop Grumman Corporation, Litton Systems)

The HRG uses a capacitive electrostatic charge between metal-coated surfaces on the quartz components to sustain the standing wave and to sense its position. An exploded view of such a device is shown in Figure 4.18a.

Figure 14.18b illustrates the operating principle of the HRG. When the vibrating element is stationary, the nodes in the vibratory motion are positioned exactly between the driving crystals, the anti-node axes A and B being shown in the figure. If the resonant body is rotated at an angular rate about an axis orthogonal to the plane containing the vibratory motion of this body, the pattern of vibration is modified by the Coriolis acceleration. The effect is to add a tangential force to the vibratory force along the diameter of the resonant body. Consequently, there is a change in the motion at the points mid-way between the driving crystals as the vibration pattern has moved through an angle ϕ relative to the case. Hence, the pick-off transducer crystals now sense movement of the resonant body, the amplitude of displacement being directly proportional to the applied rotation rate.

In recent years, attempts have been made to develop a scaled-down version of the HRG with bore hole survey applications in mind, where measurement systems designed to operate during the drilling process are frequently subjected to high levels of mechanical shock and vibration. This development set out to capitalise on the projected reliability of this type of sensor, and its expected resistance to shock and vibration. Thus far, this work has failed to yield a sensor of the required performance, at an acceptable cost. Work is continuing in Russia at the present time based on an HRG containing a 30 mm diameter resonator [9, 10].

4.4.4 Vibrating disc sensor

An alternative configuration has been developed by British Aerospace based on a planar metal disc [11]. The resonator is formed from a metal alloy disc, which is machined to form a ring that is supported by rigid spokes, as shown in Figure 4.19.

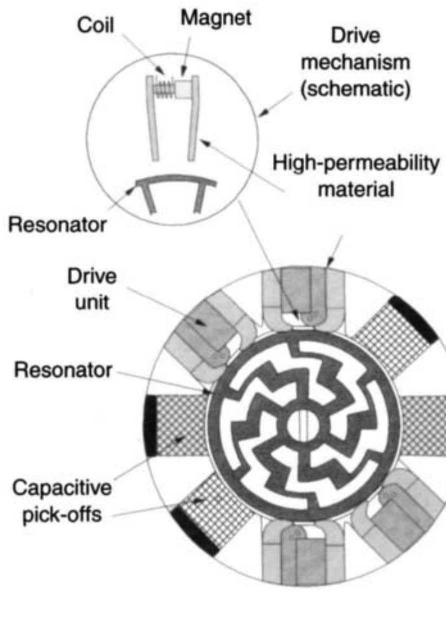


Figure 4.19 A section through a vibrating disc gyroscope

This ring is forced into resonant sinusoidal oscillation in the plane of the ring, using an alternating magnetic field, creating distortions in the shape of the ring. This motion of the ring is detected using capacitive techniques to measure the distance between a fixed plate and the edge of the ring.

The operation of this type of gyroscope is identical to the sensor described in the previous section. The vibration pattern remains fixed with respect to the ring whilst the sensor is stationary. However, the position of the nodes and anti-nodes of this vibratory motion are displaced through an angle when the sensor is rotated about an axis perpendicular to the plane containing the resonator. The magnitude of the angular displacement of the vibration pattern is proportional to the applied angular rate, and is measured using the capacitive pick-offs arranged around the edge of the resonator.

It has been suggested that the performance of this configuration is superior to the performance produced by the resonant cylinder sensor owing to the improved stability properties of the metal alloy used.

4.4.5 Tuning fork sensor

This form of device is very similar to the wine glass sensor described earlier. The sensing element is two vibrational structures mounted in parallel on a single base, each structure having a mass positioned at the end of a flexible beam. When the two structures are excited to vibrate in opposition, the effect is analogous to the motion of the tines of a tuning fork. When rotated about an axis parallel to the length of the beams, the effect of the Coriolis acceleration is to produce a torque couple about this input axis. The torque is oscillatory and is in phase with the tine mass velocity. The amplitude of the oscillation is proportional to the applied rate.

A schematic diagram showing the principle of operation of the tuning fork sensor is given in Figure 4.20.

Two specific problems delayed the development of this type of sensor:

(i) variation in the bending and torsional elastic modulii of materials with temperature;
(ii) bias instabilities caused by the lateral displacement of the tine mass centres.

Use of crystalline quartz tine forks has alleviated many of these problems.

A typical implementation of this form of technology is to use a pair of piezoelectric vibrating beams, each pair consisting of two piezoelectric 'bender' elements mounted end to end. The element that is firmly attached to the base is driven resonantly so that the second element swings but does not bend. This element senses the angular motion. When there is angular motion about the sensitive axis of this 'tuning fork', there is a momentum transfer to the perpendicular plane as a result of the Coriolis acceleration. This sensing element now bends as a consequence of this momentum transfer and an electrical signal is produced that is proportional to the applied angular rate.

4.4.6 Quartz rate sensor

The quartz rate sensor (QRS) is a direct application of the tuning fork principle. It is a single degree of freedom, open-loop, solid-state sensor. In this device, quartz is

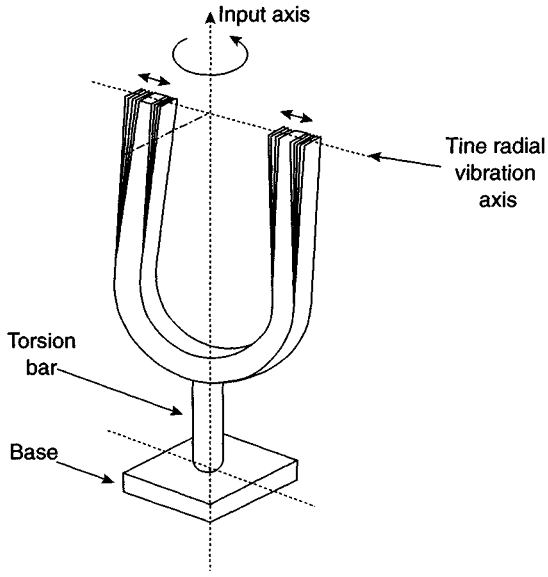


Figure 4.20 Principle of a tuning fork sensor

formed into an 'H' fork configuration, where one pair of tines has an array of electrodes. These tines are driven at their resonant frequency of about 10 kHz.

