Chapter 6

Accelerometer and multi-sensor technology

6.1 Introduction

As described in Chapter 1, inertial navigation relies upon the measurement of acceleration which can be integrated successively to provide estimates of changes in velocity and position. Measurements of acceleration are used in preference to direct measurements of velocity or position because velocity and position measurements require an external reference whilst acceleration can be measured internally.

The form of construction of devices which may be used to sense acceleration may be classified as either mechanical or 'solid-state'. The technology of mechanical sensors is well established [1, 2] and devices capable of sensing acceleration over a wide accuracy range, from 50 milli-g down to a few micro-gs and to a similar level of resolution, are currently available. There have been significant advances in the development of solid-state sensors in recent years, particularly with silicon technology.

The concept of using a single instrument to measure acceleration and angular motion has been the subject of research for a number of decades and during the 1980s was developed by a number of institutions and companies. This device has become known as the multi-sensor and has tended to be based on either vibratory technology or gyroscopic mass unbalance technology. Evaluation of this technology has generally shown it to be capable of providing estimates of linear acceleration and angular motion compatible with sub-inertial[1] navigation applications.

6.2 The measurement of translational motion

The translational acceleration of a rigid body, resulting from the forces acting upon it, is described by Newton's second law of motion. A force F acting on a body of mass

[1] The term sub-inertial is sometimes used when describing system performance for short duration navigation systems. Typically, sub-inertial systems use gyroscopes and accelerometers with measurement biases of the order of $1\,^{\circ}$/h and 1 milli-g (1σ), respectively.

m causes the body to accelerate with respect to inertial space. This acceleration (a) is given by:

$$F = ma \tag{6.1}$$

Whilst it is not practical to determine the acceleration of a vehicle by measuring the total force acting upon it, it is possible to measure the force acting on a small mass contained within the vehicle which is constrained to move with the vehicle. The small mass, known as a proof or seismic mass, forms part of an instrument called an accelerometer. In its simplest form, the accelerometer contains a proof mass connected via a spring to the case of the instrument as shown in Figure 6.1.

When the case of the instrument is subjected to an acceleration along its sensitive axis, as indicted in the figure, the proof mass tends to resist the change in movement owing to its own inertia. As a result, the mass is displaced with respect to the body. Under steady state conditions, the force acting on the mass will be balanced by the tension in the spring, the net extension of the spring providing a measure of the applied force, which is proportional to the acceleration.

The total force (F) acting on a mass (m) in space may be represented by the equation:

$$F = ma = mf + mg \tag{6.2}$$

where f is the acceleration produced by forces other than the gravitational field. In the case of a unit mass, $F = a = f + g$. The acceleration (a) may be expressed as the total force per unit mass. An accelerometer is insensitive to the gravitational acceleration (g) and thus provides an output proportional to the non-gravitational force per unit mass (f) to which the sensor is subjected along its sensitive axis. As described in Chapter 2, this is referred to as the specific force exerted on the sensor.

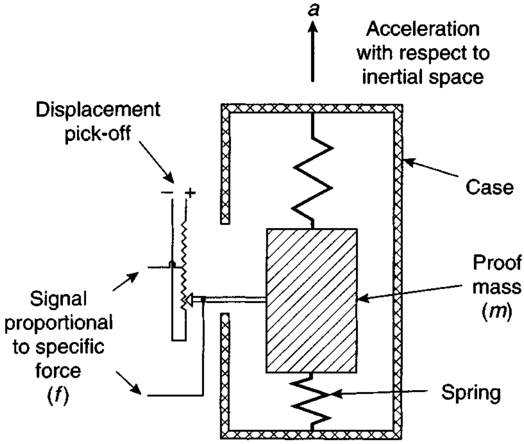

Figure 6.1 A simple accelerometer

Taking the case of an accelerometer which is falling freely within a gravitational field, the case and the proof mass will fall together with the result that there will be no net extension of the spring. Hence, the output of the instrument will remain at zero. In this situation, the acceleration of the instrument with respect to an inertially fixed set of axes, $a = g$ and the specific force is zero in accordance with the above equation. Conversely, in the situation where the instrument is held stationary, $a = 0$, the accelerometer will measure the force acting to stop it from falling. Following from eqn. (6.2), this force, $mf = -mg$, is the specific force required to offset the effect of gravitational attraction. It is clear therefore, that knowledge of the gravitational field is essential to enable the measurement provided by the accelerometer to be related to the inertial acceleration.

Many mechanical devices commonly used in present day inertial navigation systems for the measurement of specific force operate in a manner analogous to the simple spring and mass accelerometer described above.

In order to carry out the full navigation function, information is required about the translational motion along three axes, as described in Chapter 3. Commonly, three single-axis accelerometers are used to provide independent measurements of specific force, although multi-axis instruments can be used. It is common practice to mount the three accelerometers with their sensitive axes mutually orthogonal, although such a configuration is not essential, as will be discussed later.

The various principles of operation and performance of current accelerometer technology are reviewed in the following sections, covering both the mechanical and solid-state instruments. Later in the chapter, multi-sensors and angular accelerometers are reviewed in a similar way. Linear accelerometers may also be used to measure rotational motion [3]. However, owing to the need for very accurate measurements as well as precise sequencing and timing of the measurements, this technique is rarely used.

6.3 Mechanical sensors

6.3.1 Introduction

This is the broad division of sensors primarily described in Section 6.2 as mass–spring type devices. These sensors have been developed over many decades. Different construction techniques have been identified for use in different environments. Compact and reliable devices giving high accuracy and wide dynamic range have been produced in large quantities. The most precise force-feedback instruments are capable of measuring specific force very accurately, typically with resolutions of micro-g, or better. This class of mechanical sensors are used in both inertial and sub-inertial applications.

6.3.2 Principles of operation

As in the case of gyroscopes, accelerometers may be operated in either open or closed loop configurations. The basic principle of construction of an open-loop device is as follows. A proof mass is suspended in a case and confined to a zero position by means of a spring. Additionally, damping is applied to give this mass and spring system a realistic response corresponding to a proper dynamic transfer function. When the accelerations are applied to the case of the sensor, the proof mass is deflected with respect to its zero or 'null' position and the resultant spring force provides the necessary acceleration of the proof mass to move it with the case. For a single-axis sensor, the displacement of the proof mass with respect to its 'null' position within the case is proportional to the specific force applied along its input, or sensitive, axis.

