PERGAMON

Progress in Materials Science 46 (2001) 461–504

Progress in Materials Science

www.elsevier.com/locate/pmatsci

The selection of sensors

J. Shieh, J.E. Huber, N.A. Fleck *, M.F. Ashby

Department of Engineering, Cambridge University, Trumpington Street, Cambridge CB2 1PZ, UK

Abstract

A systematic method is developed to select the most appropriate sensor for a particular application. A wide range of candidate sensors exist, and many are based on coupled electrical and mechanical phenomena, such as the piezoelectric, magnetostrictive and the pyro-electric effects. Performance charts for sensors are constructed from suppliers data for commercially available devices. The selection of an appropriate sensor is based on matching the operating characteristics of sensors to the requirements of an application. The final selection is aided by additional considerations such as cost, and impedance matching. Case studies illustrate the selection procedure.

Keywords: Sensors; Selection; Sensing range; Sensing resolution; Sensing frequency

Contents

* Corresponding author. Tel.: +44-1223-332650; fax: +44-1223-332662.
E-mail address: nafl@eng.cam.ac.uk (N.A. Fleck).

0079-6425/01/$ - see front matter
PII: S0079-6425(00)00011-6

1. Introduction

The Oxford English Dictionary defines a sensor as "*a device which detects or measures some condition or property, and records, indicates, or otherwise responds to the information received*". Thus, sensors have the function of converting a *stimulus* into a *measured signal*. The stimulus can be mechanical, thermal, electromagnetic, acoustic, or chemical in origin (and so on), while the measured signal is typically electrical in nature, although pneumatic, hydraulic and optical signals may be employed. Sensors are an essential component in the operation of engineering devices, and are based upon a very wide range of underlying physical principles of operation.

Given the large number of sensors on the market, the selection of a suitable sensor for a new application is a daunting task for the Design Engineer: the purpose of this article is to provide a straightforward selection procedure. The study extends that of Huber et al. [1] for the complementary problem of actuator selection. It will become apparent that a much wider choice of sensor than actuator is available: the underlying reason appears to be that power-matching is required for an efficient actuator, whereas for sensors the achievable high stability and gain of modern-day electronics obviates a need to convert efficiently the power of a stimulus into the power of an electrical signal. The classes of sensor studied here are detailed in the Appendices.

2. Sensor performance charts

In this section, sensor performance data are presented in the form of 2D charts with performance indices of the sensor as axes. The data are based on sensing systems which are currently available on the market. Therefore, the limits shown on each chart are practical limits for readily available systems, rather than theoretical performance limits for each technology. Issues such as cost, practicality (such as impedance matching) and reliability also need to be considered when making a final selection from a list of candidate sensors.

Before displaying the charts we need to introduce some definitions of sensor characteristics; these are summarised in Table 1.[1] Most of these characteristics are quoted in manufacturers' data sheets. However, information on the reliability and robustness of a sensor are rarely given in a quantitative manner.

In the following, we shall present selection charts using a sub-set of sensor characteristics: range, resolution and frequency limits. Further, we shall limit our attention to sensors which can detect *displacement, acceleration, force,* and *temperature*.[2] Each performance chart maps the domain of existence of practical sensors. By adding to the chart the required characteristics for a particular application, a subset of potential sensors can be identified. The optimal sensor is obtained by making use of several charts and by considering additional tabular information such as cost. The utility of the approach is demonstrated in Section 3, by a series of case studies.

2.1. Displacement sensors

Consider first the performance charts for displacement sensors, with axes of resolution δ versus range R, and sensing frequency f versus range R, as shown in Figs. 1 and 2, respectively.

Table 1
Summary of the main sensor characteristics

Range	maximum minus minimum value of the measured stimulus
Resolution	smallest measurable increment in measured stimulus
Sensing frequency	maximum frequency of the stimulus which can be detected
Accuracy	error of measurement, in% full scale deflection
Size	leading dimension or mass of sensor
Opt environment	operating temperature and environmental conditions
Reliability	service life in hours or number of cycles of operation
Drift	long term stability (deviation of measurement over a time period)
Cost	purchase cost of the sensor ($ in year 2000)

[1] Note that accuracy is discussed in more detail in Appendix E and Fig. E1.