When the sensor is rotated at a given rate about the input axis, a Coriolis torque is produced, which oscillates in phase with the tine mass velocity. This torque produces a 'walking' motion of the pick-off tines, perpendicular to the vibrating plane of the driven tines. The time-varying displacement of the tines, which is proportional to the applied rate, is detected with a capacitive sensor. It is vital that the mount is strong so that it supports the quartz element, but sufficiently isolated in order to maximise the Coriolis coupling torque into the pick-off tines. Drive and pick-off signals are routed through the mount. A general arrangement of this sensor is shown in Figure 4.21.

This sensor, like other solid-state devices, can have various rate sensitivities and the full scale output can be modified by changing the electronic gain control. These parameters are functions of the signal processor which controls the input range and the signal bandwidth. Additionally, the design of the vibrating fork can have an almost infinite combination of size, thickness and electrode pattern, enabling flexibility of performance to be achieved.

Since its introduction, the performance of the QRS has improved dramatically as a result of enhancements in the design of the sensing element, improvements in the manufacturing process for the sensing element, as well as improvements in the signal processing and calibration techniques used. This has been accompanied by a reduction in the size of the tuning fork element; the sensors are micromachined using photolithographic processes, and are at the forefront of MEMS technology, as discussed in Chapter 7. These advances have resulted in gyroscopic sensors with an in-run bias of 1°/h.

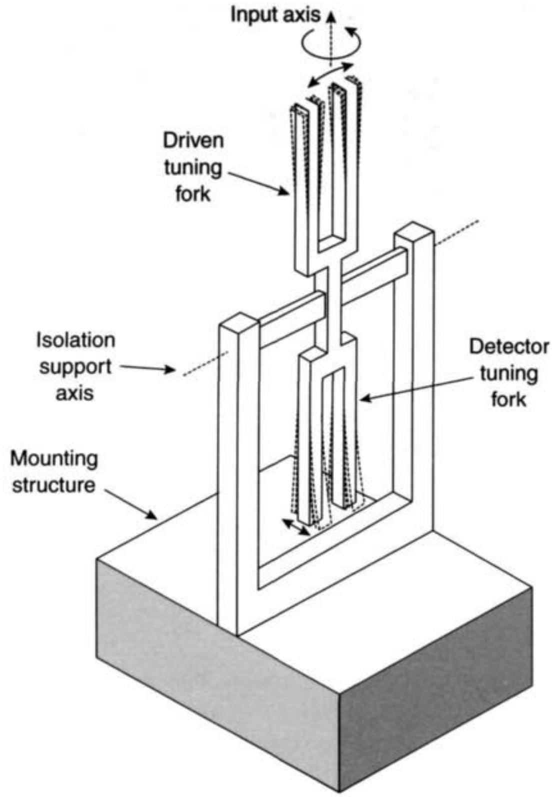


Figure 4.21 Principle of operation of a quartz rate sensor

4.4.7 Silicon sensor

The material silicon has many properties that make it suitable for the fabrication of very small components and intricate monolithic devices. It is inexpensive, very elastic, non-magnetic, it has a high strength to weight ratio and possesses excellent electrical properties allowing component formation from diffusion or surface deposition. Additionally, it can be electrically or chemically etched to very precise tolerances, of the order of micrometres.

A team at The Charles Stark Draper Laboratories, Inc. [12] has used chemical etching techniques to make a very small gyroscope from a wafer of single crystal silicon. The sensor does not have any continuously rotating parts, but part of its structure is vibrated at very high frequency. A schematic representation of this sensor is shown in Figure 4.22.

The sensor comprises a double gimbal structure with a vertical member electroplated with gold mounted on the inner gimbal. The gimbals are each supported by a set of orthogonal 'flexure pivots' as indicated in the figure. These pivots allow each

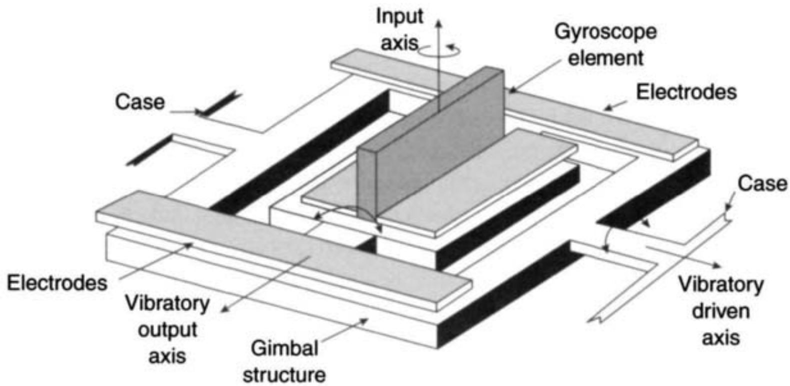


Figure 4.22 Silicon gyroscope

gimbal a small amount of torsional freedom about their respective support axes whilst remaining rigid in other directions. The outer gimbal is forced to oscillate through a small angle by applying an oscillatory electrostatic torque using pairs of electrodes mounted above and below the outer gimbal structure. When the structure is rotated about an axis perpendicular to the plane of the sensor, as indicated in the figure, the inner gimbal also starts to oscillate. The inner gimbal vibrates at the same frequency as the outer gimbal, but with an amplitude proportional to the applied angular rate. This motion is sensed electrostatically by a pair of bridging electrodes. The sensitivity of the device is determined largely by the geometrical arrangement of the structure.

In order to achieve high sensitivity and accuracy, the gyroscope is operated in a closed loop re-balance mode. The inner gimbal is torqued electrostatically in order to maintain it at a 'null' position, the torquer drive signal being proportional to the angular displacement sensed by the electrostatic pick-off, and hence to the applied angular rate. The pick-off and re-balance signals pass through the same electrodes, but use different frequencies. This method of operation allows the gyroscope to tolerate variations in the frequency of the vibratory motion. It also allows the amplitude of the vibratory motion to be increased, without cross-coupling interactions becoming unacceptably large, thus enabling an increase in the signal to noise ratio of the output signal. The electronic loops which control the operation of the gyroscope also allow compensation for imperfections in the device fabrication and changes in temperature to be applied.

The gyroscope is packaged in a sealed case to maintain a vacuum. This enables a high Q (quality factor) to be achieved in the resonant structure, enhancing further the sensitivity of the device. It is anticipated that this type of device should be capable of achieving an in-run drift performance of better than 100°/h, and be capable of measuring very high rotation rates. The device can be substantially less than 1 mm long and can be used with silicon accelerometers (discussed in Section 6.4.3) to make a very small inertial measurement unit.