A more accurate version of this type of sensor is obtained by nulling the displacement of the pendulum, since 'null' positions can be measured more accurately than displacements. With a closed loop accelerometer, the spring is replaced by an electromagnetic device that produces a force on the proof mass to maintain it at its 'null' position. Usually, a pair of coils is mounted on the proof mass within a strong magnetic field. When a deflection is sensed, an electric current is passed through the coils in order to produce a force to return the proof mass to its 'null' position. The magnitude of the current in the coils is proportional to the specific force sensed along the input axis. The force-feedback type is far more accurate than the open-loop devices and is currently the type most commonly used in inertial navigation systems.

6.3.3 Sensor errors

All accelerometers are subject to errors which limit the accuracy to which the applied specific force can be measured. The major sources of error which arise in mechanical accelerometers are listed below. Further details relating to specific types of accelerometer will be given later in this chapter where the physical effects which give rise to each type of error are discussed more fully.

Fixed bias: This is a bias or displacement from zero on the measurement of specific force which is present when the applied acceleration is zero. The size of the bias is independent of any motion to which the accelerometer may be subjected and is usually expressed in units of milli-g or micro-g depending on the precision of the device involved.

Scale-factor errors: Errors in the ratio of a change in the output signal to a change in the input acceleration which is to be measured. Scale-factor errors may be expressed as percentages of the measured full scale quantity or simply as a ratio; parts per million (ppm) being commonly used. Scale-factor non-linearity refers to the systematic deviations from the least-squares straight line, or other fitted function, which relates the output signal to the applied acceleration.

Cross-coupling errors: Erroneous accelerometer outputs resulting from accelerometer sensitivity to accelerations applied normal to the input axis. Such errors arise as a result of manufacturing imperfections which give rise to non-orthogonality of the sensor axes. Cross-coupling is often expressed as a percentage of the applied acceleration.

Vibro-pendulous errors: Dynamic cross-coupling in pendulous accelerometers arises owing to angular displacement of the pendulum which gives rise to a rectified output when subjected to vibratory motion. This type of error can arise in any pendulous accelerometer depending on the phasing between the vibration and the pendulum displacement. The magnitude of the resulting error is maximised when the vibration acts in a plane normal to the pivot axis at 45° to the sensitive axis and when the pendulum displacement is in phase with the vibration. This error may be expressed in units of g/g^2.

As in the case of gyroscopic sensors, repeatability errors, temperature dependent errors, switch-on to switch-on variations and in-run errors arise in sensors of this type. Even with careful calibration, the residual errors caused by the unpredictable error components will always be present, restricting the accuracy of inertial system performance.

6.3.4 *Force-feedback pendulous accelerometer*

6.3.4.1 *Detailed description of sensor*

These devices are also known as restrained pendulum accelerometers. The main components of such a sensor are:

1. A pendulum, which has a proof mass attached to it or as an integral part of it.
2. A suspension mechanism or hinge element. This flexible member attaches the pendulum to the case and is usually either a flexible hinge or a pivot type arrangement.
3. A pick-off device to sense motion of the pendulum. It may use optical, inductive or capacitive techniques. The optical system may be very simple, a detector measuring the change in transmittance of a light beam through a slit in the pendulum. The inductive system involves measuring the differential current in coils fixed to the case interacting with a plate on the pendulum, which affects the mutual inductance of the coils. This system measures the relative position of the pendulum between the pick-off coils and not the 'null' position. In the case of a capacitive system, movement of the pendulum causes a change in capacitance between the faces of the pendulum and two electrodes in close proximity to the pendulum. This change is sensed using a bridge circuit.
4. A force re-balance mechanism to oppose any detected movement of the pendulum. This component usually takes the form of two identical poles of two magnets arranged centrally about the proof mass and a pair of coils mounted symmetrically on the pendulum. A current flowing in the coils generates an electromagnetic restoring force. This component is often referred to as the torquer.
5. The various components are usually hermetically sealed in a case. The case may be filled with a low viscosity oil to give resistance to shock and vibratory forces in both its quiescent and active states. Alternatively, the case may be filled with a dry gas such as air.

Such a sensor is shown schematically in Figure 6.2.

Displacement of the pendulum, which occurs in the presence of an applied acceleration, is sensed by the pick-off. In the most simple devices, this displacement provides a direct measure of the applied acceleration. Generally however, a device of

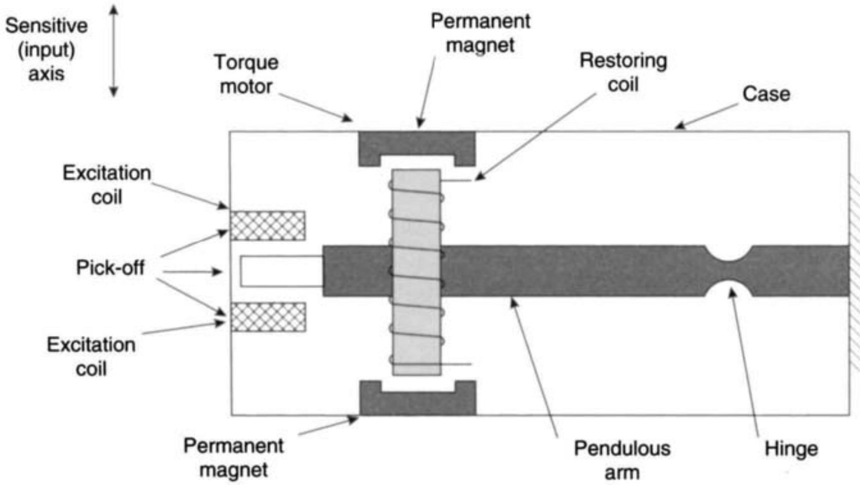

Figure 6.2 Force-feedback pendulous accelerometer

this type operates with an electronic re-balance loop to feed the pick-off signal back to the torquer. The electromagnetic force, produced by the torquer, acts to offset any displacement of the pendulum and maintain the pick-off output at zero. The current in the torquer coil is proportional to the applied acceleration. Operating the sensor in this mode means that the hinge is not under any bending stress.