[2] It is assumed implicitly that time is known to sufficient accuracy as not to limit the performance of any sensor; this is reasonable since inexpensive clocks can record time to an accuracy of 1 part in 10^6, over a wide range of timescales.

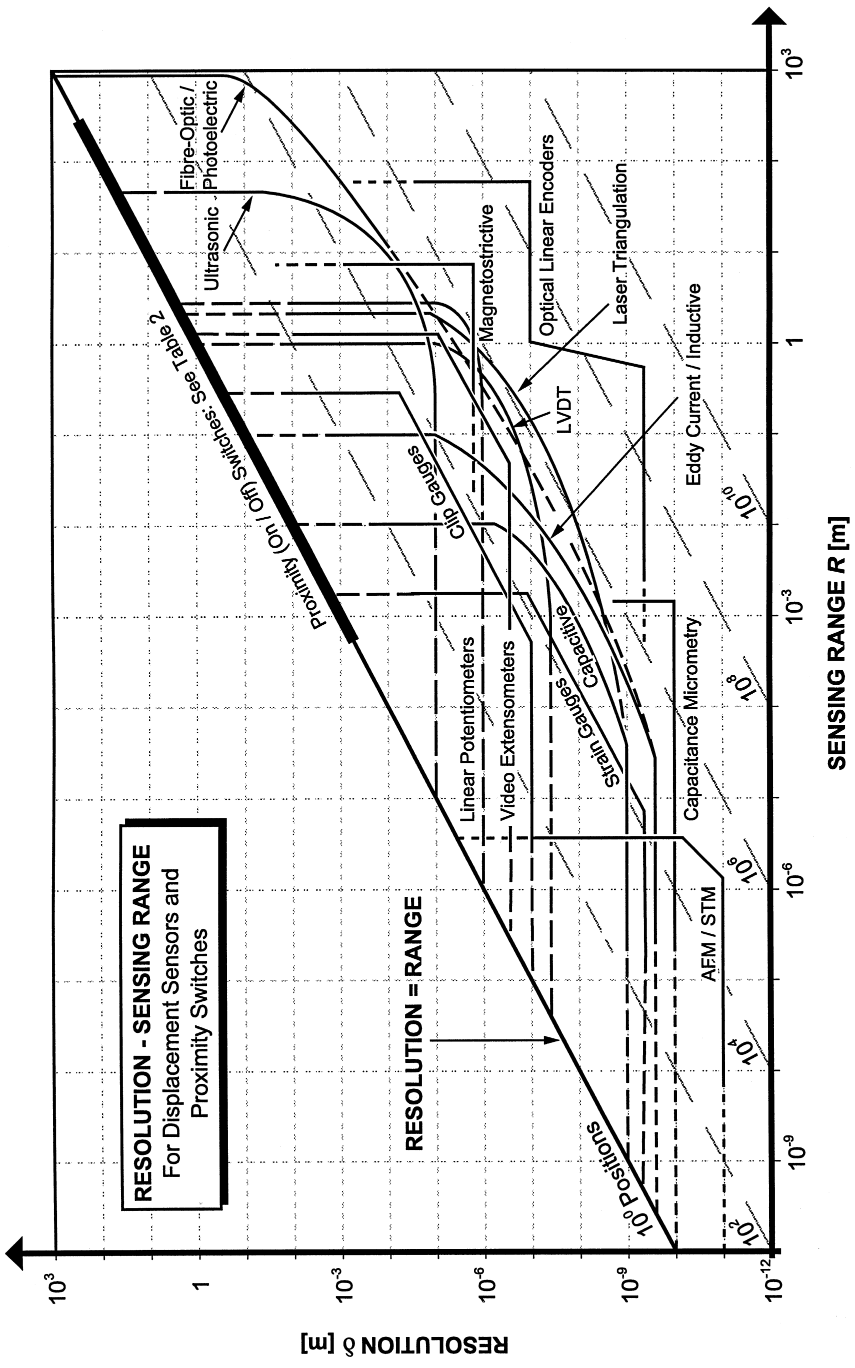

Fig. 1. Resolution versus sensing range for displacement sensors.

