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6.5 Multi-functional sensors

6.5.1 Introduction

Previous discussions in this book have indicated that elements that are vibrating change their frequency of resonance when rotated or accelerated. Alternatively, cantilevered piezoelectric materials can be used as transducers by measuring the change in electrical charge across a 'crystal' when it is deflected by an applied force. These principles have been applied by mounting several such 'elements' at particular orientations with respect to each other. This enables one sensor to produce information about both the applied acceleration along, and the rotation rate about, an axis. These instruments are often called multi-sensors.

Multi-sensors are not confined to bending cantilever or vibrating beam technologies. It will be recalled that a mechanical gyroscope, with a mass unbalance in its rotor support, will drift when subjected to an applied acceleration about an appropriate axis. This phenomenon can be applied using a cluster of three two-axis sensors, suitably oriented with appropriate known mass unbalance, to produce an inertial measurement unit that will provide information on both linear acceleration and rotation sensed about three reference axes.

The use of multi-sensors offers the distinct advantage of reducing the number of inertial instruments required to measure the rotation and linear motion of a vehicle. Only three instruments are required for some sensor types to give full inertial data in three axes. However, the information is generally mixed in each axis and needs to be separated at some particular frequency, usually the spin frequency of the assembly. There can also be problems in achieving satisfactory or compatible performance from both accelerometer and gyroscopic channels of a multi-sensor for some applications. An additional problem area can also be cross-coupling between the different channels, although careful design can minimise this effect.

6.5.2 Rotating devices

Research began on these devices in the United States and in Britain in the late 1970s. Such devices operate by detecting the change of dynamic input, or force, which is applied to a piezoelectric transducer. Such a device is mounted on a cantilever as shown in Figure 6.14 and can be attached rigidly to a rotating element. This transducer produces an alternating electric signal proportional to the applied input.

The two principal components of a rotating multi-sensor are:

1. a rotating assembly;
2. piezoelectric transducers.

Additionally, it is necessary to have a set of slip-rings to transfer the electrical signals from the transducers to the electrical connecting pins on the case.

Piezoelectric accelerometers do not have very low threshold, nor do they have good day-to-day stability characteristics. These deficiencies can be reduced if the sensor is designed to operate at only a set frequency, and then use synchronous demodulation to remove d.c. uncertainties.

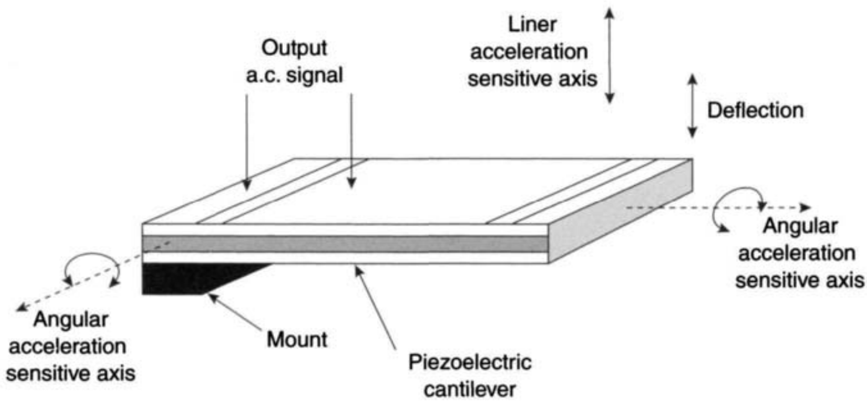

Figure 6.14 Piezoelectric accelerometer

Typically, there are four piezoelectric transducers mounted rigidly as cantilevers to the rotating assembly. The transducers are mounted in pairs, each pair being orthogonal to each other and orthogonal to the spin axis of the rotating member as shown in Figure 6.15. The construction and mounting is such that one set of transducers generates signals which are proportional to angular rate, whilst the other set produces signals proportional to linear acceleration.

Each transducer is made of layers of piezoelectric ceramic. These are ferroelectric materials, which are non-symmetric crystals and have a built-in electric dipole. In its polarised form, any stress applied to the structure results in a variation of the dipole moments causing a voltage to appear across the electrodes. Thus the material can convert mechanical energy to electrical signals and vice versa.

When a stationary cantilevered beam is oriented so that an applied acceleration deflects the beam, then a steady voltage results. However, if the beam is now rotated about an axis, so that when it has rotated by 180° the direction of the deflection is in the opposite direction, then the signal will have the reverse sense. In the case of continuous rotation of the beam, the output signal voltage is a sinusoid, with a frequency equal to the rotation frequency, the peak voltage being proportional to the applied acceleration.