4.4.7.1 Silicon vibrating disc sensor

It is possible that the resonator for the vibrating disc gyroscope outlined in Section 4.4.4 could also be manufactured from silicon. This material possesses many characteristics that would be ideal for this type of component: low cost, elasticity and high strength to weight ratio for example. However, if silicon were to be used, it would be necessary to use an alternative technique to force the structure to vibrate, such as the use of piezoelectric devices. One clear advantage that silicon could offer would be a size reduction, probably with reduced cost of manufacture.

4.4.8 Vibrating wire rate sensor

This device, also known as the vibrating string gyroscope, has three fundamental components within its case, as shown in Figure 4.23:

1. the vibrating element in the form of a taut conductor;
2. the drive magnet;
3. the signal or pick-off magnet.

The principle of operation is similar to that of Foucault's pendulum. If a wire or string is oscillating in a plane and the supports of the vibrating element turn through an angle, then the plane of vibration remains fixed in space despite the fact that the string rotates with its supports.

An alternating current at a selected drive frequency is applied to the wire between the points A and B, as indicated in Figure 4.23. The interaction between the magnetic field around the wire and that of the drive magnet sets up a standing wave vibration of the wire. A second magnet, the signal magnet, is arranged with its magnetic field at right angles to the drive magnet as indicated in the figure.

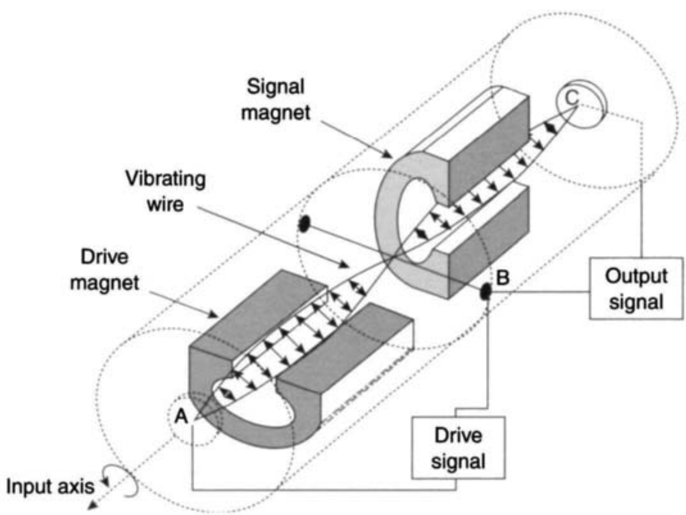


Figure 4.23 Illustration of a vibrating wire rate sensor

Consider now the effects of rotations about an axis that passes between the points A and C. When the gyroscope is not being rotated about this axis, the vibration of the wire between the poles of the signal magnet will not induce any change in the current in the wire. Thus, when the signal emerging from the point C is compared with the applied signal in a suitable demodulator, there will be no resultant signal. In the situation where the device is rotated about the axis AC, a rotation of the signal magnet with respect to the plane of vibration will arise. This causes the signal magnet to modify the current flowing in the wire and thus to modulate the carrier. Comparison of the drive and output signals now yields a resultant signal which is a measure of the applied angular rate about the axis AC.

It is usual to choose the natural frequency of the wire and the drive frequency to be in the region of 20 kHz or more so that the vibrations are well above those that are likely to be produced by environmental vibrations. This prevents synchronous vibration of the sensor's case along the pick-off axis being interpreted as an input rotation.

4.4.9 General characteristics of vibratory sensors

All vibrating sensors tend to have a very short reaction time, that is, rapid start-up capability, and some designs are very rugged. Significant sources of error with these devices are their sensitivity to changes in ambient temperature and the potential for cross talk between similar sensors mounted on the same structure. Careful design can minimise these effects and the errors they introduce into the output signal. These devices are usually termed solid-state sensors and offer good shelf-life and good dormancy characteristics as they do not have bearings, lubricants or any other fluid within their case. Good reliability is possible because of the need for only one bonded joint and the power leads can be connected, with suitable design, at a point which does not move. The form of design also ensures low power consumption.

These types of sensor are subject to biases and scale-factor errors equivalent to those which arise in conventional gyroscopes. Typical performance of the miniature vibratory sensors is not compatible with the requirements of inertial navigation systems, but have much to offer for control and stabilisation processes.

The performance range of such miniature devices is as follows:

g-Independent bias including temperature effects	0.1–1°/s
g-Dependent bias	0.01–0.05°/s/g
Scale-factor temperature sensitivity over operating temperature	0.01–0.05%/°C
Scale-factor non-linearity (at maximum rotation rate)	0.03–0.3%
Bandwidth	60–500 Hz
Shock resistance	>25 000g

In addition, such sensors can be sensitive to vibration although, with careful design, such effects can be minimised. The error equation used to define performance may be expressed in a form similar to that used for the conventional mechanical gyroscopes, as discussed in Section 4.2.

4.5 Cryogenic devices

4.5.1 Nuclear magnetic resonance gyroscope

Investigation started in the 1960s into the application of the phenomenon of nuclear magnetic resonance (NMR) to the sensing of angular rotation. The NMR gyroscope has many attractions, particularly as it will not have any moving parts. Its performance will be governed by the characteristics of the atomic material and will not demand the ultimate in accuracy from precision engineering techniques. Hence, in theory, it offers the prospect of a gyroscope with no limit to either its dynamic range or linearity and therefore, potentially, an ideal sensor for use in strapdown inertial navigation.

NMR [13] is a physical effect arising from the interaction between the nuclei of certain elements and an external magnetic field. Generally, nuclei possess spin angular momentum and, associated with it, a magnetic dipole moment. In the presence of a magnetic field, H, the spinning nuclei are subjected to a torque which results in a precession of the nuclear spin axis about the direction of the magnetic field. This is known as the Larmor precession and has a characteristic angular frequency, ω_L, given by the relation:

$$\omega_L = \gamma H \tag{4.10}$$

where γ is the ratio of the magnetic dipole moment to the angular momentum, known as the gyromagnetic ratio peculiar to any species of nuclei.

When an angular rate, Ω is applied to a cell containing the precessing nuclei, then the readout mechanism is in a rotating axis frame, resulting in an apparent change in the precessing frequency of the atoms. This rotation of the cell is equivalent to applying a torque to an inertial element in a conventional gyroscope as the precessing nuclei act as an inertial element. Thus, the observed precessional frequency, ω_{obs}, becomes:

$$\omega_{obs} = \omega_L + \Omega \tag{4.11}$$

or

$$\omega_{obs} = \gamma H + \Omega$$

Therefore, the determination of the applied rate Ω is dependent on establishing a constant magnetic field at the sensing element and the measurement of a nuclear precessional frequency.