6.3.4.2 *Sources of error*

Accelerometers of this type are capable of very high performance with good linearity, small biases and with a dynamic range in the region of 10^4–10^5. This is a dimensionless quantity obtained by dividing the maximum acceleration which the sensor can measure by its resolution. The dominant sources of error are as follows:

measurement bias which arises as a result of residual spring torques and 'null' shift in the electrical pick-off device used;
scale-factor error, principally caused by temperature effects and non-ideal behaviour of components;
cross axis coupling which gives rise to a measurement bias when the sensor is under 'g' loading in the direction of the hinge axis or the pendulum axis, the latter being essentially a hinge interaction effect;
vibro-pendulous error which can give rise to a measurement bias under certain conditions when the sensor is subject to vibration along the sensitive and pendulum axes simultaneously;
random bias caused by instabilities within the sensor assembly.

Further errors occur in the measurements provided by pendulous accelerometers, such as those resulting from hysteresis effects, non-repeatability of bias and higher order scale-factor errors. Changes in the characteristics of the permanent magnets may also change the scale-factor by a process known as ageing. This may be corrected by periodic recalibration.

The measurement provided by such sensor ($\tilde{a}_x$) may be expressed in terms of the applied acceleration acting along its sensitive axis (a_x) and the accelerations acting along the pendulum and hinge axes, a_y and a_z, respectively, by the equation:

$$\tilde{a}_x = (1 + S_x)a_x + M_y a_y + M_z a_z + B_f + B_v a_x a_y + n_x \tag{6.3}$$

where S_x is the scale-factor error, usually expressed in polynomial form to include non-linear effects, M_y, M_z are the cross axis coupling factors, B_f is the measurement bias, B_v is the vibro-pendulous error coefficient and n_x is the random bias.

6.3.4.3 *Typical performance characteristics*

Typical performance figures for the moderate accuracy sensors are as follows:

Input range	up to $\pm 100g$
Scale-factor stability	$\sim$0.1%
Scale-factor non-linearity	$\sim$0.05% of full scale
Fixed bias	$0.0001g$–$0.01g$
Bias repeatability	$0.001g$–$0.03g$
Bias temperature coefficient	$\sim 0.001g/°C$
Hysteresis	$<0.002g$
Threshold	$\sim 0.00001g$
Bandwidth	up to 400 Hz

Most of these figures are improved significantly with the very high accuracy accelerometers. Biases as low as a few micro-*g* can be achieved with very high precision sensors, whereas those likely to experience high accelerations in very dynamic environments usually have a bias of a few milli-*g*.

6.3.5 *Pendulous accelerometer hinge elements*

The hinge element of a pendulous accelerometer is the component that enables the proof mass to move in one plane normal to the hinge axis. It must be stiff normal to the hinge line to maintain the mechanical stability of the hinge relative to the case under conditions of dynamic loading. However, it must be flexible about the hinge line and must minimise unpredictable spring restraint torques that cannot be distinguished from applied accelerations. The hinge must not be overstressed by either shock acceleration or vibratory motion. It must also return to its 'null' position exactly when the proof mass is displaced, in order to give the sensor good bias stability. Hinge elements exist that enable the proof mass to move in two orthogonal directions. These are essentially a complex combination of two single-axis elements as described in Section 6.3.6.

The two basic forms of hinge elements are flexures and pivots, there being several variations of each type.

6.3.5.1 Flexure hinges

The materials used to form the hinge are selected for their low mechanical hysteresis in order to minimise unpredictable spring torque errors. Hysteresis effects are minimised by choosing the hinge dimensions so that hinge stresses under dynamic forces, and pendulum movement, are well below the yield stress for the hinge material. A material that is commonly used is the alloy beryllium–copper since, because of the high ratio of its yield stress to its Young's modulus [4], it is capable of sustaining a large deflection without exceeding its yield stress. Fused quartz is another very suitable material. Some designs have both the pendulum and the hinge etched from a quartz substrate.

The main advantages of flexure hinges are that they exhibit very low static friction so offer almost infinite resolution and very low threshold. However, these hinges have a significant temperature dependent bias that requires calibration and compensation for the most accurate applications. Additionally, these hinges can be susceptible to damage from shock accelerations and also demand very tight tolerance, typically in the region of a micrometer, if the desired flexure compliance is to be attained.

6.3.5.2 Jewelled pivot hinges

This form of hinge supports the pendulum between a pair of spring-loaded synthetic jewel assemblies. The spring loading provides three-dimensional shock protection. These hinges have very small temperature dependent bias characteristics. However, stiction, under very quiescent conditions, can limit the resolution and wear of the pivots in very harsh vibratory environments can be a problem. This can be partially alleviated by the use of very hard materials on the bearing surface such as silicon carbide.

There are many applications, particularly those requiring a low maximum acceleration capability (20*g* or less), where jewel and pivot hinges can offer a cheaper and more sensitive instrument. However, with higher accelerations and high vibratory environments, flexure hinges tend to provide enhanced performance.

6.3.6 Two-axes force-feedback accelerometer

This form of instrument has many applications including some of the most demanding; such as ship's inertial navigation systems. This sensor has a pendulum which has freedom to swing about two orthogonal axes. Like the single-axis device, described earlier, it is restrained to its 'null' position by electrically energised coils working in a permanent magnetic field.

Clearly, it is necessary to have a hinge that constrains the pendulum to deflect about these two orthogonal axes, albeit by very small angles. Typically, the pendulum is attached rigidly to a plate at its top end, which is attached by two weak leaf springs to another plate. This second plate is attached to the case by means of a second pair of similar hinges, which are mounted at 90° to the first pair of hinges. Motion of the pendulum is often damped by filling the case with silicone fluid.

The principle of operation is identical to that described above for the single-axis sensor. Its performance is similar to that which can be obtained using the higher grade single-axis devices.

6.3.7 Open-loop accelerometers

A common form of this sensor is the mass–spring device of the type described in Section 6.2. Generally, these instruments are less stable and less accurate than the closed loop accelerometers. Undesirable characteristics inherent in open-loop accelerometers are sensitivity to supply voltage variations, non-linearity of the displacement caused by the applied acceleration and high thermal coefficients of bias and scale-factor. Consequently, they are generally inappropriate for most inertial navigation applications and therefore the mechanical variant will not be discussed further. Currently, however, an optical open-loop pendulous fibre optic accelerometer is being developed and the principle of operation will be discussed in the following section.