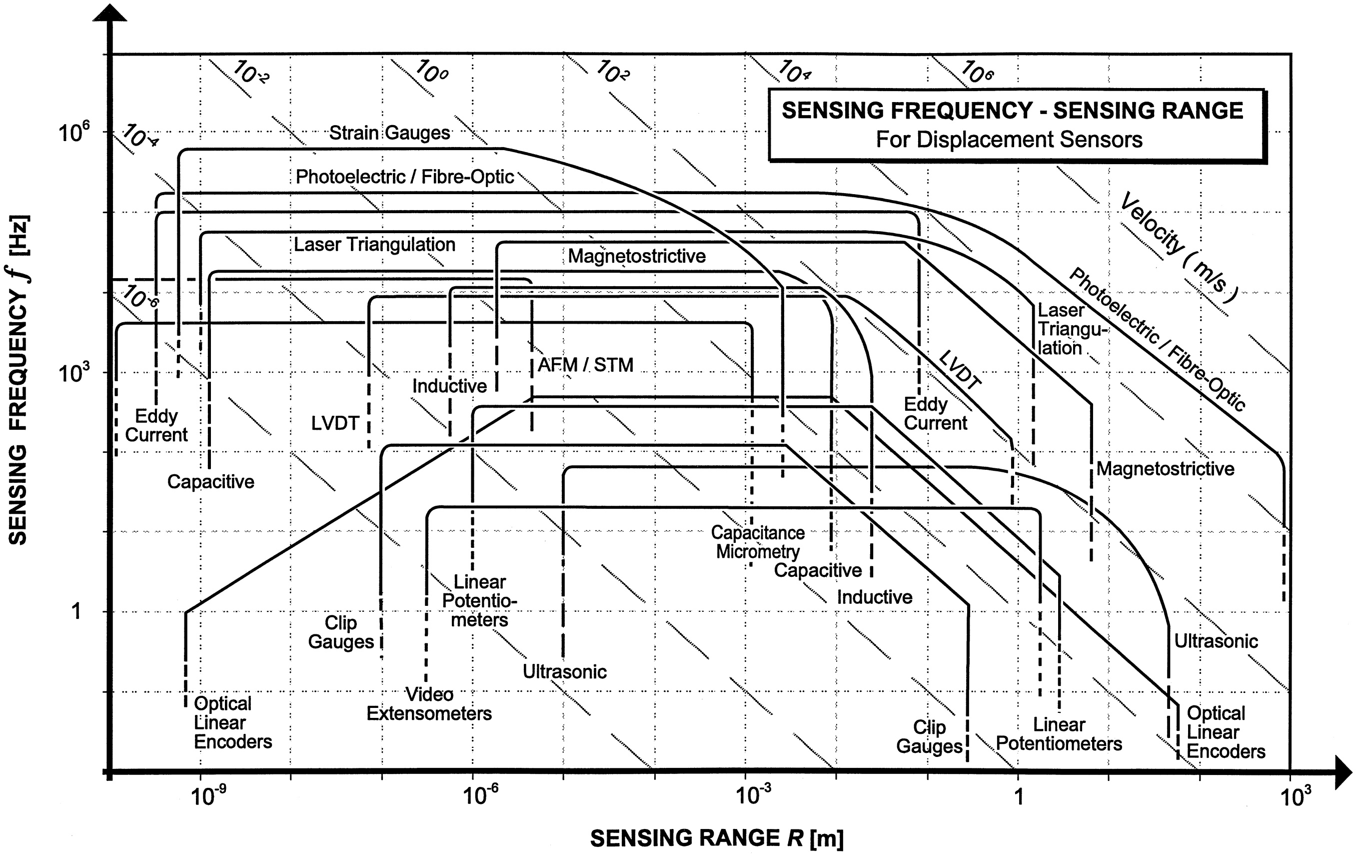

Fig. 2. Sensing frequency versus sensing range for displacement sensors.

