applications, where very high measurement resolution is required, although the measurement range afforded is extremely small and a coarser-resolution instrument must be used in parallel with it to extend the measurement range. Gyroscopes, in both mechanical and optical forms, are used to measure small angular displacements up to $\pm 10^\circ$ in magnitude in inertial navigation systems and similar applications.

20.2.10 Calibration of Rotational Displacement Transducers

The coded-disk shaft encoder is normally used for the calibration of rotary potentiometers and differential transformers. A typical model provides a reference standard with measurement uncertainty of $\pm 0.1\%$ of the full-scale reading. If greater accuracy is required, for example, in calibrating encoders of lesser accuracy, encoders with measurement uncertainty down to of $\pm 0.0001\%$ of the full-scale reading can be obtained and used as a reference standard, although these have a very high associated cost.

20.3 Rotational Velocity

The main application of rotational velocity transducers is in speed control systems. They also provide the usual means of measuring translational velocities, which are transformed into rotational motions for measurement purposes by suitable gearing. Many different instruments and techniques are available for measuring rotational velocity as presented below. MEMS gyroscopes have also been added to the list in this new edition. These measure transient rather than continuous velocities, but are now widely used in many applications.

20.3.1 Digital Tachometers

Digital tachometers, or to give them their proper title, digital *tachometric generators*, are usually noncontact instruments that sense the passage of equally spaced marks on the surface of a rotating disk or shaft. Measurement resolution is governed by the number of marks around the circumference. Various types of sensor are used, such as optical, inductive, and magnetic ones. As each mark is sensed, a pulse is generated and input to an electronic pulse counter. Usually, velocity is calculated in terms of the pulse count in unit time, which of course only yields information about the mean velocity. If the velocity is changing, instantaneous velocity can be calculated at each instant of time that an output pulse occurs, using the scheme shown in Figure 20.16. In this circuit, the pulses from the transducer gate the train of pulses from a 1 MHz clock into a counter. Control logic resets the counter and updates the digital output value after receipt of each pulse from the transducer. The measurement resolution of this system is the highest when the speed of rotation is low.

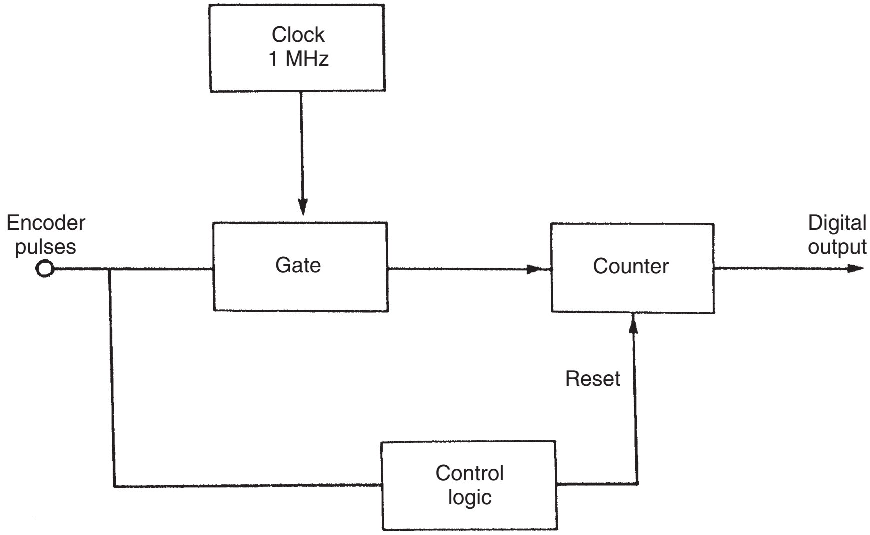

Figure 20.16
Scheme to measure instantaneous angular velocities.

Optical sensing

Digital tachometers with optical sensors are often known as *optical tachometers*. Optical pulses can be generated by one of the two alternative photoelectric techniques illustrated in Figure 20.17. In the scheme shown in Figure 20.17(a), the pulses are produced as the windows in a slotted disk pass in sequence between a light source and a detector. The alternative scheme, shown in Figure 20.17(b), has both light source and detector mounted on the same side of a reflective disk that has black sectors painted onto it at regular angular intervals. Light sources are normally either lasers or LEDs, with photodiodes and phototransistors being used as detectors. Optical tachometers yield better accuracy than other forms of digital tachometer. However, they are less reliable than other forms because dust and dirt can block light paths.