As noted above, there are usually two identical cantilevered beams mounted on the rotating assembly, with their flexing axes co-linear with the spin axis. In this orientation, these transducers sense linear acceleration in the plane perpendicular to the spin axis. These rotating beams produce a suppressed carrier modulated spin frequency signal, with a peak amplitude proportional to the amplitude of the applied acceleration. The amplitude is a maximum when these transducers sense the total applied acceleration, and becomes a minimum when rotated through 90°. The principle of detection of angular rate is based on the gyroscopic behaviour of an elastically restrained body which is rotated about an axis. Usually, the cantilevered transducers are mounted 180° apart on the rotating assembly, for common mode rejection and also

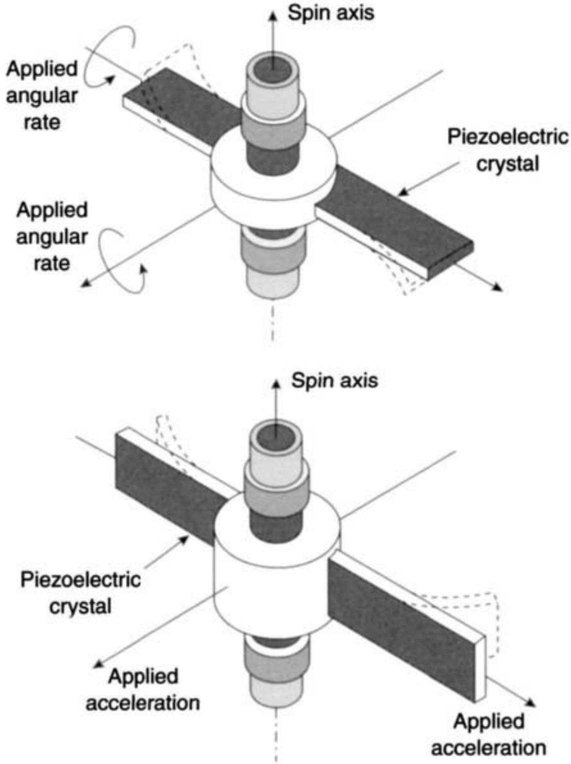

Figure 6.15 Principle of operation of a rotating multi-sensor

signal enhancement. As mounted, these transducer elements act both as the inertial members and the restraining springs.

When an angular rotation rate is applied to the spinning assembly, about an axis orthogonal to the spin axis, the angular momentum of the rotating transducers generates a forcing function, bending the transducer. This forcing function is a suppressed carrier signal modulated at the spin frequency of the mounting assembly. A plot of the amplitude of the signal generated is a sinusoid, its magnitude being proportional to the magnitude of the applied rate. The phase of the output is such that the maximum signal occurs when the sensing transducer is co-linear with the applied input. The minimum voltage occurs one quarter of a rotation away from the maximum signal.

Clearly, such an instrument can sense accelerations applied along two axes in the plane perpendicular to the spin axis. Similarly, it can sense angular rotation rates applied along two axes in the plane orthogonal to the spin axis. Therefore only two sensors are required to be mounted so that their spin axes are not parallel to enable three axes of angular rate data and three axes of linear acceleration data to be generated. The redundant information generated along and about the fourth axis is available for system checks.

These sensors are open-loop devices and consequently tend to have poorer scale-factor characteristics when compared with closed loop sensors such as the floated rate integrating gyroscope. Additionally, the scale-factor can change as the piezoelectric crystals age. However, these open-loop devices do not consume extra power, and consequently do not liberate heat, when measuring high rates of rotation.

These sensors are capable of very accurate measurement of angular rotation rates and linear acceleration. To achieve the high accuracies required for inertial navigation purposes, careful calibration and characterisation is necessary and temperature compensation is usually vital. Currently, the very accurate instruments tend to be quite large; up to 150 mm long by 35 mm diameter. This is offset by the fact that this single sensor provides four of the six measurements required by a navigation system.

Careful choice of certain components is necessary in order to contain certain error sources. Use of 'low noise' bearings minimises the noise coupled into the crystals producing a background signal. Noise generated by the slip rings is synchronous with the piezoelectric signals and consequently represents an acceleration or angular rate error. The measurement bandwidth of the sensor is dependent on the spin speed of the rotating assembly. Consequently, as it requires at least two readings per cycle to define a sinusoid, the rotating assembly must have a spin frequency at least twice that of the measurement bandwidth. For high bandwidth applications, this can lead to significant generation of bearing noise giving rise to potential saturation of the electronic measurement system.