2.1.1. Resolution — sensing range chart (Fig. 1)

The performance regime of resolution δ versus range R for each class of sensor is marked by a closed domain with boundaries given by heavy lines (see Fig. 1). The upper limit of operation is met when the coarsest achievable resolution equals the operating range $\delta = R$. Sensors of largest sensing range lie towards the right of the figure, while sensors of finest resolution lie towards the bottom. It is striking that the range of displacement sensor spans 13 orders of magnitude in both range and resolution, with a large number of competing technologies available. On these logarithmic axes, lines of slope $+1$ link classes of sensors with the same number of distinct measurable positions, R/δ. Sensors close to the single position line $\delta = R$ are suitable as simple proximity (on/off) switches, or where few discrete positions are required. Proximity sensors are marked by a single thick band in Fig. 1: more detailed information on the sensing range and maximum switching frequency of proximity switches are summarised in Table 2. Sensors located towards the lower right of Fig. 1 allow for continuous displacement measurement, with high information content. Displacement sensors other than the proximity switches are able to provide a continuous output response that is proportional to the target's position within the sensing range. Fig. 1 shows that the majority of sensors have a resolving power of 10^3–10^6 positions; this corresponds to approximately 10–20 bits for sensors with a digital output.

It is clear from Fig. 1 that the sensing range of displacement sensors cluster in the region 10^{-5}–10^1 m. To the left of this cluster, the displacement sensors of AFM and STM, which operate on the principles of atomic forces and current tunnelling, have *z*-axis-sensing ranges on the order of microns or less. For sensing tasks of 10 m or above, sensors based on the non-contacting technologies of linear encoding, ultrasonics and photoelectrics become viable. Optical linear encoders adopting interferometric techniques can achieve a much higher resolution than conventional encoders; however, their sensing range is limited by the lithographed carrier (scale). A switch in technology accounts for the jump in resolution of optical linear encoders around the sensing range of 0.7 m in Fig. 1.

Note that "radar", which is capable of locating objects at distances of several thousand kilometres,[3] is not included in Fig. 1. Radar systems operate by transmit-

Table 2
Specification of proximity switches

Proximity switch type	Maximum switching distance (m)	Maximum switching frequency (Hz)
Inductive	6×10^{-4}–1×10^{-1}	5–5000
Capacitive	1×10^{-3}–6×10^{-2}	1–200
Magnetic	3×10^{-3}–8.5×10^{-2}	400–5000
Pneumatic cylinder sensors (magnetic)	Piston diameter 8×10^{-3}–3.2×10^{-1}	300–5000
Ultrasonic	1.2×10^{-1}–5.2	1–50
Photoelectric	3×10^{-3}–300	20–20,000

[3] One such system is the AN/FPS-115 PAVE PAWS Radar from Rome Air Development Centre (RADAC), USA Air Force.

ting high-frequency radio waves and utilise the echo and Doppler shift principles to determine the position and speed of the target. Generally speaking, as the required sensing range increases, sensors based on non-contact techniques become the most practicable choice due to their flexibility, fast sensing speed and small physical size in relation to the length scale detected. Fig. 1 shows that sensors based on optical techniques, such as fibre-optic, photoelectric and laser triangulation, cover the widest span in sensing range with reasonably high resolution.

For displacement sensors, the sensing range is governed by factors such as technology limitation, probe (or sensing face) size and the material properties of the target. For example, the sensing distance of ultrasonic sensors is inversely proportional to the operating frequency; therefore, a maximum sensing range cut-off exists at about $R = 50$ m. Eddy current sensors of larger sensing face are able to produce longer, wider and stronger electromagnetic fields, which increase their sensing range. Resolution is usually controlled by the speed, sensitivity and accuracy of the measuring circuits or feedback loops; noise level and thermal drift impose significant influences also. Sensors adopting more advanced materials and manufacturing processes can achieve higher resolution; for example, high-quality resistive film potentiometers have a resolution of better than 1 μm over a range of 1 m (i.e. 10^6 positions) whereas typical coil potentiometers achieve only 10^3 positions.

2.1.2. Sensing frequency — sensing range chart (Fig. 2)

When a displacement sensor is used to monitor an oscillating body, a consideration of sensing frequency becomes relevant. Fig. 2 displays the upper limit of sensing frequency and the sensor range for each class of displacement sensor. It is assumed that the smallest possible sensing range of a displacement sensor equals its resolution; therefore in Fig. 2, the left-hand side boundary of each sensor class corresponds to its finest resolution.[4] However, sensors close to this boundary are only suitable as simple switches, or where few discrete positions are to be measured.