Inductive sensing

Variable reluctance velocity transducers, also known as *induction tachometers*, are a form of digital tachometer that use inductive sensing. They are widely used in the automotive industry within antiskid devices, antilock braking systems and traction control. One relatively simple and cheap form of this type of device was described earlier in Section 13.2 (Figure 13.2). A more sophisticated version, shown in Figure 20.18, has a rotating disk that is constructed from a bonded-fiber material into which soft iron poles are inserted at regular intervals around its periphery. The sensor consists of a permanent magnet with a shaped pole piece, which carries a wound coil. The distance between the pickup and the

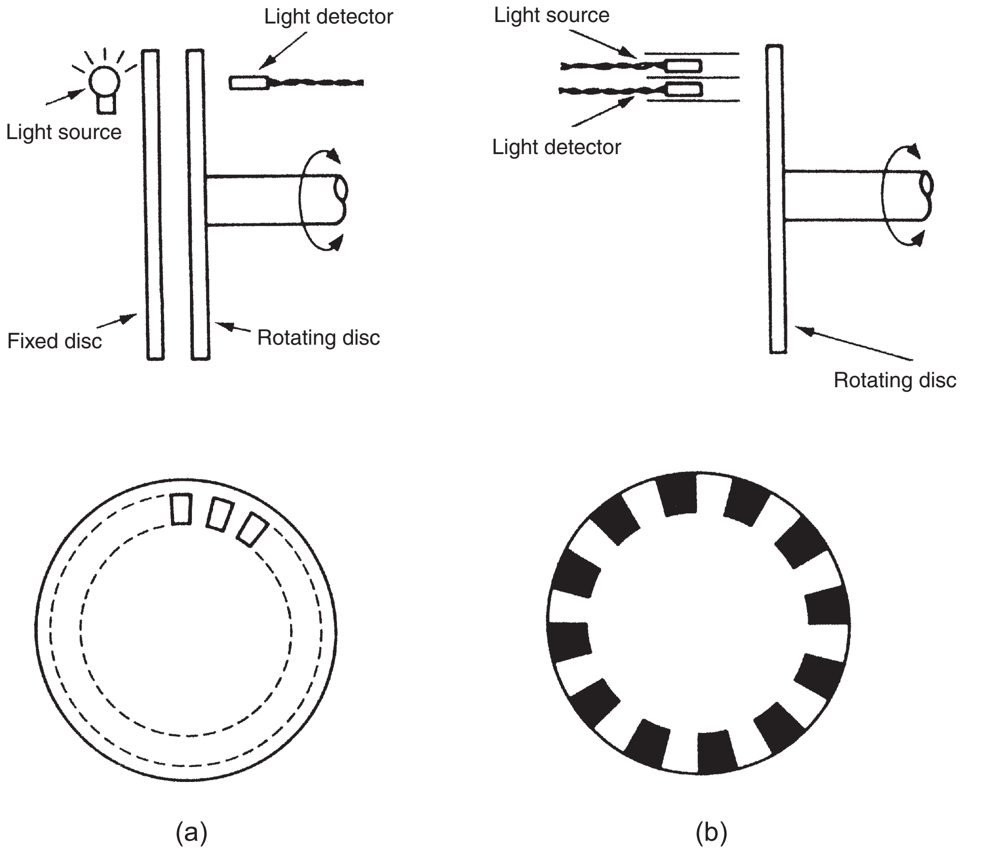

Figure 20.17
Photoelectric pulse generation techniques: (a) Detail of windows in rotating disk; (b) detail of disk with alternate black and white sectors.

outer perimeter of the disk is typically 0.5 mm. As the disk rotates, the soft iron inserts on the disk move in turn past the pickup unit. As each iron insert moves toward the pole piece, the reluctance of the magnetic circuit increases and hence the flux in the pole piece also increases. Similarly, the flux in the pole piece decreases as each iron insert moves away from the sensor. The changing magnetic flux inside the pickup coil causes a voltage to be induced in the coil, whose magnitude is proportional to the rate of change of flux. This voltage is positive while the flux is increasing and negative while it is decreasing. Thus, the output is a sequence of positive and negative pulses, whose frequency is proportional to the rotational velocity of the disk. The maximum angular velocity that the instrument can measure is limited to about 10,000 rpm because of the finite width of the induced pulses. As the velocity increases, the distance between the pulses is reduced, and at a certain velocity, the pulses start to overlap. At this point, the pulse counter ceases to be able to distinguish the separate pulses. The optical tachometer has significant