6.3.7.1 Optical fibre accelerometer

The fundamental principle of operation of this sensor is identical to the mechanical device. The major difference essentially lies in the form of the pick-off mechanism and pendulous mechanism which allows accelerations about two axes to be sensed. Optical fibres have excellent mechanical strength and elastic modulus characteristics, and additionally have negligible thermal expansion over the normal operating temperature range of inertial sensors, but need to be selected carefully to have isoelastic properties.

In this sensor, the pendulum is a length of fibre cable with a proof mass attached, together with a micro-lens at the bottom of the fibre and light from a solid-state laser coupled into the top. When an acceleration is applied to the case along any axis normal to the fibre, the bottom is deflected. Its displacement is sensed and measured by means of the laser light passing through the optical fibre and being focused on to a two dimensional photo-sensitive array. A suitable array is a charge coupled imaging device (CCID) which can provide both x and y coordinates of the displacement. A schematic diagram of a fibre optic pendulous accelerometer is shown in Figure 6.3.

Several parameters determine the range of this sensor, viz.

- size of proof mass;
- diameter of the optical fibre;
- length of optical fibre;
- height of the suspension point above the photo-sensitive detectors;
- size of the photo-sensitive array.

Currently, the accuracy is limited by the pixel density of the photo-sensitive array. Performance data are not currently available.

6.4 Solid-state accelerometers

During recent years, there has been intensive research effort to investigate various phenomena that could be used to produce a solid-state accelerometer. Various devices have been demonstrated, with surface acoustic wave, silicon and quartz devices being

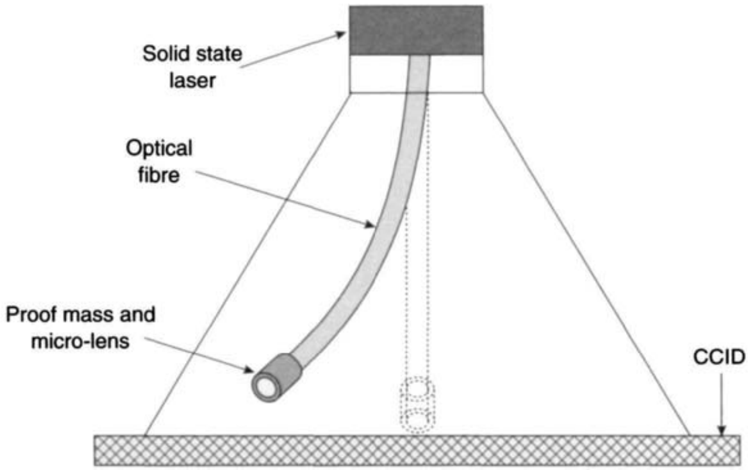

Figure 6.3 Pendulous fibre optic accelerometer

most successful. These sensors are small, rugged, reliable and offer the characteristics needed for strapdown applications.

Many of the devices discussed below have been the subject of research studies into the concepts only and have not been developed for particular applications as far as the authors are aware. In these cases, performance figures are not given.

6.4.1 Vibratory devices

These are open-loop devices which use quartz crystal technology. A common configuration uses a pair of quartz crystal beams mounted symmetrically back-to-back, each supporting a 'proof mass' pendulum. A schematic representation of such a device is shown in Figure 6.4.

Each beam is made to vibrate at its own resonant frequency. In the absence of any acceleration along the axis sensitive to acceleration, both beams vibrate at the same resonant frequency. However, when an acceleration is applied along the sensitive axis, one beam experiences compression whilst the other is stretched, or under tension, owing to the inertial reaction of the proof mass. The result is that the beam in compression experiences a decrease in frequency, whereas the beam in tension has an increase in frequency. The difference in frequency is measured and this is directly proportional to the applied acceleration.

Some of the errors often associated with this type of technology can be minimised by careful design. The symmetrical arrangement of the beams produces a cancellation of several errors that exist if only one beam is used. Error effects that are usually alleviated, or even eliminated, by this design include variations in nominal beam frequency owing to temperature changes and ageing of the quartz, asymmetrical scale-factor non-linearities, anisoinertia errors and vibro-pendulous effects.

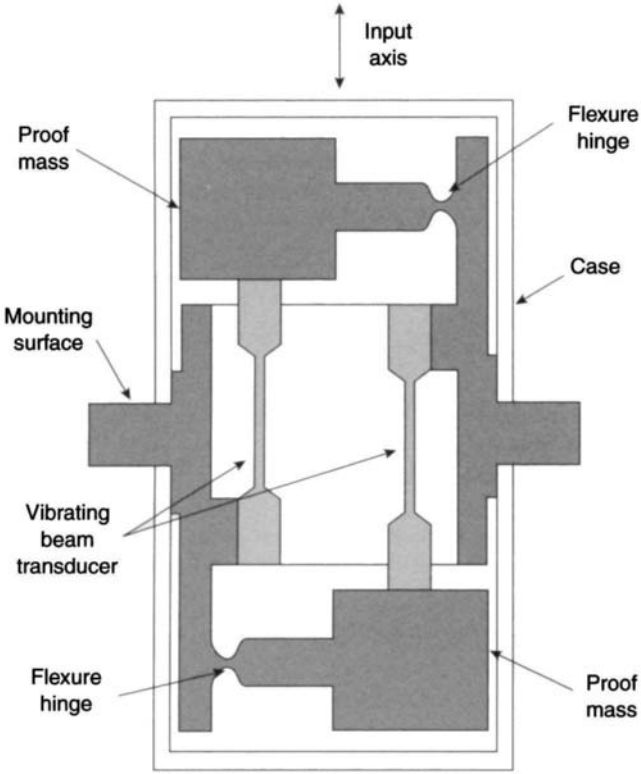

Figure 6.4 Vibrating beam accelerometer

Typical performance data are shown below:

Input range	±200*g*
Scale-factor stability	~100 ppm
Scale-factor non-linearity	~0.05% of full scale
Bias	~0.1–1 milli-*g*
Threshold	<10 micro-*g*
Bandwidth	>100 Hz