Lines of slope -1 in Fig. 2 link classes of sensors with the same sensing speed, fR. For contact sensors such as the LVDT and linear potentiometer, the sensing speed is limited by the inertia of moving parts. In contrast, many non-contact sensors utilise mechanical or electromagnetic waves and operate by adopting the time-of-flight approach; therefore, their maximum sensing speed is limited by the associated wave speed. For example, the maximum sensing speed of magnetostrictive sensors is limited by the speed of a strain pulse travelling in the waveguide alloy, which is about 2.8×103 m s^{-1}.

The sensing frequency of displacement sensors is commonly dependent on the noise levels exhibited by the measuring electronic circuits. Additionally, some physical and mechanical limits can also impose constraints. For example, the dynamic response of a strain gauge is limited by the wave speed in the substrate. For sensors with moving mass (for example, linear encoder, LVDT and linear potentiometer),

[4] For example, a capacitive sensor of 20 μm sensing range, nm resolution of 20 kHz frequency response would have an x-axis-span of 10^{-9}–2×10^{-5} m and a maximum y-axis value of 20 kHz in Fig. 2.

the effects of inertial loading must be considered in cyclic operation. For optical linear encoders the sensing frequency increases with range on the left-hand side of the performance chart, according to the following argument. The resolution becomes finer (i.e. δ decreases in an approximately linear manner) with a reduced scan speed V of the recording head. Since the sensor frequency f is proportional to the scan speed V, we deduce that f increases linearly with δ, and therefore f is linear in the minimum range of the device.

2.2. Linear velocity sensors

Although velocity and acceleration are the first and second derivatives of displacement with respect to time, velocity and acceleration measurements are not usually achieved by time differentiation of a displacement signal due to the presence of noise in the signal. The converse does not hold: some accelerometers, especially navigation-grade servo accelerometers, have sufficiently high stability and low drift that it is possible to integrate their signals to obtain accurate velocity and displacement information.

The most common types of velocity sensor of contacting type are electromagnetic, piezoelectric and cable extension-based. Electromagnetic velocity sensors use the principle of magnetic induction, with a permanent magnet and a fixed geometry coil, such that the induced (output) voltage is directly proportional to the magnet's velocity relative to the coil. Piezo-velocity transducers (PVTs) are piezoelectric accelerometers with an internal integration circuit which produces a velocity signal. Cable extension-based transducers use a multi-turn potentiometer (or an incremental/absolute encoder) and a tachometer to measure the rotary position and rotating speed of a drum that has a cable wound onto it. Since the drum radius is known, the velocity and displacement of the cable head can be determined.[5]

Optical and microwave velocity sensors are non-contacting, and utilise the optical-grating or Doppler frequency shift principle to calculate the velocity of the moving target. Typical specifications for each class of linear velocity sensor are listed in Table 3.

Table 3
Specification of linear velocity sensors

Sensor class	Maximum sensing range (m/s)	Resolution (number of positions)	Maximum operating frequency (Hz)
Magnetic induction	25–360	5×10^4–5×10^5	100–1500
PVT	0.25–1.3	1×10^5–5×10^5	~7000
Cable-extension	0.7–15	1×10^5–1×10^6	1–100
Optical and microwave	13–165	$\sim1\times10^5$	> 10,000

[5] The frequency response of cable extension-based transducers can be derived from the displacement and velocity data. This would enable them to be compared with other classes of displacement sensors shown in Fig. 2.

2.3. Accelerometers

The performance of accelerometers can be conveniently summarised in terms of their range R, resolution δ and sensing frequency f, in similar manner to that described above for displacement sensors. The units of acceleration are 'g', the acceleration due to Earth's gravity (9.81 m s^{-2}).

2.3.1. Resolution — sensing range chart (Fig. 3)

The heavy lines in Fig. 3 show the locus of the values of resolution δ and sensing range R for the main types of available accelerometer. The operating regime for each sensor has the upper limit $R = \delta$. Lines of slope + 1 link classes of sensors with the same number of distinct measurable positions, R/δ. It is clear from Fig. 3 that the majority of accelerometers have a resolving power of about 10^6 positions; inertial navigation-grade force-balance accelerometers can discriminate more than 10^8 discrete positions.