Variations in temperature can also lead to changes in bearing generated noise as a result of variations in the bearing characteristics such as internal loading and viscosity changes to the lubricant. Additionally, variations in the temperature can alter the reference electronics used to resolve the acceleration and angular signals. This appears like a scale-factor error.

Typical performance data are given below:

Gyroscope:	
Maximum input rate	300–400°/s
g-Independent bias	1–10°/h
g-Dependent/mass unbalance bias	5–10°/h/g
Anisoelastic bias	0.1–0.2°/h/g^2
Scale-factor stability	0.1–2%
Scale-factor non-linearity	0.03–0.1%
Bandwidth	60–100 Hz
Accelerometer:	
Input range	up to $\pm 100g$
Scale-factor stability	0.1–2%
Scale-factor non-linearity	0.03–0.1%
Bias	1–10 milli-g
Threshold	1–10 micro-g
Bandwidth	>70 Hz

One concept that was the subject of a recent research programme was based on the use of rotating surface acoustic wave accelerometers mounted on a common shaft, instead of piezoelectric sensors. Angular motion and linear acceleration of the sensor's case are sensed by mounting pairs of surface acoustic wave accelerometers as cantilevers on a body that is rotated at a constant speed. When angular motion or linear acceleration is applied, the cantilevers are deflected owing to the various physical effects described earlier for the piezoelectric based sensor. The output signals are also generated using similar techniques.

The use of the surface acoustic wave elements offered several advantages as various effects, such as temperature induced biases, can be compensated. These effects can be compensated by the use of two surface acoustic wave oscillators on the same cantilever, as described in Section 6.4.2. Additionally, a digital output can be generated directly on the element and passed through the slip rings allowing the effect of noise on small signals to be eliminated. However, work on this sensor appears to be dormant.

6.5.3 Vibratory multi-sensor

Research into this form of sensor has been most active in the United States. It is a single-axis device based on vibrating sensor technology enabling measurements to be made of both angular rotation rates and linear acceleration. The sensor measures continuous angular rates by the oscillating Coriolis acceleration induced on an accelerometer which is being vibrated, and forces subject to oscillatory linear velocity. Typically, the accelerometer in this device uses silicon solid-state technology.

The principal components of this instrument are:

1. an accelerometer;
2. a vibrator (vibratory platform).

The principle of operation is essentially that of a pendulous accelerometer which is vibrated along its hinge or pivot axis (Figure 6.16). As a result of this vibration, an oscillatory linear velocity is imparted to the pendulum. Consequently, the accelerometer will sense a Coriolis acceleration at the frequency of vibration proportional to the angular motion applied about the axis of the pendulum. Additionally, the accelerometer will measure any linear acceleration applied along its input axis. The electrical signal generated by such a sensor will have a d.c. value proportional to the applied linear acceleration and an a.c. signal at the vibration excitation frequency. The latter signal can be demodulated to produce a signal which is proportional to the applied rotation rate about the axis of the pendulum.

In a practical device, an accelerometer using vibrating beam technology is excited by piezoelectric crystals. Typically, two accelerometers are vibrated 180° out of phase to give common mode rejection, thus preventing random inputs at the vibrating frequency from corrupting measurements. This type of sensor has many advantages through the elimination of rotating elements and bearings, but has the disadvantage of small signal-to-noise ratio for the angular rate measurement. Schemes have been devised to mount three accelerometers at various orientations on a plate, enabling

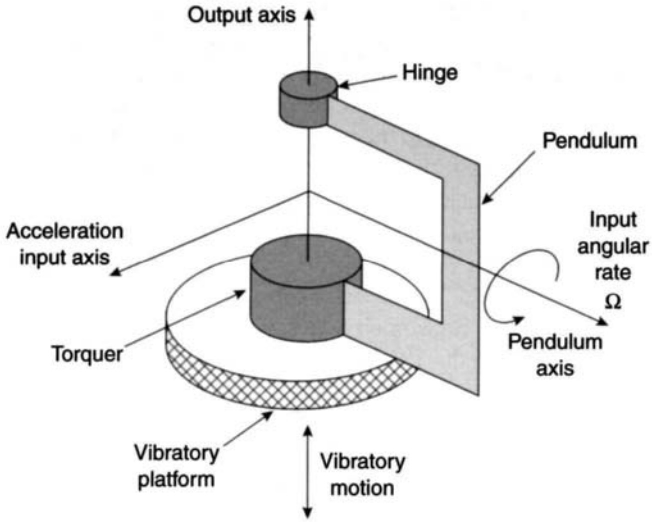

Figure 6.16 Principle of operation of a vibratory multi-sensor

them to be vibrated, or dithered, about the body diagonal of the reference axis set. Using one common activation axis has several advantages, such as the elimination of cross-talk and aliasing between the sensors. It also allows some common electronic circuits to be used resulting in a very compact three axis inertial measurement unit.