6.4.2 Surface acoustic wave accelerometer

This sensor is an open-loop instrument that has a surface acoustic wave resonator electrode pattern on the surface of a piezoelectric quartz cantilever beam [5, 6]. This beam is rigidly fixed at one end to the 'case' of the structure but is free to move at the other end, where a proof mass is rigidly attached, as shown in Figure 6.5. A surface

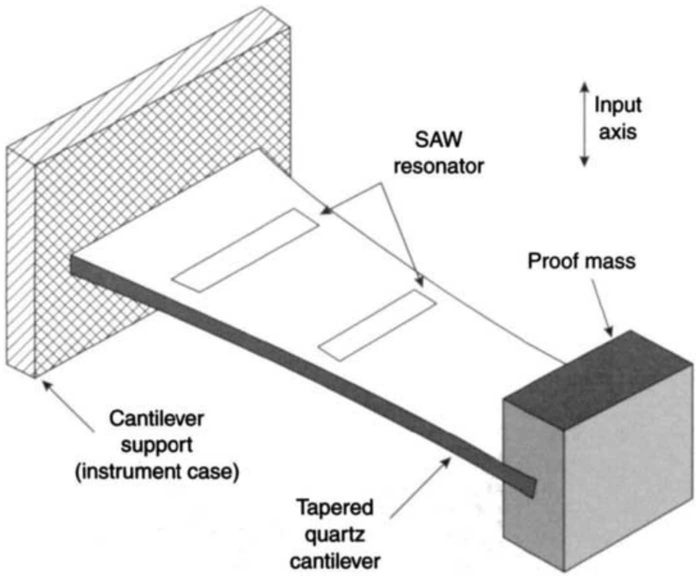

Figure 6.5 Surface acoustic wave accelerometer

acoustic wave train [7] is generated by use of the positive feedback between a pair of the metal electrode inter-digital arrays, its wavelength being determined by the separation of the metal electrodes, often called fingers.

When an acceleration is applied normal to the plane containing the beam, the inertial reaction of the assembly causes the beam to bend. When the surface of the beam is subjected to an applied strain, as occurs when the beam bends, the frequency of the surface acoustic wave changes in proportion to the applied strain. Comparison of this change with the reference frequency provides a direct measure of the acceleration applied along the sensitive axis.

The effects of temperature and other effects of a temporal nature can be minimised by generating the reference frequency from a second oscillator on the same beam. Lock-in type effects are prevented by ensuring that this reference signal is at a slightly different frequency from that used as the 'sensitive' frequency.

Typical performance data are shown below:

Input range	$\pm 100g$
Scale-factor stability	0.1–0.5%
Scale-factor non-linearity	<0.1%
Bias	<0.5 milli-g
Threshold	1–10 micro-g
Bandwidth	~400 Hz

6.4.3 Silicon sensors

Over the last decade or so, there have been research studies directed to fabricating accelerometers from silicon [8, 9]. As a material, silicon has many advantages over other materials [10]. 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.

In one concept, micro-machining techniques were used to form cantilevered beams of silicon dioxide over shallow cavities etched in silicon. The end of the cantilever beam was gold plated to provide the proof mass and hence increase the sensitivity of the instrument. The cantilever was metal plated along its top surface to form one plate of a capacitor, the silicon substrate forming the other plate of the capacitor, as illustrated in Figure 6.6. This form of accelerometer can be operated

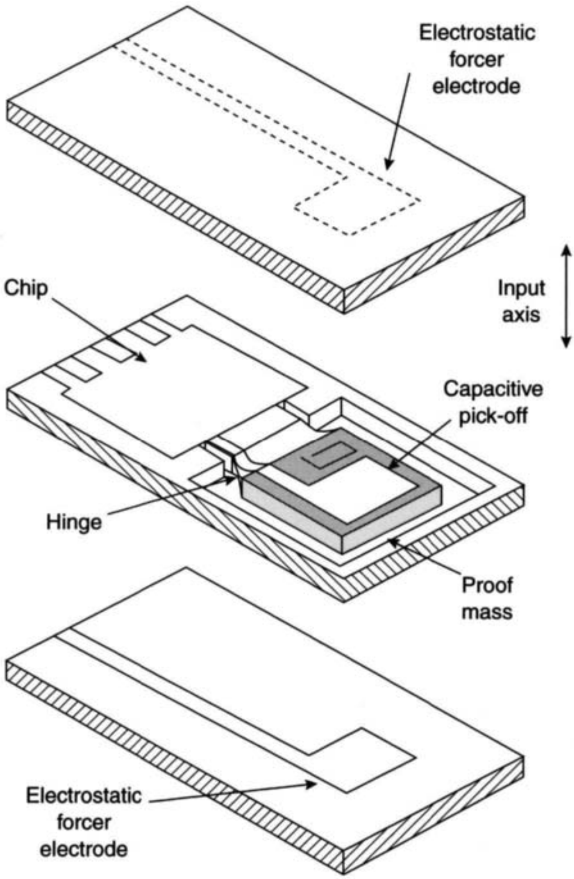

Figure 6.6 Silicon accelerometer

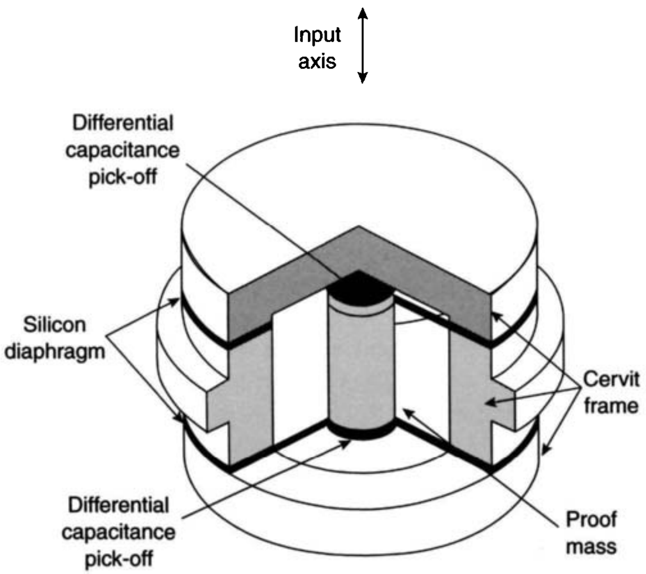

Figure 6.7 Monolithic accelerometer

in either an open-loop mode or as a closed loop device. In the open-loop mode, the capacitance between a pair of metal plates changes with the deflection of the cantilever, that is, the applied acceleration. In the closed loop mode, as shown in Figure 6.6, a pair of electrodes are used to null any deflections of the cantilever. Use of the closed loop mode increases its sensitivity. Although such devices tend not to be very accurate, they are very small and quite rugged.