All accelerometers can sense both acceleration and deceleration; therefore in Fig. 3 an accelerometer's sensing range is represented by twice its maximum acceleration. Piezoresistive accelerometers have the highest output range (up to $\pm$200,000 g). Force-balance (servo) accelerometers tend to have a smaller sensing range than other classes due to their closed-loop design. Due to this servo-loop, such accelerometers are capable of sub-micro-g resolution. Piezoelectric accelerometers are rugged and versatile and cover the widest span in operating range, from micro-g to high impact measurement, at fine resolution. It is important to distinguish between the sensing range and robustness. An accelerometer may have to measure only 100 g full scale, but might be required to survive an initial shock of 10,000 g preceding (or following) the low-level event.

Accelerometers of high sensing range typically have high natural frequencies, by the following argument. High acceleration produces a high force on the inertial mass, and so a high spring stiffness is needed to limit displacements. Consequently the accelerometer has a high natural frequency [2]. In general, the greater the sensitivity of a sensor, the lower is its upper limit of acceleration without non-linear saturation of the device. The resolution is generally governed by the noise level of the sensor. A determination of the system noise level requires a consideration of all the possible noise sources — the sensor, connecting cable, amplifier (internal or external) and data acquisition equipment. High-sensitivity accelerometers have the largest signal-to-noise ratios (SNR), and the finest resolutions. High sensitivity and a good SNR, however, comes at the penalty of sensing range, resonance frequency, size and weight [2]. High sensitivity accelerometers are often designed specially for micro-g measuring tasks at low frequencies.

2.3.2. Sensing frequency — sensing range chart (Fig. 4)

Accelerometers are widely used for vibration measurement, and so the sensing frequency is an important performance parameter. Fig. 4 allows for a comparison of sensing frequency and sensing range; the heavy lines bound the upper limit of sensing frequency of each class of accelerometers. The sensor characteristics plotted