Anticipated performance parameters for this form of multi-sensor are as follows:

Gyroscope:	
Maximum input rate	±1000°/s
g-Independent bias	5–10°/h
Scale-factor stability	~0.1%
Scale-factor non-linearity	~0.05%
Bandwidth	>100 Hz
Accelerometer:	
Input range	up to ±200g
Scale-factor stability	~0.05%
Scale-factor non-linearity	<0.1%
Threshold	~10 micro-g
Bandwidth	>100 Hz

6.5.4 Mass unbalanced gyroscope

Angular momentum gyroscopes, such as the floated rate integrating gyroscope and the dynamically tuned gyroscope, are precision instruments requiring careful assembly to achieve the levels of performance normally required for most applications. During manufacture, particular care must be taken to ensure that the spinning rotor, or rate integrating gyroscope rotor/float combination, is balanced accurately. In the presence of a linear acceleration normal to the float axis in the case of the rate integrating gyroscope, or normal to the rotor spin axis in the dynamically tuned gyroscope, any mass unbalance will induce a torque, causing the rotor to precess, and so produce an erroneous rate measurement. However, by introducing a known amount of mass unbalance into gyroscopes of this type, it is possible to obtain a measure of the acceleration to which the instrument is subjected, in addition to the angular rates which it is sensing. Much of the pioneering work on this form of sensor was undertaken in Germany and the United States, but more recently in France [15].

This concept dates from the 1950s and indeed, instruments have been manufactured based on this principle for many years. The Honeywell precision integrating gyroscopic accelerometer (PIGA) is one such device. This type of device was also developed in the United Kingdom by Ferranti, now part of BAE Systems. The design of the PIGA was based on a single-axis floated gyroscope, in which the rotor was made pendulous with respect to the output axis of the instrument. Generally, this form of sensor was intended for use on stable platforms.

More recently, attention has focused on a development of the dynamically tuned gyroscope, which has the centre of suspension of its rotor displaced slightly with respect to its centre of gravity.

The displacement occurs along the motor drive shaft, in a manner that causes accelerations applied perpendicular to the drive shaft, that is, parallel to the input axes, to produce torques which cause precession of the rotor. This is shown schematically in Figure 6.17. As with the conventional dynamically tuned gyroscope, the device operates in a torque re-balance mode. However, in this case the pick-off outputs are fed back to null the precession caused by both the input rates and the applied accelerations.

A perfect two-axes gyroscope operating in a torque re-balance mode has the steady state relationship between the input rates, ω_x and ω_y, and the applied torquer moments, M_x and M_y, given by:

$$\begin{aligned} \omega_x &= -\frac{M_y}{H} \\ \omega_y &= \frac{M_x}{H} \end{aligned} \tag{6.4}$$

where H is the angular momentum of the rotor. If, in addition to the torquer moments, moments act as a result of the unbalance in the rotor suspension, the above equations take the form shown below, where the unbalance torques are proportional to the applied accelerations, a_x and a_y,

$$\begin{aligned} \omega_x &= -\frac{M_y + Ba_x}{H} \\ \omega_y &= \frac{M_x - Ba_y}{H} \end{aligned} \tag{6.5}$$

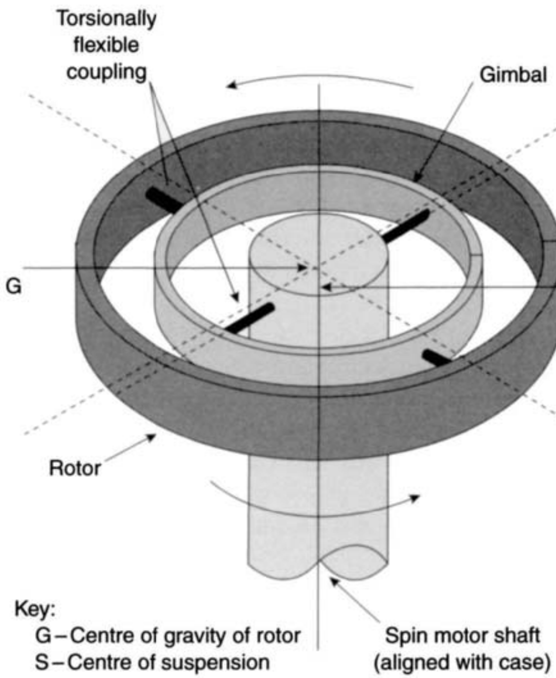

Figure 6.17 Mass unbalanced gyroscope rotor configuration

The factor B is a function of the displacement between the rotor centre of gravity and its centre of suspension, and the inertia of the rotor about an axis perpendicular to its spin axis. Rearranging eqn. (6.4) and writing $B/H = b$, the measurements, m_1 and m_2, provided by a single sensor may be expressed as follows:

$$\begin{aligned} m_1 &= -\frac{M_y}{H} = \omega_x + ba_x \\ m_2 &= \frac{M_x}{H} = \omega_y + ba_y \end{aligned} \tag{6.6}$$

Thus, a single gyroscope can provide a weighted sum of the turn rate about, and the acceleration along, each input axis. The constant b is referred to as the mass unbalance coefficient and may be expressed in units of °/s/g. The choice of b depends on many factors including the required measurement range of the gyroscope and the motion of the vehicle in which it is to be installed.

By combining three mass unbalanced gyroscopes of this type in an inertial measurement unit, it is possible to obtain estimates of angular rates and linear accelerations in three mutually orthogonal directions provided:

- the mass unbalance coefficient is different for each gyroscope;
- the spin axes of the gyroscopes are not co-planar.

A conventional strapdown system using dynamically tuned gyroscopes would require two such gyroscopes and three accelerometers. It is postulated therefore, that the three accelerometers may be replaced by one additional gyroscope to form a mass unbalanced 'navigation' system. Such a system has the advantage of using identical re-balance loop electronics for all sensors, and uses fully the information from each input axis. Potential disadvantages include reduced dynamic range compared with the conventional system, some additional computing complexity associated with the extraction of separate angular rate and linear acceleration estimates. Additionally, there is the possibility of additional dynamic cross-coupling between these quantities.

Analysis of the effects of bias, scale-factor and cross-coupling errors in a mass unbalanced system, reveals that each error term produces inaccuracies in the estimates of both angular rate and linear acceleration, the latter being functions of the mass unbalance coefficient, b. For example, take the case of an orthogonal system in which the mass unbalance coefficients for two of the gyroscopes are equal, but of opposite sign, and zero for the third gyroscope. The general form of the rate and acceleration estimation errors, $\delta\boldsymbol{\omega}$ and $\delta\mathbf{a}$, in such a system is illustrated by the following matrix form:

$$\begin{bmatrix} \delta\dot{\boldsymbol{\omega}} \\ \cdots \\ \delta\dot{\mathbf{a}} \end{bmatrix} = \begin{bmatrix} \mathbf{B}_\mathrm{f} \\ \cdots \\ \dfrac{\mathbf{B}_\mathrm{f}}{b} \end{bmatrix} + \begin{bmatrix} \mathbf{S} & \vdots & b\mathbf{S} + \mathbf{B}_g \\ \cdots & \vdots & \cdots\cdots \\ \dfrac{\mathbf{S}}{b} & \vdots & \mathbf{S} + \dfrac{\mathbf{B}_g}{b} \end{bmatrix} \begin{bmatrix} \boldsymbol{\omega} \\ \cdots \\ \mathbf{a} \end{bmatrix} \tag{6.7}$$

where $\mathbf{B}_\mathrm{f}$ is the fixed bias, $\mathbf{B}_g$ is the g-dependent bias or uncertainty in the mass unbalance coefficient, $\mathbf{S}$ is the matrix containing scale-factor errors and cross-coupling terms, $\mathbf{a}$ is the applied linear acceleration and $\boldsymbol{\omega}$ is the applied turn rate.

Preliminary tests of this type of device carried out under laboratory conditions [15] suggest that measurements of turn rate and acceleration can be derived to an accuracy of significantly less than 100°/h and less than 10 milli-g, respectively, and that the scale-factor error for such a device would be less than 10^{-3}. Errors in the acceleration measurements may be deduced, to a large extent, from the axial unbalance factor, which is assumed here to be in the region of 5°/h/g. In addition to the usual bias and scale-factor errors which arise when separate gyroscope and accelerometers are used, some additional cross-coupling between the rate and acceleration estimates arises in a mass unbalanced system.