A monolithic accelerometer was developed in the United States during the early 1980s. A cylindrical proof mass was supported by single crystal silicon diaphragm discs which were hinged on a cervit frame, as shown in Figure 6.7. This instrument was operated open-loop, using a differential capacitive pick-off on each end to detect motion of the proof mass when subjected to an applied acceleration. The materials were chosen to provide a thermally stable path. The major problem areas with this instrument have centred around difficulties machining the materials, achieving adequate scale-factor linearity and bonding the components together. Currently, performance data are not available for this sensor.

Another form of silicon accelerometer that is currently under development has frequency sensitive resonant tie bars integrally attached to a silicon seismic mass. These tie bars are maintained at mechanical resonance, typically vibrating at frequencies between 40 and 100 kHz depending on the configuration. When an acceleration is applied along the sensitive axis, movement of the seismic mass induces a strain in the tie bars resulting in a change in frequency of the order of tens of hertz for each applied unit *g*. This change in frequency is reasonably detectable. A conceptual diagram of this sensor is shown in Figure 6.8.

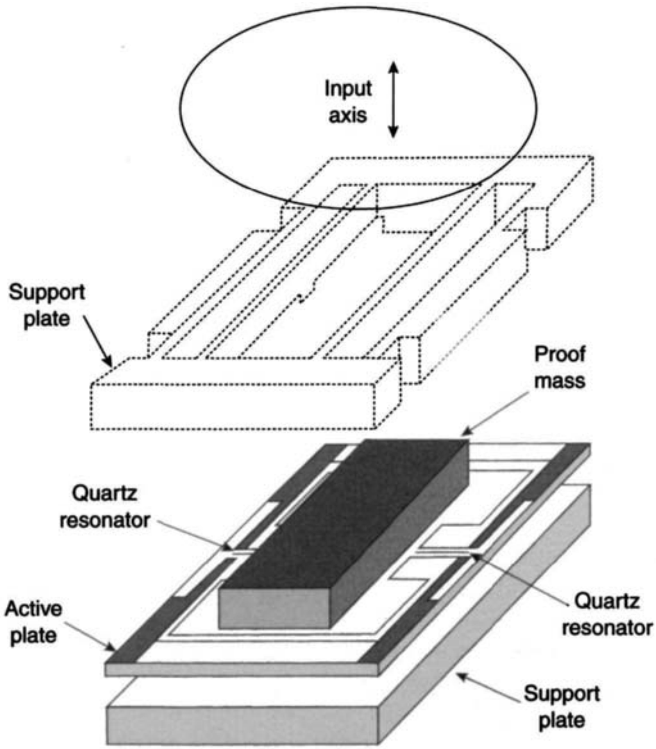

Figure 6.8 *Resonant silicon accelerometer*

Typical performance parameters are:

Input range	$\pm 100g$
Scale-factor stability	0.5–2%
Scale-factor non-linearity	0.1–0.4%
Bias (with compensation)	<25 milli-g
Threshold	1–10 micro-g
Bandwidth	~400 Hz

Work in the United Kingdom has investigated a thermal excitation method as an alternative to the use of piezoelectric transducers for excitation of the proof mass. This thermal excitation technique is achieved by depositing a form of bimetallic strip on the tie bars, which is used in place of the piezoelectric transducer.

A bimetallic element is formed on a tie bar by the deposition of a resistor on the top surface of a tie bar. Application of a potential difference to this resistive load produces localised heating on the top surface of the tie bar. Consequently, there is an expansion of the hot surface with respect to the cooler surface which causes the tie bar to bend. If an alternating potential is applied to this resistive load, then the localised heating will be periodic and the top surface of the tie bar will expand and contract with respect to the lower surface, depending on the heating cycle of the resistive material. The frequency of the applied current is chosen to be synchronous with one of the natural resonant frequencies of the tie bars. As a result of this periodic bending of the tie bars, the proof mass is forced to oscillate as described above for the piezoelectric excitation technique.

A second resistor is located on each of the driving tie bars and is used as a detector to sense the oscillation frequency. This is then used as the feedback signal to modify the frequency of the applied alternating current. The drive and control electronics can also be formed in the silicon material. Quality factors in excess of 1000 have been demonstrated with such designs.

Variation in the heating effect produced by the resistive material on the tie bars is achieved by applying a suitable bias in combination with the alternating drive current. Consequently, the variation in the polarity of this applied potential allows the heating effect of the resistive material to be modulated at the frequency of this applied potential.

The main motivation for the development of this excitation technique was that an all silicon sensor could be developed. Several techniques exist for the deposition of the resistive heating elements on to the tie bars. Examples include direct diffusion doping or polysilicon deposition. Similar techniques can be used to form the detector.

6.4.4 Fibre optic accelerometer

The use of fibre optical elements is very attractive for many applications as the fibre optical waveguide is immune to electromagnetic interference. One form of fibre optic sensor has already been described, as it is very similar in operation to the pendulous accelerometers; the fibre optics merely providing an alternative form of readout. Other forms of fibre optic accelerometer rely on some physical change in a component which can be sensed using electromagnetic radiation.

Ensuring that these changes are linear functions of acceleration in known directions remains a difficult development problem, although the use of fibre technologies gives a very sensitive position readout.

6.4.4.1 Mach–Zehnder interferometric accelerometer

A Mach–Zehnder interferometer [11] uses either one or two optical fibres attached to an inertial mass as its sensitive element. When an acceleration is applied along the axis of the optical fibre, this will produce a small change in length which is proportional to the applied acceleration. The change in length can be detected by interferometric techniques similar to those described for the fibre optic gyroscope. The use of two optical fibres allows each fibre to form an arm of the interferometer and the use of nulling techniques enables greater sensitivity to be achieved, along with compensation for temperature changes in the fibres. Additionally, it is necessary to constrain the proof mass to move only along the sensitive axis of the instrument.