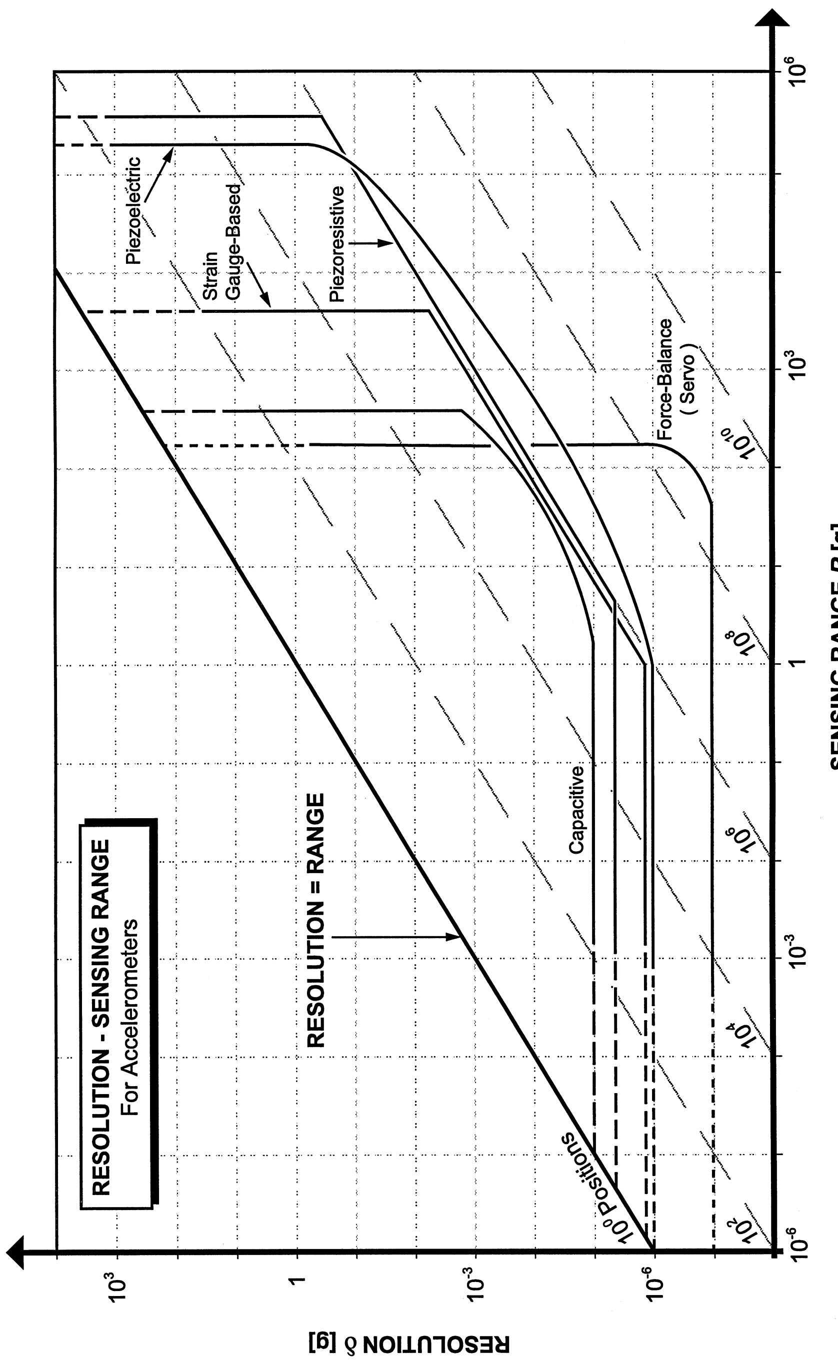

Fig. 3. Resolution versus sensing range for accelerometers.