6.6 Angular accelerometers

This form of inertial sensor provides a means for sensing angular motion. Traditionally, non-gyroscopic angular motion sensors have used a balanced mass suspended in bearings which generated a torque proportional to the applied angular acceleration. When the mass is constrained by a spring, the angular displacement is a measure of the angular acceleration.

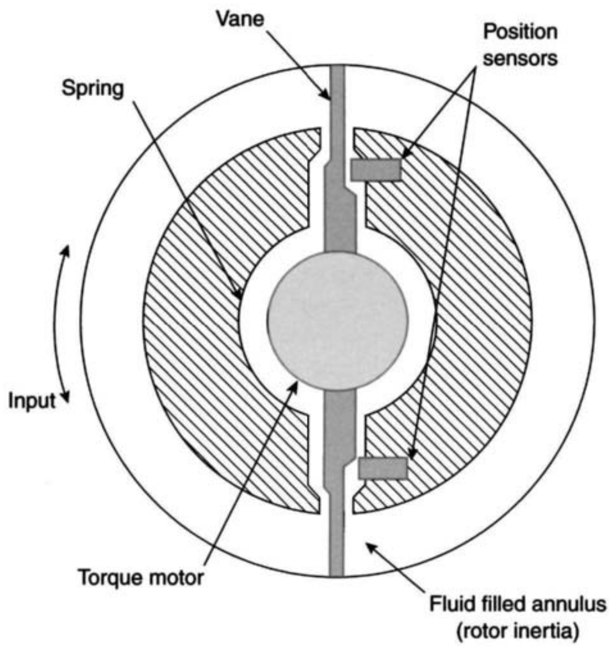

Figure 6.18 *Fluid rotor angular accelerometer*

There have been significant developments in the technology used in angular accelerometers. Small, compact, rugged and accurate sensors can now be produced, and have been applied to several applications. The devices may be operated in a closed or open-loop mode, depending on the configuration.

6.6.1 Liquid rotor angular accelerometer

Recently, progress in the development of this type of instrument in the United States has enabled it to evolve from a heavy, and often fragile, device to a small lightweight sensor. The modern devices have almost instantaneous readiness, reduced power consumption, enhanced ruggedness and increased sensitivity when compared with the older designs and have eliminated rotating elements.

A schematic diagram of a liquid rotor angular accelerometer is shown in Figure 6.18.

The fluid-filled sensor has an annular tube containing a liquid such as silicone oil, or a high density liquid of the type used in rate-integrating gyroscopes. This liquid forms the seismic or proof mass in the sensor. The annular tube is blocked by a disc connected to a galvanometer movement, supported by jewel and pivot bearings. This arrangement forms a servoed torque generator.

Application of an angular acceleration about the axis of the annular tube, would accelerate this tube leaving the inertial mass behind. However, the disc causes the fluid to move with the case, with a consequential reaction at the disc. This motion is sensed by the position-sensing mechanism and provides feedback to the galvanometer torquer, which provides the torques necessary to accelerate the fluid with the case. The magnitude of this feedback signal is directly proportional to the angular acceleration acting about the input axis.

This form of system provides a good deal of flexibility as the electronic gain can be set to generate full scale deflections for any given displacement of the disc. Various other parameters, such as the cross section, diameter and sensing area of the tube, as well as the density of the fluid in this tube, may be selected individually to provide the desired frequency response and sensitivity.

One common problem with this sensor is the effects of change in temperature and thermal gradients across the sensor which can produce non-linear responses and sensitivity to linear acceleration. Changes in ambient temperature can be corrected using a volume compensator. However, careful design and thermal screening are necessary to avoid thermal gradients across the instruments.

Typical performance parameters are given below:

Input acceleration	up to 50 rad/s^2
Scale-factor linearity	~0.1% of full range
Bias	~0.001 rad/s^2
Bias temperature coefficient	~0.0005 rad/s^2/°C
Threshold	~0.005% of full range
Bandwidth	up to 60 Hz

6.6.2 Gas rotor angular accelerometer

This design of angular accelerometer has some similarities with the instrument which uses a liquid rotor. However, in this case, a high density gas at a high pressure is contained in a single tube, its end being attached to a pressure sensor. Generally, this device is operated in an open-loop mode.

When angular motion is applied about an axis perpendicular to the plane containing the gas filled tube, there is relative motion between the tube and the gas. This motion is sensed using the pressure sensor which forms a barrier across the tube and prevents free flow around it.