Several techniques [14, 15] employing optical pumping and optical readout systems have been investigated to allow the small frequency shift induced by the rotation of the sensor to be detected. Optical pumping techniques will transfer an assembly of spins from an equilibrium to a non-equilibrium state. Light of the right frequency directed along the direction of the magnetic field will excite magnetic substances so that the chances of observing the transition of spins from one state to another is enhanced. Transitions are brought about by applying a weak oscillating field at 90° to the static field, H. When the frequency of the oscillating field is close to the Larmor frequency of the excited spins, the orientation of the nuclear spins is reversed. This effect can be detected by circularly polarised light directed at 90° to the direction of the static field. The orientation of the magnetic moments affects the plane of polarisation of this light and hence, after passing through an analyser, the resulting intensity modulation may be picked up by a photodetector.

Techniques for compensating for instability of the external field H involve the measurement of the Larmor frequencies of two magnetic substances contained within one sample cell.

The Northrop Grumman Corporation (formerly Litton Industries) produced a design as shown in Figure 4.24. The NMR cell contains rubidium vapour, krypton and xenon. These gaseous materials are used as they have suitably long

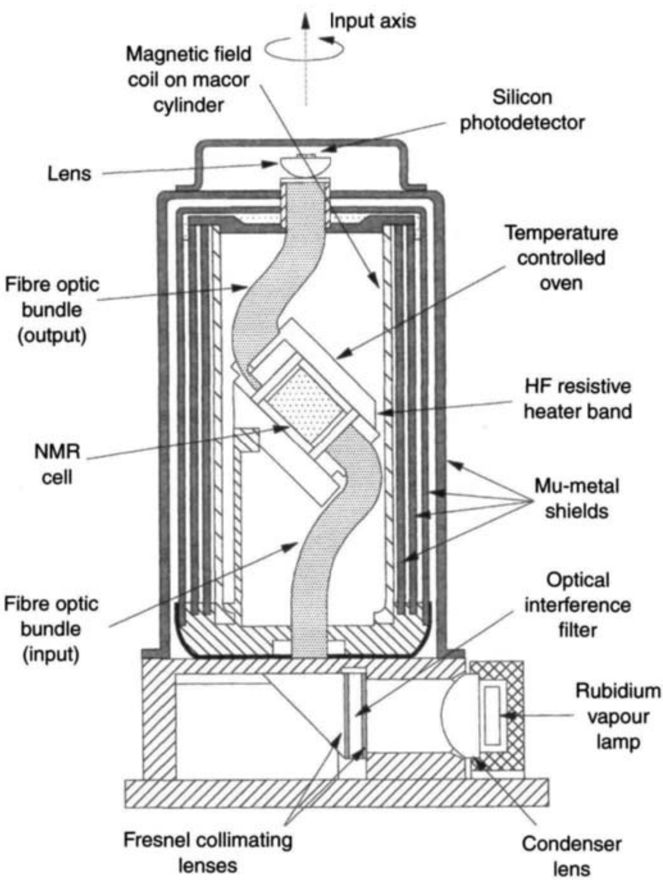


Figure 4.24 Experimental nuclear magnetic resonance gyroscope configuration

relaxation times enabling good sensitivity to be achieved from the very accurate determination of the observed precession frequencies. This design employs one light beam for both pumping and detection.

Clearly, a practical device requires a very uniform and constant magnetic field over the active sample of material. One way, and possibly the only practical technique, is to apply the unique properties of superconductors, such as the cryogenic Meissner effect [16, 17]. A cylinder made of superconducting material operating at a temperature below its critical temperature, will prevent magnetic flux from entering or leaving the central space. Hence, not only will this material shield the nuclear material, it will also trap the flux within the space as its temperature cools below the critical temperature of the superconductor.

One method of detecting the Larmor precession of the nuclear material placed inside the superconducting tube is to use a superconducting quantum interference device (SQUID) magnetometer [17]. In fact, these devices were used during the early development of cryogenic NMR gyroscopes to detect the free induction decay of a sample substance in a superconducting cylinder. The sample substance used was ^{3}He which, being gaseous at cryogenic temperatures, has the advantage of long relaxation times. This technique was unsuccessful because of the very poor signal to noise characteristics.

The cryogenic NMR gyroscope, as shown in Figure 4.25 [18], has many attractions, particularly the solid-state nature of the construction and the extremely low drift that is possible, as low as arc seconds per annum. This accuracy and the anticipated size of a few litres suggest the most likely application to be ship's strapdown navigation systems.

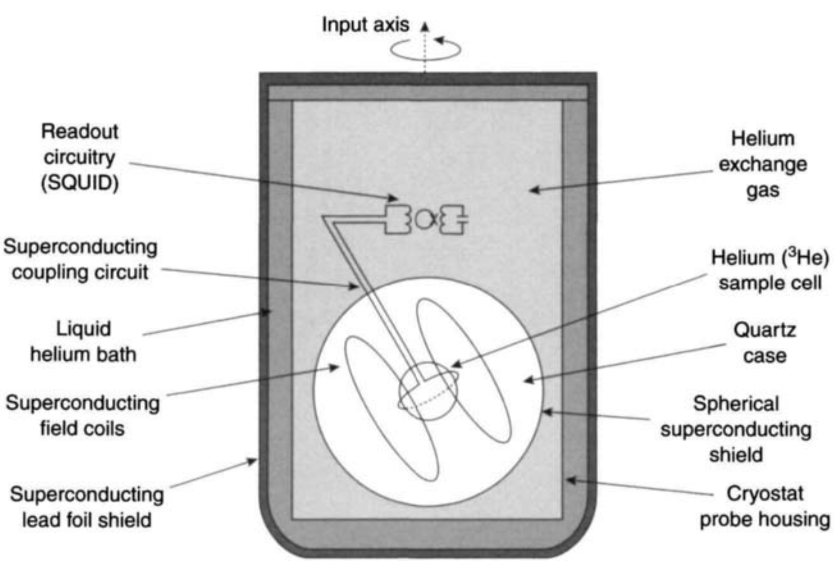


Figure 4.25 Cryogenic nuclear magnetic resonance gyroscope

In the 1970s, the NMR gyroscope and the ring laser gyroscope (discussed in Chapter 5) were looked upon as rival technologies for higher accuracy navigation applications. Although the manufacture of a viable sensor based on NMR technology appeared feasible, its development was overshadowed by massive investment in ring laser technology throughout the 1970s and 1980s, the latter being considered the more promising technology at that time. As far as the authors are aware, there has been little in the way of research effort and resources directed towards the NMR sensor in recent years and, as a result, the full potential of such devices has never been realised; the major thrust for the 'super-high' accuracy devices now appears to lie focused on cold-atom sensors (discussed in Section 5.2).