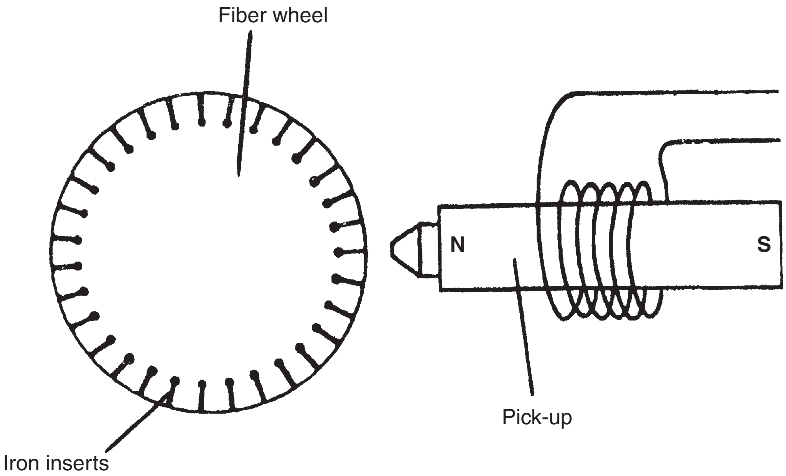

Figure 20.18
Variable reluctance transducer.

advantages in this respect, since the pulse width is much narrower, allowing measurement of higher velocities.

A simpler and cheaper form of variable reluctance transducer also exists that uses a ferromagnetic gear wheel in place of a fiber disk. The motion of the tip of each gear tooth toward and away from the pickup unit causes a similar variation in the flux pattern to that produced by the iron inserts in the fiber disk. However, the pulses produced by these means are less sharp, and, consequently, the maximum angular velocity measurable is lower.

Magnetic (Hall-effect) sensing

The rotating element in *Hall-effect* or *magnetostrictive tachometers* has a very simple design in the form of a toothed metal gear wheel. The sensor is a solid-state, Hall-effect device that is placed between the gear wheel and a permanent magnet. When an inter-tooth gap on the gear wheel is adjacent to the sensor, the full magnetic field from the magnet passes through it. Later, as a tooth approaches the sensor, the tooth diverts some of the magnetic field, and so the field through the sensor is reduced. This causes the sensor to produce an output voltage that is proportional to the rotational speed of the gear wheel.

20.3.2 Stroboscopic Methods

The stroboscopic technique of rotational velocity measurement operates on a similar physical principle to digital tachometers except that the pulses involved consist of flashes of light generated electronically and whose frequency is adjustable so that it can be matched with the frequency of occurrence of some feature on the rotating body being measured. This feature can either be some naturally occurring one such as gear teeth or the spokes of a wheel, or it can be an artificially created pattern of black and white stripes. In either case, the rotating body appears stationary when the frequencies of the light pulses and body features are in synchronism. Flashing rates available in commercial stroboscopes vary from 110 up to 150,000 per minute according to the range of velocity measurement required, and typical measurement inaccuracy is $\pm 1\%$ of the reading. The instrument is usually in the form of a hand-held device that is pointed toward the rotating body.

It must be noted that measurement of the flashing rate at which the rotating body appears stationary does not automatically indicate the rotational velocity, because synchronism also occurs when the flashing rate is some integral submultiple of the rotational speed. The practical procedure followed is therefore to adjust the flashing rate until synchronism is obtained at the largest flashing rate possible, R_1. The flashing rate is then carefully decreased until synchronism is again achieved at the next lower flashing rate, R_2. The rotational velocity is then given by

$$V = \frac{R_1 R_2}{R_1 - R_2}$$

20.3.3 Analog Tachometers

Analog tachometers are less accurate than digital tachometers but are nevertheless still used successfully in many applications. Various forms exist as follows:

The *DC tachometer* has an output that is approximately proportional to its speed of rotation. Its basic structure is identical to that found in a standard DC generator used for producing power, and is shown in Figure 20.19. Both permanent-magnet types and separately excited field types are used. However, certain aspects of the design are