The pressure generated by the gas rotor is usually quite small, typically in the range 10–100 Pa. Hence the pressure sensor must have high sensitivity. Additionally, it must impart a stiffness to the system to produce the necessary dynamic characteristics of the instrument. A pressure sensor with an electrically conductive membrane positioned between two circular electrodes, is one possible simple design that could be used to detect the gas motion. In this case, when a differential pressure is applied across the membrane, resulting from the motion of the gas, its displacement results in a differential capacitance change between the membrane and the electrodes. Alternative pressure sensors giving greater accuracy can also be used, although they are usually more expensive.

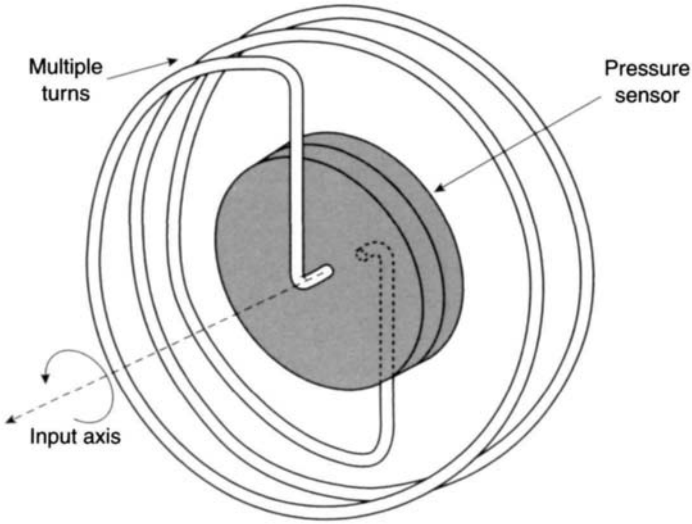

Figure 6.19 *Gas rotor sensor*

The tube containing the gas can be formed into any shape. However, a helix is the most common. The pressure generated is proportional to the mean radius of the helix, the number of turns, the density of the gas and, of course, the applied acceleration. Successful designs, with diameter of about 40 mm and a few tens of turns have been demonstrated. A constriction in the tube was necessary to provide damping of the motion of the gas.

A schematic diagram of a gas rotor angular accelerometer is shown in Figure 6.19.

As in the case of the liquid rotor, temperature gradients across the sensor must be avoided. Additionally, careful screening of leads and components is necessary to avoid stray capacitances corrupting the output signals.

Inherently, this design is very robust and offers a long operational life and low cost. However, there does not appear to be any current development activity of this type of sensor, in contrast with the status of the liquid rotor devices.

6.7 Inclinometers

An inclinometer is a gravity reference device capable of sensing tilt. The instrument is basically a special implementation of a linear accelerometer with low maximum acceleration capability. The accelerometer output is usually processed to give a d.c. voltage directly proportional to the angle of tilt. Typical applications of the inclinometer are platform levelling for target acquisition systems and fire control systems, and in inertial component testing.

6.8 Summary of accelerometer and multi-sensor technology

Many different types of inertial sensors can be used for sensing and measuring the magnitude of an 'accelerating' force. These sensors are of many different types and design. The review has included the mechanical sensors, using the classical pendulum principle, to the modern solid-state devices. Generally, all these instruments are suitable for strapdown applications and in such an environment will give accuracies ranging from tens of micro-gravitational acceleration (micro-g) to fractions of a 'g'.

The mechanical accelerometers come in various forms, with a selection of materials and designs for the pendulum's hinge mechanism. These sensors may be fluid filled in order to improve the damping of the motion of the pendulum. The pendulum may be constrained to very small displacements, through the use of force-feedback techniques, in order to achieve high accuracy. Alternatively, the sensor may be operated in an open-loop mode.

Solid-state technology offers various techniques that may be applied to enable small, reliable and relatively inexpensive instruments to be produced. A variety of techniques have been reviewed, including the use of optical fibres, vibratory devices, surface acoustic wave devices and the use of silicon materials. These sensors are generally operated in an open-loop mode, but some designs are amenable to the use of closed loop techniques. In the case of the closed loop mode, the displacement of the 'proof mass' is generally not returned to its 'null' position. Instead, the sensor operates by nulling an observed effect, such as a frequency change or a modified resonant condition.

A summary of typical performance characteristics[2] for a range of accelerometers is given in the following table.

Characteristic	Accelerometer type				
	Force-feedback pendulous	Vibrating fibre optic	Vibrating quartz	SAW	Silicon
Input range (g)	±100	±20	±200	±100	±100
Scale-factor stability (%)	0.1	0.001	0.01	0.1–0.5	0.5–2
Scale-factor non-linearity (% full scale)	0.05	0.05	0.05	<0.1	0.1–0.4
Fixed bias (milli-g)	0.1–10	1	0.1–1	<0.5	<25
Threshold (micro-g)	10	1	<10	1–10	1–10
Bandwidth (Hz)	400	100	400	400	400

[2] These are typical values applicable over the range of parameters stated. In many cases, the values given could be improved. However, it is not normally possible to have all the best case values in an single unit. These values are only for general indicative purposes.