4.5.2 SARDIN

Another example of a rotation sensor which exploits superconductivity has been proposed by Brady [19]. This sensor is known by the acronym SARDIN (Superconducting Absolute Rate Determining INstrument). The device is basically a superconducting cylindrical capacitor, the behaviour of which is governed by the principle that a closed superconducting ring always keeps the amount of flux linking it at a constant value. It does this by generating supercurrents which flow in the ring for an indefinite length of time encountering no resistance to their motion.

Consider two concentric cylinders of superconducting material, one cylinder being raised to a potential V relative to the other. If the assembly is rotated around its central axis with angular velocity Ω, then the moving charges constitute currents which give rise to a net magnetic flux in the region between the two cylinders. As the magnetic flux inside a loop of superconductor cannot change, this field must be backed off by further supercurrents (I) induced in each cylinder. A rigorous mathematical treatment of this effect [20] gives the governing equation:

$$I = \frac{C_0 V r \Omega}{\varepsilon} \tag{4.12}$$

where C_0 is the capacitance per unit length of the assembly, r is the mean radius and ε is the permittivity of the dielectric between the two cylinders.

With a voltage of 225 V applied to such a device, having a mean radius of 2 cm, coupled to a SQUID magnetometer and an ammeter, Brady reported an angular rate sensitivity of 1 rad/s.

Following initial attempts to produce a superconducting rate sensor of this type in the early 1980s, development was not pursued because of the difficulties encountered in detecting the very small output signals generated. However, the development of higher temperature superconductors coupled with enhancements in signal processing techniques could possibly make this a viable technique in the future.

4.6 Electrostatically suspended gyroscope

Work started to develop this class of gyroscope, also known as the ESG, during the 1950s in the United States. The aim was to suspend a rotating sphere, known as a gyroscopic ball, by means of an electric field in an evacuated cavity. This form of suspension eliminates the undesirable characteristics of conventional gyroscopes such as bearings, flotation (in a liquid) or suspension.

The principle of operation is that a precision sphere, usually made of beryllium, is initially spun to very high speed whilst being suspended electrostatically in a hard vacuum. This sphere is then allowed to coast, its spin axis maintaining a fixed direction in inertial space provided the sphere and suspension do not have any imperfections which can introduce torques on the sphere. Any angular movement of the case of the gyroscope in space can be determined optically or electrically by reference to this spin axis. Navigation may be achieved by determining the apparent change of this reference axis with respect to a local reference direction such as the local vertical. A schematic diagram of the ESG is shown in Figure 4.26.

The development of the ESG was very successful, producing very accurate sensors capable of achieving drifts of the order of 0.0001°/h. The sensors were developed primarily for use on stable platforms, giving navigation accuracies of the order of 0.1 nautical miles per hour. However, they are capable of being used in a strapdown application, particularly in a benign environment.

The major difficulties with this sensor have been associated with:

- manufacturing the inertial element, that is, the ball, to sufficient accuracy to eliminate mass unbalance;
- producing a readout device that does not disturb the motion of the sphere;
- producing a design that avoids 'grounding the ball' or dropping the ball as it is sometimes referred to;
- avoiding self-destruction if the power supply fails.

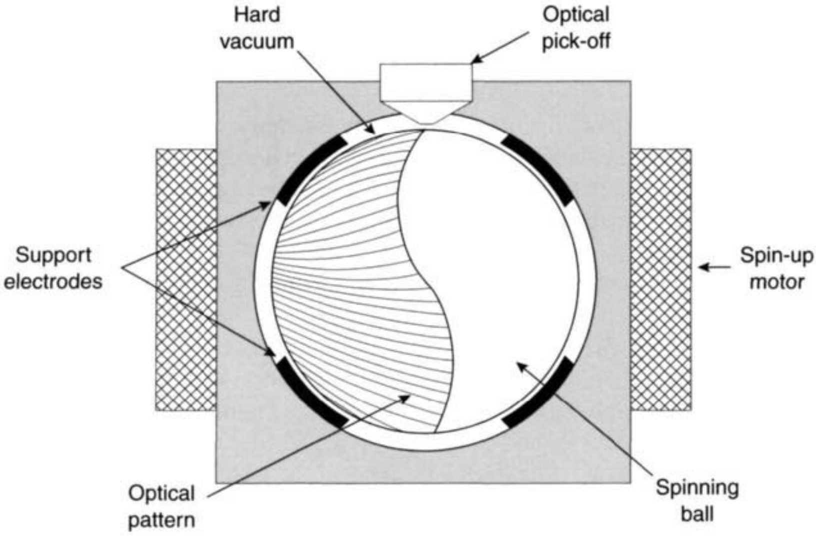


Figure 4.26 Electrostatically supported gyroscope

Errors in the production of the spherical inertial element lead to oscillations, nutations and whirls when the sphere is rotated at the very high speed which is necessary, typically of the order of 150 000 rpm. These undesired excursions are not very well damped because of the high vacuum inside the sensor. Additionally, the sensor requires special techniques to provide shock and vibration protection as the gyroscope does not have any inherent mechanism to damp out linear disturbances of the sphere. The addition of the anti-shock and anti-vibration mounts add to the size of the sensor.

The ESG is a very high accuracy sensor and has been used for many decades in specialised applications in aircraft, ships and submarines. This sensor has also been suggested for detecting acceleration. Since the support electrodes provide the only forces to accelerate the sphere to keep it moving with its case, measurement of these forces provide a measure of acceleration.

Unfortunately, despite being a very simple concept, the design is complex and the gyroscope is large and expensive. However, it is one of the most accurate conventional gyroscopes ever to be designed and produced.

A similar sensor was produced by Rockwell in the United States known as the gas-bearing free rotor gyroscope. This sensor was based on a spherical bearing, like a ball and socket arrangement, using a self-acting gas-lubricated bearing to support the ball. However, this sensor differs from the ESG as it only has limited angular freedom and is not really suitable for strapdown applications.