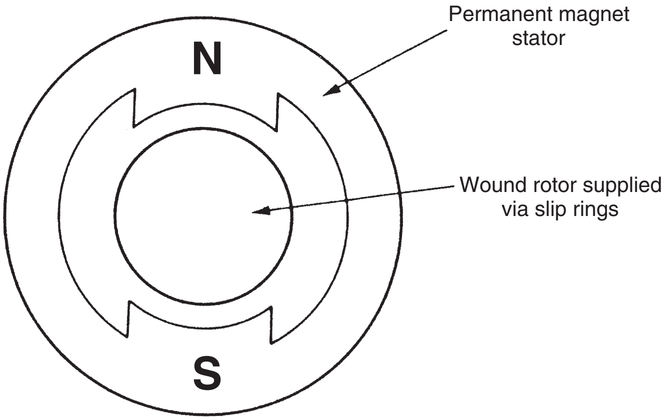

Figure 20.19
DC tachometer.

optimized to improve its accuracy as a speed-measuring instrument. One significant design modification is to reduce the weight of the rotor by constructing the windings on a hollow fiberglass shell. The effect of this is to minimize any loading effect of the instrument on the system being measured. The DC output voltage from the instrument is of a relatively high magnitude, giving a high measurement sensitivity that is typically 5 V per 1000 rpm. The direction of rotation is determined by the polarity of the output voltage. A common range of measurement is 0–6000 rpm. Maximum nonlinearity is usually about ±1% of the full-scale reading. One problem with these devices that can cause difficulties under some circumstances is the presence of an AC ripple in the output signal. The magnitude of this can be up to 2% of the output DC level.

The *AC tachometer* has an output approximately proportional to rotational speed like the DC tachogenerator. Its mechanical structure takes the form of a two-phase induction motor, with two stator windings and (usually) a drag-cup rotor, as shown in Figure 20.20. One of the stator windings is excited with an AC voltage and the measurement signal is taken from the output voltage induced in the second winding. The magnitude of this output voltage is zero when the rotor is stationary, and otherwise is proportional to the angular velocity of the rotor. The direction of rotation is determined by the phase of the output voltage, which switches by 180° as the direction reverses. Therefore, both the phase and magnitude of the output voltage have to be measured. A typical range of measurement is 0–4000 rpm, with an inaccuracy of ±0.05% of full-scale reading. Cheaper versions with a squirrel-cage rotor also exist, but measurement inaccuracy in these is typically ±0.25%.

The *drag-cup tachometer*, also known as an *eddy-current tachometer*, has a central spindle carrying a permanent magnet that rotates inside a nonmagnetic drag-cup consisting of a cylindrical sleeve of electrically conductive material, as shown in Figure 20.21. As the spindle and magnet rotate, a voltage is induced that causes circulating eddy currents in the

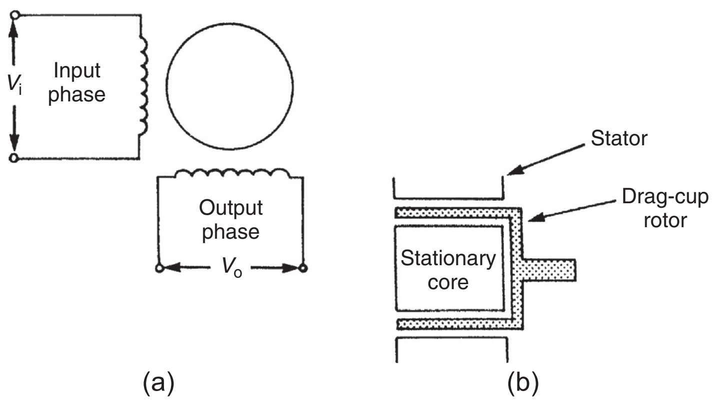

Figure 20.20
AC tachometer. (a) Layout of windings; (b) sketch of stator and rotor.