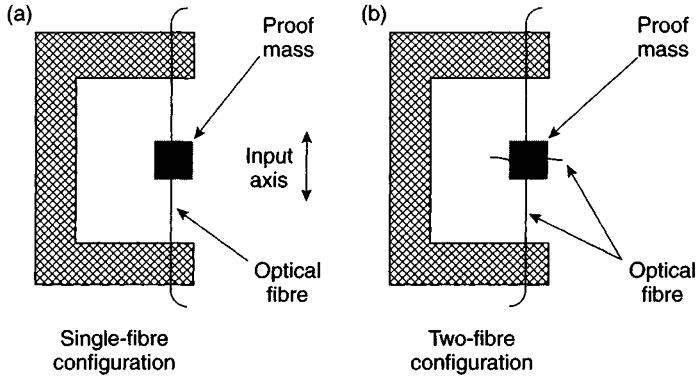

Figure 6.9 Sensitive elements of a Mach–Zehnder interferometric accelerometer

Schematic illustrations of the sensitive elements of two possible configurations are shown in Figure 6.9.

A very sensitive sensing element for accelerometers can be produced by winding a fibre optic coil around a compliant former, such as a rubber cylinder. When an acceleration is applied to the sensing element it changes dimensions and hence produces a phase change in the interferometer which is proportional to the applied acceleration. The sensitivity of the device is proportional to the number of optical fibre turns on the cylinder. Maximum sensitivity can be achieved by operating the device in a feedback mode, as shown in Figure 6.10. The intensities of the two light beams in the interferometer are detected separately and compared in a differential amplifier. The output signal from this component can then be used to 'drive' a piezoelectric device to null the phase change introduced by the distortion of the sensing element. The output of the differential amplifier is proportional to the applied acceleration. Again, it is necessary to constrain the movement of the element to be only along the sensitive axis of the device. Other technological concerns are the longer term stability of the compliant component and the effect of the different thermal expansion coefficients.

6.4.4.2 Vibrating fibre optic accelerometer

A short length of single mode optical fibre is fastened and tensioned between two pivot points in a rigid structure. This structure is vibrated so that the optical fibre oscillates at its fundamental frequency. In the absence of any applied acceleration, the displacements are symmetrical and the maximum stretch occurs at the maximum displacement with relaxation as it passes the centre line. Light passing through this optical fibre is phase modulated at $2f$, and at higher-order even harmonics of f, where f is the fundamental frequency. However, when the sensitive element is subjected to an acceleration parallel to the plane containing the oscillation, the displacement of the fibre will now be asymmetrical.

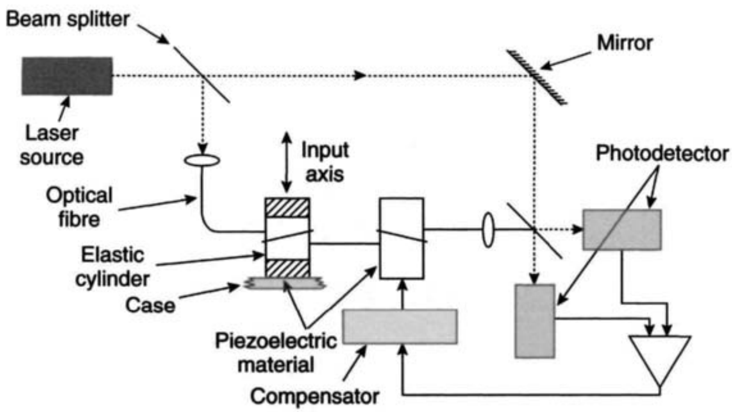

Figure 6.10 Interference accelerometer

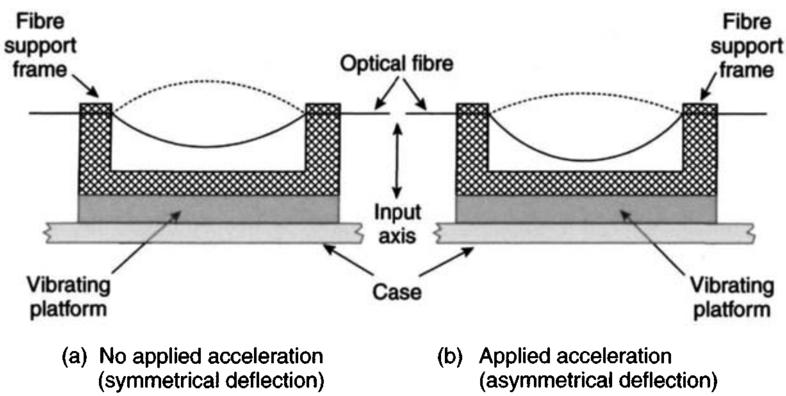

Figure 6.11 Oscillating modes of a vibrating fibre accelerometer

Light passing through the optical fibre will now be phase modulated at f and at the odd harmonics of f. The first and odd harmonic phase modulation has an amplitude proportional to the applied acceleration, and its phase relative to the drive signal will depend on the sense of the applied acceleration. Again, fibre optic interferometric techniques are used to sense the phase changes. Care is necessary in the choice of fundamental frequency and the design to reduce the effects of orthogonal acceleration sensitivities and environmental vibratory motion. The displacement of the fibre is shown schematically under the conditions of no acceleration and applied acceleration in Figure 6.11.

It may be possible to produce an amplitude modulation system by using 'lossy' multi-mode optical fibre, which is optimised for micro-bending losses, described in Figure 6.11. In this case, light which is guided along the vibrating optical

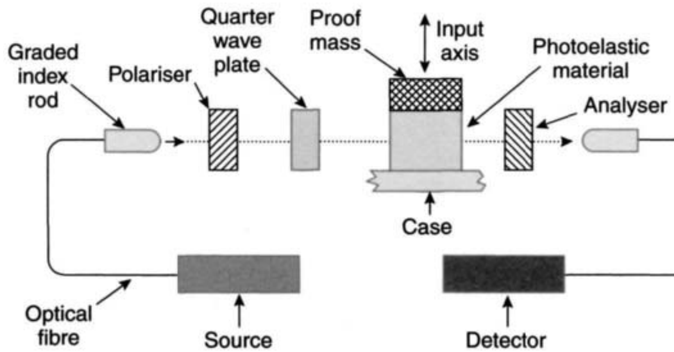

Figure 6.12 *Photo-elastic accelerometer*

fibre, is coupled into the cladding surrounding the optical core at the support points. This occurs as a consequence of the bending of the fibre decreasing the barrier between the core and cladding modes. Such a system would not need to use interferometry to determine the magnitude of the applied acceleration. This is because this technique converts the device from a phase modulator to an amplitude modulator.