4.7 Other devices for sensing angular motion

There are a number of other devices that are either used or could be developed to sense angular motion. They are considered separately as they do not fit easily in any of the above classes of gyroscope, and are generally not the 'prime' angular motion sensor used in a strapdown navigation system. Included in this category are fluidic sensors and fluxgate magnetometers, both of which offer well-established technology suitable for various applications. The sensors tend to be small, reliable and rugged. Fluidic devices are often used for providing short-term references, as in stabilisation tasks, whereas magnetometers are generally used for long term aiding of systems.

4.7.1 Fluidic (flueric) sensors

This term has several meanings, such as sensors which make use of the flow of fluid for either the propulsion of the rotor or its support. Another meaning, and of more direct relevance to the immediate consideration here, is the use of a fluid for the sensing of angular motion. Sometimes, this class of angular motion sensor is known by the term flueric; the term fluidic being reserved to describe those sensors that use a fluid either for support or for powering the rotor. The text will concentrate on the use of a fluid for the sensing of angular motion, that is, flueric sensors.

Development of this type of sensor started in the 1960s. They appear to offer an interesting alternative to the electromechanical instruments. Despite much effort, it has not proved possible to make this type of sensor suitable directly for inertial navigation applications. The major difficulty is achieving adequate stability, resolution and insensitivity to environmental effects, particularly temperature changes. However, this class of sensor has found many applications, including flight control, stabilisation and in flight safety systems.

One form of sensor is a flueric gyroscope. In this device, there is a spherical cavity with porous walls and a rotating mass or swirl of gas within the cavity. When the sensor case is rotated, the direction of the swirl of gas remains fixed and the displacement can be detected by monitoring pressure changes. Figure 4.27 depicts the form of this sensor.

Another form of this class of instrument has a continuous laminar flow of gas from an orifice which impinges on a pair of hot wire detectors. When angular motion is applied about axes orthogonal to the gas flow, the gas jet appears to be deflected laterally relative to the case. This results in a differential cooling of the hot wires, with a consequential change in resistance which is detected using a bridge circuit. The output signal is proportional to the applied angular rate. This form of sensor is shown schematically in Figure 4.28. It tends to be sensitive to temperature gradients, acceleration, vibration and shock.

These sensors may either use fluid bled from an engine, such as a jet engine's efflux, or may be pumped in a closed cycle.

Such sensors provide an inexpensive short-term reference with turn rate measurement accuracies of around 1% of the applied rate. Generally, they also show significant sensitivity to most environmental features, particularly temperature changes. However, some designs are very rugged and reliable and are capable of operating over a wide temperature range.

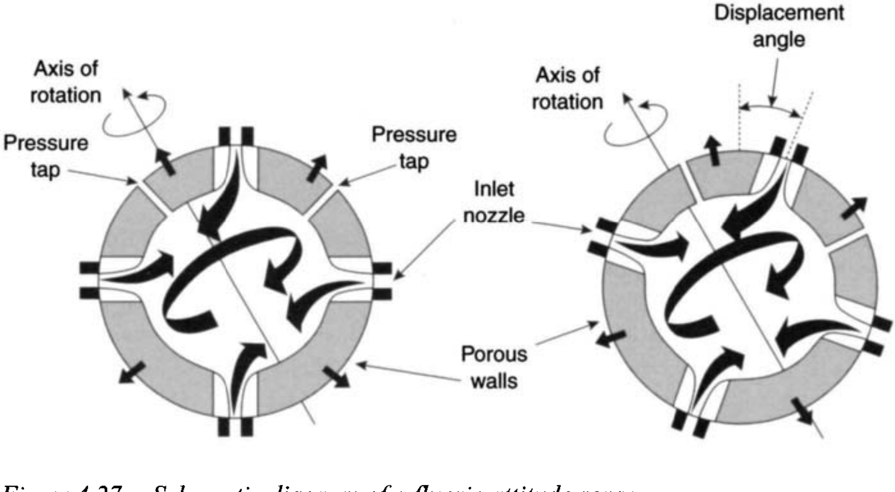


Figure 4.27 Schematic diagram of a flueric attitude sensor

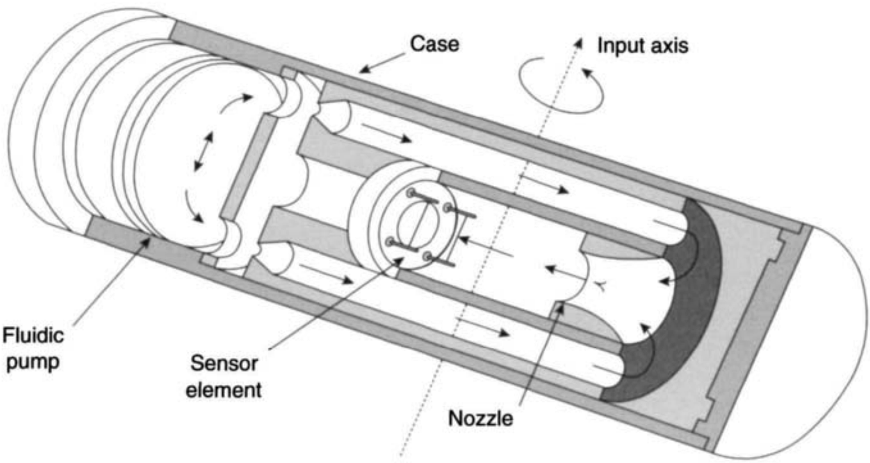


Figure 4.28 *Gas jet sensor*

4.7.2 Fluxgate magnetometers

It was during the 1950s that an airborne magnetometer was developed at the Royal Aircraft Establishment, Farnborough (now DSTI and QinetiQ) for attitude measurement. Since that time, there have been many developments of this type of attitude sensor [21, 22]. It is usually based on fluxgate elements. A magnetometer has three such magnetic sensing elements that are mounted mutually orthogonal to each other. These axes are usually arranged to be aligned with the principal axes of the vehicle. This configuration enables the attitude of the vehicle to be determined with respect to the Earth's magnetic vector. The magnetometer alone can not give an unequivocal measurement of a vehicle's attitude. Measurements made with such a sensor define the angle between the Earth's magnetic field and a particular axis of the vehicle. However, this axis can lie anywhere on the surface of a cone of semi-angle equal to that angle about the magnetic vector. Hence, an additional measurement is required to determine attitude with respect to another reference such as the gravity vector.

The basic operation of a fluxgate magnetometer is similar to the operation of an electrical transformer. However, the magnitude of the excitation signal is chosen to drive the core, linking the excitation and pick-up coils, into saturation on alternate peaks of the excitation signal. The high permeability of the core magnifies the effect of the changing magnetic field (H) generated from the changing current in the excitation coil. A simple fluxgate magnetometer element in shown in Figure 4.29.