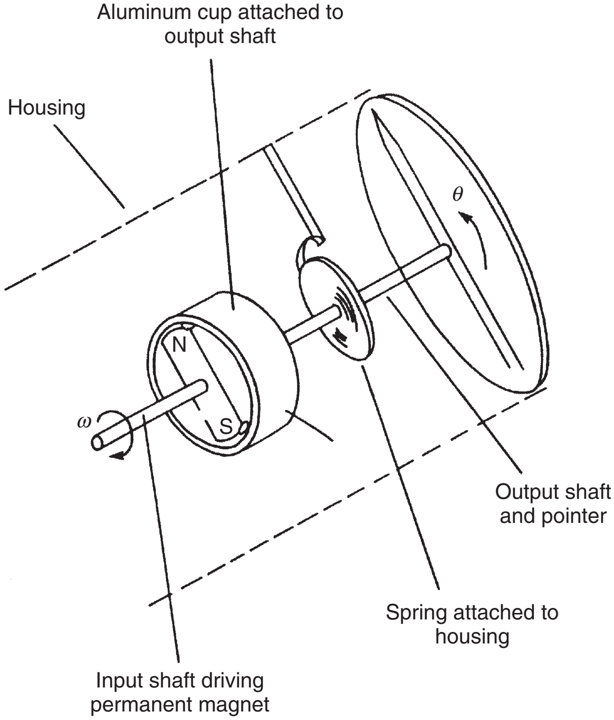

Figure 20.21
Drag-cup tachometer.

cup. These currents interact with the magnetic field from the permanent magnet and produce a torque. In response, the drag-cup turns until the induced torque is balanced by the torque due to the restraining springs connected to the cup. When equilibrium is reached, the angular displacement of the cup is proportional to the rotational velocity of the central spindle. The instrument has a typical measurement inaccuracy of $\pm 0.5\%$ and is commonly used in the speedometers of motor vehicles and also as a speed indicator for aeroengines. It is capable of measuring velocities up to 15,000 rpm.

Analog-output forms of the *variable reluctance velocity transducer* (see Section 20.3.1) also exist in which the output voltage pulses are converted into an analog, varying-amplitude, DC voltage by means of a frequency-to-voltage converter circuit. However, the measurement accuracy is inferior to digital output forms.

20.3.4 The Rate Gyroscope

The rate gyro, illustrated in Figure 20.22, has an almost identical construction to the rate-integrating gyro (Figure 20.14), and differs only by including a spring system that acts as an additional restraint on the rotational motion of the frame. The instrument measures the absolute angular velocity of a body, and is widely used for generating stabilizing

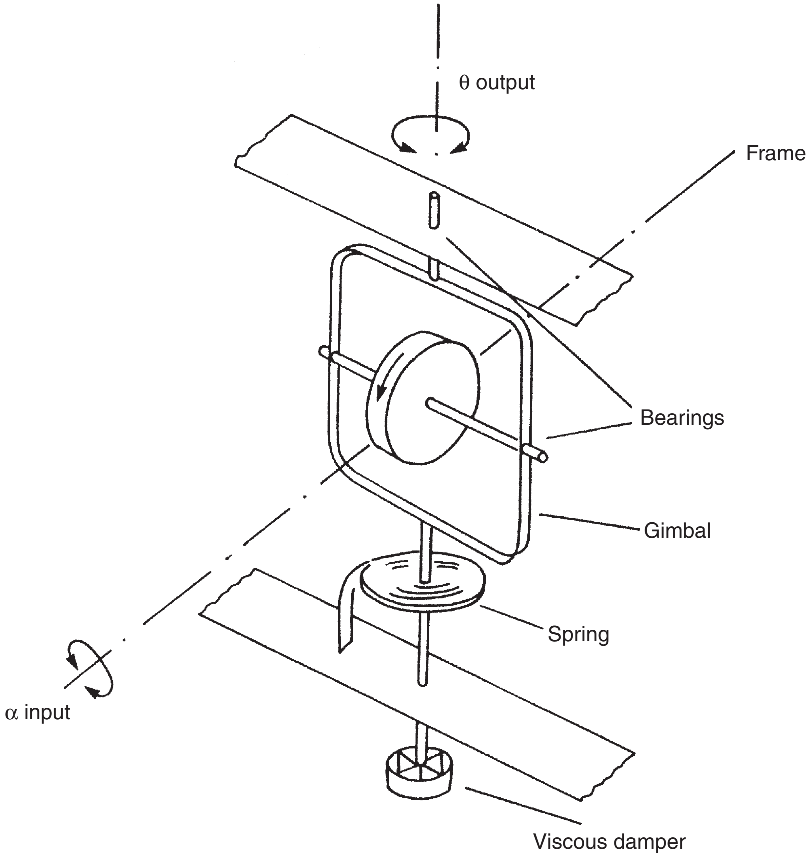

Figure 20.22
Rate gyroscope.