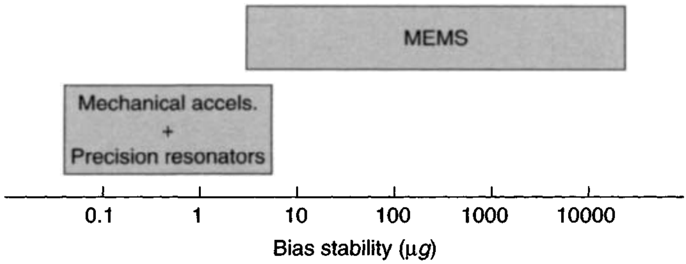

Figure 6.20 Near-term accelerometer performance summary

It is noted that substantially higher performance can be achieved using force-feedback devices. Precision devices capable of detecting accelerations as small as a few micro-g have been made with scale-factor stabilities of 10^{-5}%. However, such instruments are not normally designed to measure accelerations of $\pm 100g$.

Since the 1980s, there have been significant developments in the performance of so-called multi-sensors enabling a simple instrument to sense both linear and angular motion along and about two axes. These sensors offer significant potential for many applications in the future.

Finally, there has been progress in the state of the art of the manufacture of angular accelerometers, which can offer an alternative to the use of gyroscopes for some applications. The use of a fluid ring rotor to sense the applied motion has enabled small, sensitive, rugged and reliable angular accelerometers to be produced.

The performance of developed inertial sensors for near-term applications requiring acceleration measurements is shown in Figure 6.20.

It is believed that applications calling for high accuracy accelerometers will continue to incorporate mechanical sensors, with some use of resonant devices. In other application areas, MEMS sensors (see Chapter 7) are expected to become most widely used.

References

1 McLAREN, I.: 'Open and closed loop accelerometers'. AGARD, Agardograph No. 160, 6, 1974

2 SMITHSON, T.G.: 'A review of the mechanical design and development of a high performance accelerometer'. Proceedings *I.Mech.E., Mechanical Technology of Inertial Sensors*, C49/87, 1987

3 SCHULER, A.R., GRAMMATIKOS, A., and FEGBY, K.A.: 'Measuring rotational motion with linear accelerometers', *IEEE Transactions on Aerospace and Electronic Systems*, 1967, **AES-3** (3), p. 465

4 NEWMAN, F.H., and SEARLE, V.H.L.: 'The general properties of matter' (Edward Arnold, 1963)

5 PARKER, D.F., and MAUGIN, G.A. (Eds.): 'Recent developments in surface acoustic waves' (Springer Verlag, 1988)

6 ACHENBACH, J.D.: 'Wave propagation in electric solids' (North-Holland, 1973)
7 INTERNATIONAL SPECIALIST SEMINAR: 'Component performance and system applications of surface acoustic wave devices'. Proceedings, *Institution of Electrical and Electronic Engineers*, 1973
8 BARTH, P.W.: 'Silicon sensors meet integrated circuits', *IEE Spectrum*, 1981, **9**, p. 33
9 MIDDLEHOEK, S., and AUDET, S.A.: 'Silicon sensors' (Academic Press, 1989)
10 PETERSEN, K.E.: 'Silicon as a mechanical material'. *Proceedings IEEE*, 1982, **70** (5), pp. 420–457
11 YOUNG, M.: 'Optics and lasers' (Springer Verlag, 1992)
12 LUCKOSZ, W.: 'Integrated optical nanomechanical devices as modulators, switches, and as tunable frequency filters, and as acoustical sensors'. *SPIE*, 1973, *Integrated Optics and Microstructures*, 1992
13 MOREY, W.W.: 'Distributed fibre grating sensors'. Proceedings *OFS '90*, 1990, pp. 285–289
14 KERSEY, A.D., BERKOFF, T.A., and MORSEY, W.W.: 'Fibre-grating based strain sensor with phase sensitive detection'. Proceedings 1st European Conference on *Smart structures and materials*, 1992, pp. 61–62
15 MICHELIN, J.L., and MASSON, P.: 'Strapdown inertial systems for tactical missiles using mass unbalanced two-axis rate gyros'. AGARD Lecture Series No. 133, 1984