The magnetic induction (B) in the core increases as the applied magnetic field from the excitation coil increases up to a maximum value (B_{max}), determined by the core material. As the magnetic field increases beyond the saturating value (H_{sat}) the induction remains constant. This is illustrated in the B–H curves shown in Figure 4.30. This effect is reversible, so as the magnetic field decreases below the saturation value the induction decreases until it reaches its negative saturation ($-B_{max}$).

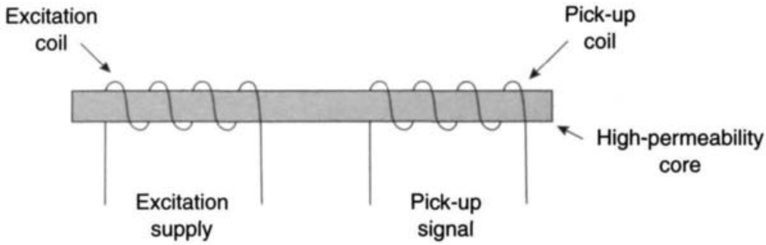


Figure 4.29 A simple fluxgate magnetometer

A voltage signal is only induced in the pick-up coil whilst the magnetic induction in the core is changing. Consequently, there is no signal in the pick-up coil during periods of induction saturation. The figure also shows the induction waveforms which result when a square wave signal is applied to the excitation coil with and without an external magnetic field acting along the core. In addition, the figure includes the resulting voltage waveform across the pick-off coil and the 'driving' magnetic field profile.

In the absence of an external magnetic field, the positive and negative excursions in the voltage appearing across the pick-off coil are of equal magnitude, as shown in the left-hand side of Figure 4.30, and there is no net output from the device. In the presence of an external magnetic field, this field acts either to aid or to impede the field generated by the alternating current in the excitation coil. As a result, the core is saturated more rapidly and remains in saturation slightly longer for one cycle of the excitation, the cycle in which the excitation and external fields are acting in the same direction. The converse is true when these fields are in opposition. As shown in the right-hand side of the figure, the induction waveform is no longer symmetrical and a modified voltage waveform appears across the pick-off coil. The amount of the advance and delay in the voltage waveform is proportional to the strength of the external magnetic field.

The change in the voltage waveform characteristic is not easy to measure in the simple scheme described above. A preferred arrangement which enables a signal proportional to the size of the external magnetic field to be extracted with relative ease is shown in Figure 4.31.

In this device, a pair of cores are used with the excitation coils wound in series opposition. In this case, the magnetic induction in the two cores cancel out in the absence of an external magnetic field. However, when an external field is present, the magnetic induction waveforms for the two cores are modified in the manner described above. The resulting voltage waveforms for each of the cores are shown in the bottom of Figure 4.31. The pick-up coil is wound so that it sums these two contributions giving rise to the sum channel waveform shown in the figure. This signal can be applied to a low pass filter and a steady output produced indicating the magnitude of the external magnetic field.