signals within vehicle navigation systems. The typical measurement resolution given by the instrument is 0.01°/s and rotation rates up to 50°/s can be measured. The angular velocity, α, of the body is related to the angular deflection of the gyroscope, θ, by the equation

$$\frac{\theta}{\alpha}(D) = \frac{H}{MD^2 + \beta D + K} \tag{20.2}$$

where H is the angular momentum of the spinning wheel, M is the moment of inertia of the system, β is the viscous damping coefficient, K is the spring constant, and D is the D-operator.

This relationship (20.2) is a second-order differential equation, and we must consequently expect the device to have a response typical of second-order instruments, as discussed in Chapter 2. Therefore, the instrument must be designed carefully so that the output response is neither oscillatory nor too slow in reaching a final reading. To assist in the design process, it is useful to reexpress Eqn (20.2) in the following form:

$$\frac{\theta}{\alpha}(D) = \frac{K'}{D^2/\omega^2 + 2\xi D/\omega + 1} \tag{20.3}$$

where $K' = H/K$, $\omega = \sqrt{K/M}$ and $\xi = \frac{\beta}{2\sqrt{KM}}$.

The static sensitivity of the instrument, K', is made as large as possible by using a high-speed motor to spin the wheel and so make H high. Reducing the spring constant K further improves the sensitivity, but this cannot be reduced too far as it makes the resonant frequency ω of the instrument too small. The value of β is usually chosen such that the damping ratio ξ is as close to 0.7 as possible.

20.3.5 Fiber-Optic Gyroscope

This is a relatively new instrument that makes use of fiber-optic technology. Incident light from a source is separated by a beam splitter into a pair of beams a and b, as shown in Figure 20.23. These travel in opposite directions around an optic-fiber coil (which may be several hundred meters long) and emerge from the coil as the beams marked a' and b'. The beams a' and b' are directed by the beam splitter into an interferometer. Any motion of the coil causes a phase shift between a' and b' which is detected by the interferometer.

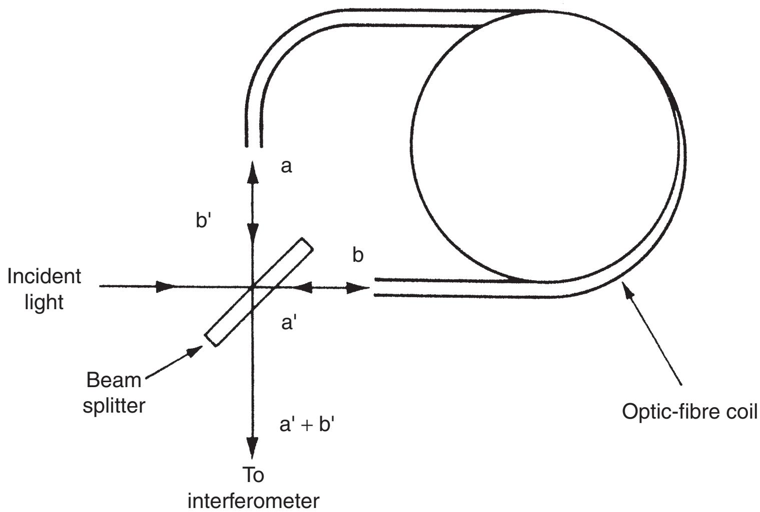

Figure 20.23
Fiber-optic gyroscope.

20.3.6 MEMS Gyroscope

MEMS gyroscopes are now widely available for measuring rotational velocity (however, it should be noted that no suitable MEMS technology has yet been found for measuring angular position). The typical structure of an MEMS gyroscope is shown in Figure 20.24. This operates on a tuning fork principle, and consists of two equal masses M that oscillate and are always moving in opposite directions to each other. When the gyroscope is subjected to an angular velocity ω, a Coriolis force, F is generated on each mass given by $F = -2M\omega \times v$, where v is the instantaneous velocity of the masses. The Coriolis forces on the masses act in opposite directions and cause a lateral displacement of the masses relative to each other. This displacement causes a change in capacitance between the two masses that is proportional to the magnitude of the angular velocity ω applied. This change in capacitance is either converted to a digital number in digital MEMS gyroscopes or into an analog voltage in the case of analog MEMS gyroscopes.