6.4.4.3 Photo-elastic fibre optic accelerometers

The sensitive element in this device is a birefringent material [11]. Suitably polarised light is coupled into the sensitive element using multi-mode optical fibre. When an acceleration is applied to the photo-elastic material the transmission of light through it changes and the change is proportional to the applied acceleration. Research is continuing with this form of sensor. A schematic diagram of an engineering concept is shown in Figure 6.12.

6.4.4.4 Bragg grating fibre accelerometer

Research work in the United States and in Europe, at the Microelectronic Centre of Denmark, has demonstrated an accelerometer containing a Bragg grating in an optical waveguide. The centre wavelength of a Bragg grating is determined by the characteristics of the grating but can be changed by changes in the temperature, strain and pressure applied to the grating [12, 13]. Thus, an optical waveguide containing a Bragg grating is distorted when an acceleration is applied along the waveguide, the wavelength of light transmitted along the waveguide changes. This change in wavelength is proportional to the applied acceleration. The change is small but can be detected using a fibre interferometer [14].

The effect of the applied acceleration can be enhanced if the fibre waveguide is rigidly bonded to a proof mass. The general layout of this sensor is shown in the schematic diagram in Figure 6.13a. Care is necessary to ensure that the proof mass and fibre move in the direction of the applied acceleration and do not deflect

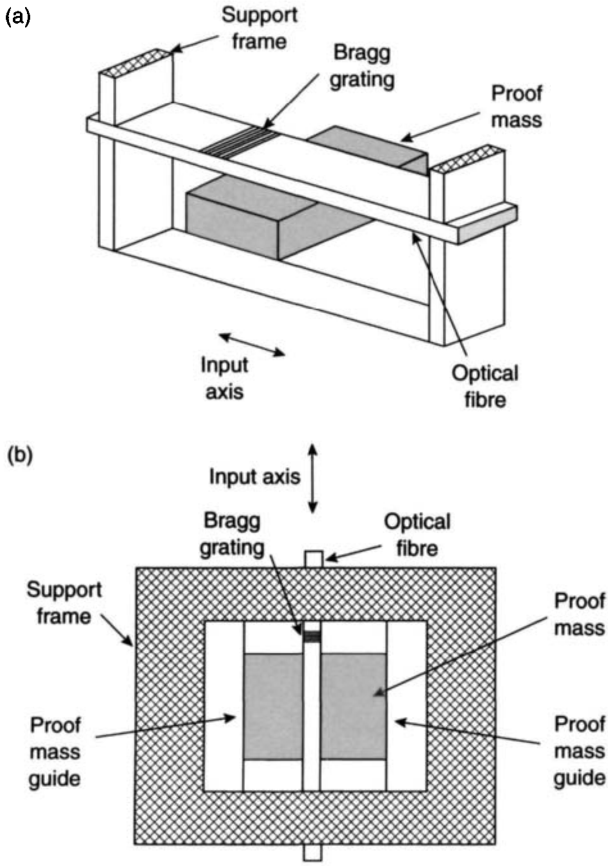

Figure 6.13 Bragg grating fibre accelerometer. (a) Schematic layout. (b) Section view

when cross-axis accelerations are applied. This is accomplished using 'guides' as shown in Figure 6.13b. Clearly, care is necessary to ensure that movement of the proof mass is not impeded by these 'guides'. Performance data are not available, but initial measurements suggest sensitivities of these devices to be in the micro-g regime.

6.4.4.5 Combined fibre optic sensors

The use of similar materials such as solid-state lasers, photo-detectors, optical fibres and common techniques in the fabrication of the sensors, suggests that there is plenty of scope for producing integrated devices, enabling both angular rate and linear acceleration to be sensed in a single device. The operation of the individual aspects of each sensor has already been dealt with in each appropriate section and will not be repeated here. The major problems are associated with the integration of the individual components and the sharing of components. Additionally, it is necessary to isolate particular processes, such as modulation frequencies, in order that effects can be identified uniquely.

6.4.5 Optical accelerometers

It appears that there have been relatively small developments in this class of sensor. The value of optical readout techniques is well recognised, particularly with respect to enhanced sensitivity leading to greater resolution and accuracy. This class of device may provide resolution in the nano-g range and be valuable for detecting seismic disturbances or gravity gradients, but of course other features of the accelerometer must be compatible with this aspect of performance, particularly the noise in the output signal. This class of performance is comparable with the MEMS tunnelling devices (Section 7.4.4), and so may compete for similar applications.

There is some continuing research involving fibre optical accelerometers and fibre Bragg devices; the physical principles of these devices are reviewed in Section 6.4.4.

Measurement of applied acceleration has been demonstrated using optical micro-spheres. In this case the light coupled into an optically resonant micro-sphere changes as the sphere moves towards a waveguide.

6.4.6 Other acceleration sensors

Many physical effects have been exploited over the last half century or more in an attempt to measure acceleration. For completeness, two other interesting concepts known to the authors are discussed below. Generally, these programmes are not active, but either or both could become active if there is a significant change in a relevant technology.

6.4.6.1 Solid-state ferroelectric accelerometer

Attempts have been made to use the piezo-optic and dielectric properties of ferromagnetic materials. It was hoped to measure the magnitude of the applied acceleration as a function of the strain or pressure induced in a thin fibre of this material. However, technological limitations in the past prevented the feasibility of the device being demonstrated.

6.4.6.2 Solution electrolytic accelerometer

This is a solid-state ion device, making use of a shift in ions in a solution owing to the application of an acceleration. This motion causes a resultant change in the potential in the electrolyte and this potential change was found to be proportional to the applied acceleration, with good linearity. However, the electrolyte is, by its very nature thermally sensitive. This device was originally developed as part of the German missile programme during World War II.