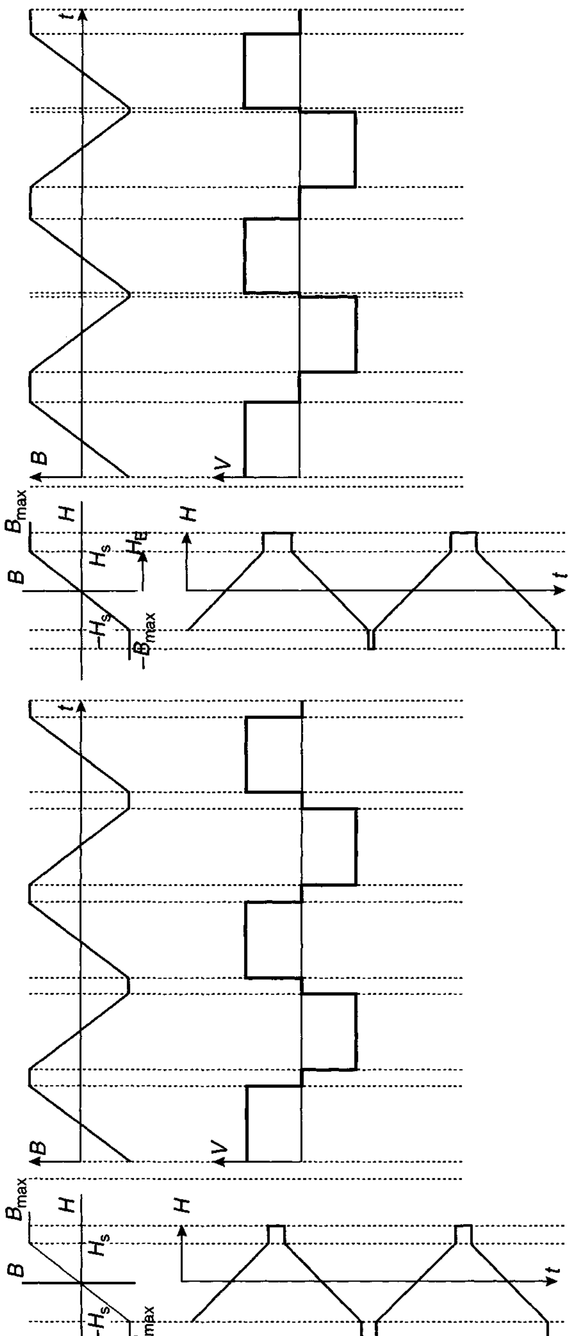


Figure 4.30 *Magnetometer waveforms*

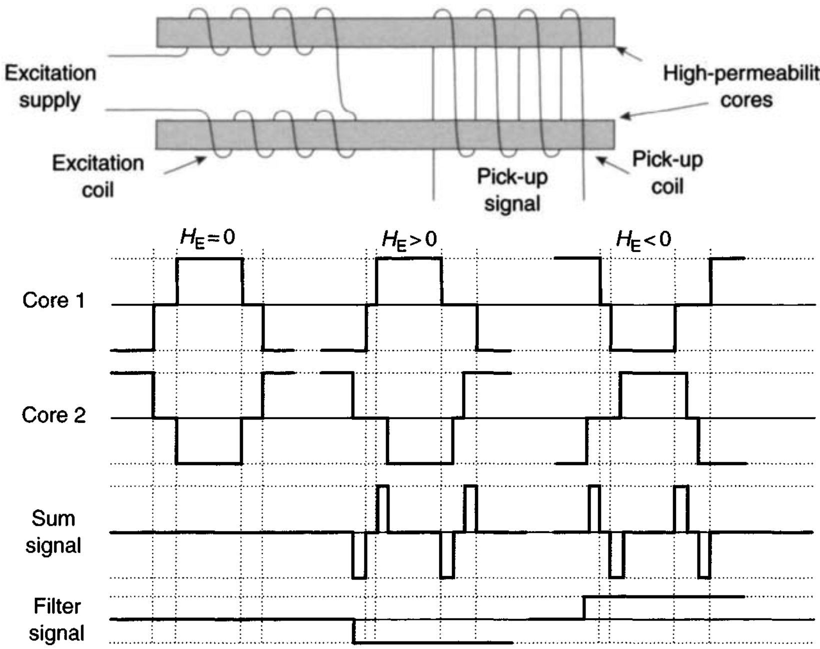


Figure 4.31 Twin-core fluxgate magnetometer and waveforms

This analysis for the two core configuration is dependent on the use of perfectly matched cores and windings. This fundamental requirement for accurate measurement of the magnetic field is very difficult to achieve in a practical device. A common solution to this problem is to use a circular toroidal core over wound with an excitation coil. The excitation coil is energised with an alternating current signal having a frequency of 1–1.5 kHz. The pick-up coil is a single coil wound over the toroid. A second coil can be wound over the toroid at right angles to the pick-up coil, and this can be used as a nulling device. This magnetometer arrangement is shown in Figure 4.32.

When operated in a closed loop mode, commonly known as the closed loop second harmonic mode, a current is passed through the second over-wound coil to null the effects of the detected magnetic flux. It is the amplitude of this current which is used to give a measurement of ambient magnetic field strength. The output from this coil is filtered to select only the second harmonic frequency, hence avoiding saturation of the amplifiers by unwanted frequencies.

The major problem with this form of instrument is that it has poor angular resolution capability, typically about 0.1°, and sensitivity to magnetic anomalies. However, this latter sensitivity can be valuable provided the magnetic anomaly in the region of operation is stable and well charted. A more serious limitation is often posed by the effects of the structure of the vehicle in which the sensor in mounted. The vehicle is likely to have ferromagnetic materials present as well as changing fields associated

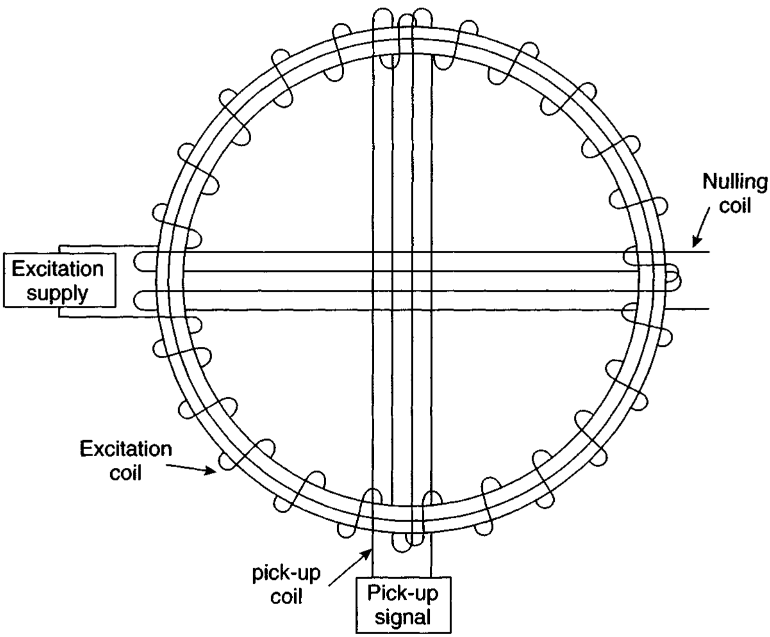


Figure 4.32 Toroidal fluxgate magnetometer

with power supplies and other instrumentation. Hence, such extraneous magnetic fields are likely to determine the precision with which the attitude of the vehicle can be determined, with respect to the magnetic field vector of the Earth. Therefore, these sensors are usually mounted at the extremities of a vehicle, as far away as possible from the source of extraneous fields. In some applications, it is possible to route wiring so as to cancel induced fields or else calibrate the sensor in its host vehicle.

A further potential problem arises in a strapdown configuration in a rolling airframe travelling at latitudes where the dip angle of the Earth's magnetic field is large. The roll motion will produce the effect of an alternating field on the magnetometer. An error will result unless the frequency response of the magnetometer is adequate to 'follow' this rate of change of field intensity. In some circumstances it may be necessary to incorporate another sensor to monitor the rapid roll rate in order to compensate the output of the magnetometer.

Generally, fluxgate magnetometers are cheap, small, rugged and reliable, and are capable of working over a very wide temperature range. They are commonly used in low cost systems to provide an attitude reference in pilotless aircraft for example, or in more sophisticated reference systems to provide a long term attitude reference. In this case, the data supplied by the magnetometer supplement the estimates made by other sensors, such as gyroscopes, enabling the attitude error to be bounded.

The dimensions of the high-permeability core can be modified to give the desired response characteristics. For example, shorter length cores give greater linearity, whereas long thin cores provide a higher output for a given drive power, hence greater sensitivity.

4.7.3 The transmission line gyroscope

The use of the inertia of an electromagnetic field as the rotation sensing element has been demonstrated many times, in applications such as the ring laser gyroscope and the fibre gyroscope, and is discussed in the following chapter. Consideration has also been given by some researchers to the use of non-propagating fields such as the electrostatic gyroscope.

Analysis has also been undertaken by Forder [23] of general relativistic effects which may be observed in a closed ring of parallel wire or coaxial transmission line, appropriately energised, with either static or propagating electromagnetic fields. Three distinct effects can be identified, viz. electrostatic, magnetostatic and electromagnetic, allowing this type of device to be operated as an angular motion sensor in a number of different modes. It is predicted that the changes in line voltage and current detected in a circular loop of transmission line of radius R and line impedance Z rotated at an angular rate Ω are given by:

$$\Delta V = -(ZI)\Omega R/c$$

or

$$\Delta V = -(V/Z)\Omega R/c \qquad (4.13)$$

where V is the charging potential, I is the line current and c is the speed of light.

Clearly, one of the major difficulties with the implementation of such devices is the detection of the very small changes in potential and current predicted above. However, practical forms of such sensors based on the above predictions may become feasible and practical in the future as various technologies advance.

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