In common with other types of MEMS devices, MEMS gyroscopes are relatively cheap to produce and provide high performance with low power consumption. They are entirely insensitive to linear motion and only respond to angular motion. Any motion of the device in the x, y, or z direction (as shown in Figure 20.24) causes both masses to move by the same amount in the direction of the motion. Hence, there is no relative displacement between the two masses and so there is no change in capacitance.

MEMS gyroscopes are now used in a wide range of applications for measuring rotational velocities up to 2700°/s. They are used in digital cameras to provide image stabilization by detecting rotations due to camera shake. Within motor vehicles, they have several uses. One use is to measure changes in vehicle orientation during loss of a GPS signal and so allow satellite navigation systems to continue to function. Another use is to activate the electronic stability control system when the vehicle swerves to avoid a collision. Yet another use is to trigger the deployment of an air bag when a vehicle roll-over condition is detected.

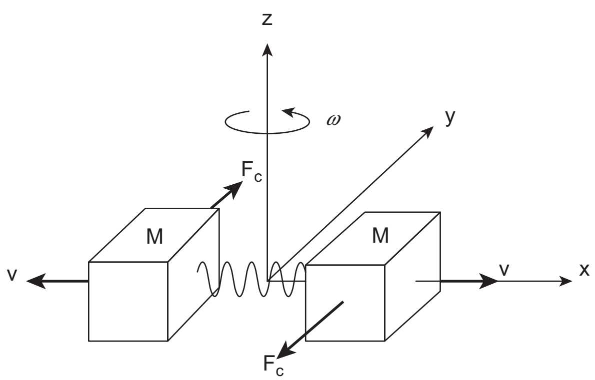

Figure 20.24
Typical structure of an MEMS gyroscope.

20.3.7 Differentiation of Angular Displacement Measurements

Angular velocity measurements can be obtained by differentiating the output signal from angular displacement transducers. Unfortunately, the process of differentiation amplifies any noise in the measurement signal, and therefore this technique has been used only rarely in the past. However, the technique has become more feasible with the advent of intelligent instruments. For example, using an intelligent instrument to differentiate and process the output from a resolver can produce a velocity measurement with a maximum inaccuracy of $\pm 1\%$.

20.3.8 Integration of the Output from an Accelerometer

In measurement systems that already contain an angular acceleration transducer, it is possible to obtain a velocity measurement by integrating the acceleration measurement signal. This produces a signal of acceptable quality, as the process of integration attenuates any measurement noise. However, the method is of limited value in many measurement situations because the measurement obtained is the average velocity over a period of time, rather than a profile of the instantaneous velocities as motion takes place along a particular path.

20.3.9 Choice between Rotational Velocity Transducers

Choice between different rotational velocity transducers is influenced strongly by whether an analog or digital form of output is required. Distinction also has to be made between devices that measure continuous velocity and those that measure short-term, transient velocities. Digital output instruments are now widely used for the measurement of continuous velocities and choice has to be made between the variable reluctance transducer, devices using electronic light pulse-counting methods, and the stroboscope. The first two of these are used to measure angular speeds up to about 10,000 rpm and the last one can measure speeds up to 25,000 rpm.

Probably the most common form of analog output device used for measuring continuous velocities is the DC tachometer. This is a relatively simple device that measures speeds up to about 5000 rpm with a maximum inaccuracy of $\pm 1\%$. Where better accuracy is required within a similar range of speed measurement, AC tachometers are used. The squirrel-cage rotor type has an inaccuracy of only $\pm 0.25\%$ and drag-cup rotor types can have inaccuracies as low as $\pm 0.05\%$.

The drag-cup tachometer also has an analog output but its typical inaccuracy of $\pm 5\%$. However, it is cheap and therefore suitable for use in vehicle speedometers, where an inaccuracy of $\pm 5\%$ is normally acceptable.

The case of measuring short-term, transient velocities is the province of MEMS gyroscopes. Versions measuring rotation rates up to 2000°/s are widely available and some manufacturers produce devices that can measure rates up to 2700°/s.