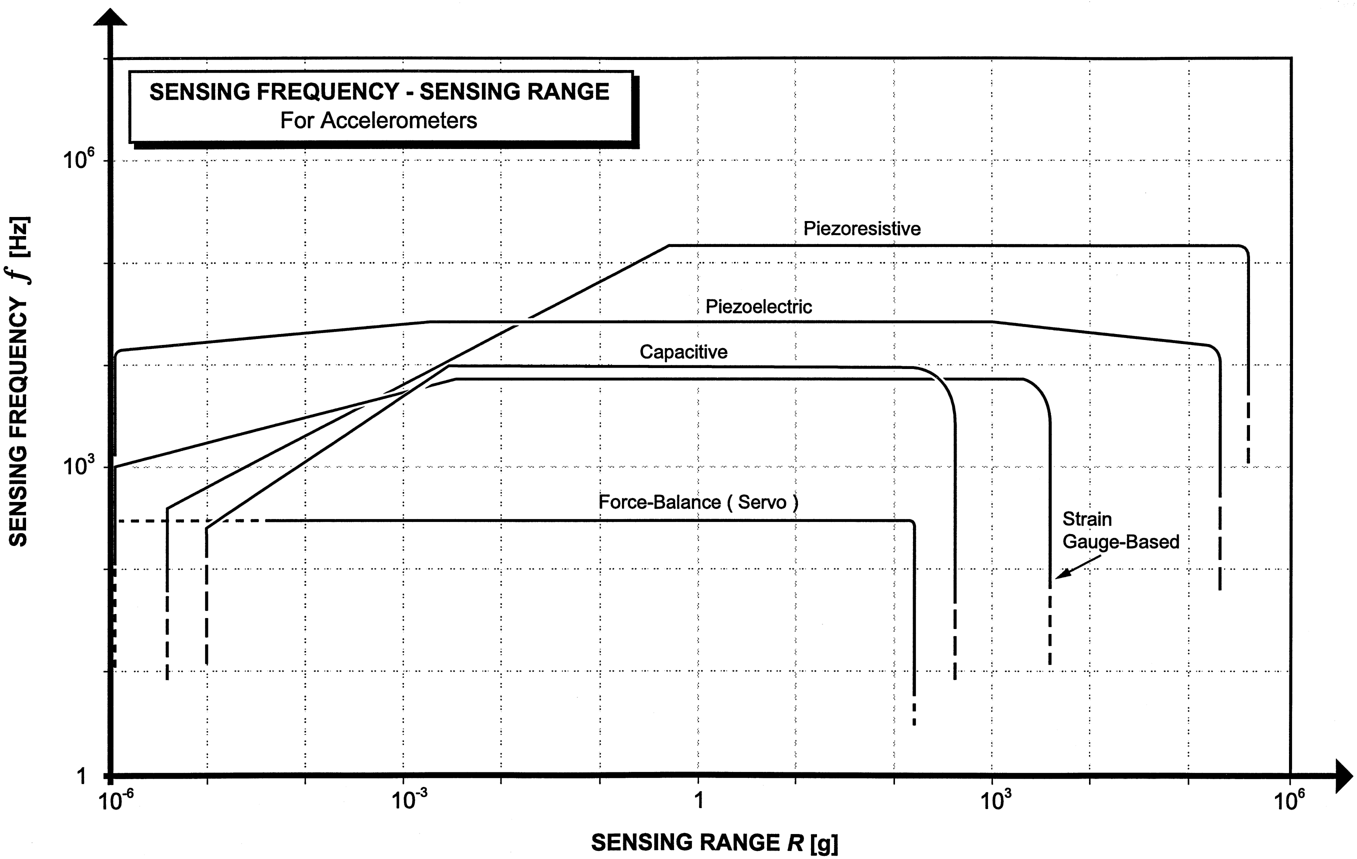

Fig. 4. Sensing frequency versus sensing range for accelerometers.

in Fig. 4 reveal that piezoelectric and piezoresistive accelerometers have a sensing frequency exceeding 10 kHz, making them suitable for high-frequency measurement such as gear noise analysis, rotating machinery monitoring and so on. A high sensing frequency requires a high ratio of stiffness to mass and therefore comes at the cost of having poorer sensitivity and resolution. This trade-off can be seen in Fig. 4: on the left-hand limit of performance, where the range equals the resolution, the upper limit of sensing frequency of all accelerometer classes increases with increasing range (except for servo-control, due to its closed-loop design).

Accelerometers operate best at frequencies well below the resonant frequency; then, under harmonic excitation, the ratio of measured displacement of the inertial mass to the applied acceleration is independent of frequency. The upper limit of sensing frequency is usually determined by the resonance of the sensor and is typically 1/5 to 1/2 of the resonance frequency. All accelerometers, except those of piezoelectric type, are DC-coupled devices[6] and have a lower frequency limit of zero; they can be used to measure velocity and displacement by time integration of the response [2].

The mass of an accelerometer can affect the dynamic characteristics of the structure to which it is mounted and introduce mass loading errors. The typical practice is to use the lightest, smallest accelerometer that still satisfies all the performance requirements [2,3].

2.4. Force sensors

2.4.1. Resolution — sensing range chart (Fig. 5)

A resolution δ versus range R performance chart is given in Fig. 5 for force sensors; in similar manner to that described above, the performance boundary for each class of force sensor is marked, with an upper boundary given by the limit, $\delta = R$. Lines of slope $+1$ link classes of sensors with the same number of distinct measurable positions. For a sensor that can detect both tensile and compressive forces, the sensing range in Fig. 5 is represented by the sum of the ranges of compression and tension.[7] A distinction should be made between sensing range and overload capacity. Most force sensors or transducers are designed to survive loads that exceed their normal range by a factor of 3–15. Fig. 5 shows that hydraulic load cells have the highest output range (more than 10 MN). Their upper sensing limit is set by the strength of the internal diaphragm. Micromachined piezoresistive force sensors contain a fragile spring element which limits their sensing range. Strain gauge-based force transducers are of numerous designs, ranging from a 15 mm long thin beam to a 400 mm diameter low profile load cell. A large number of diverse configurations allow them to form a group that has the widest span in sensing range among all sensor classes. Note, however, that individual devices do not span the full range.

---

[6] Accelerometers, which have a DC component in the output signal, are externally supplied with energy. Because they are sensitive to earth's gravity, the gravitational effect should be eliminated before the output at no mechanical input is determined.

[7] Note that for some piezoelectric force sensors, the magnitudes of compression and tension ranges can be significantly different (maximum of 10 times the difference).

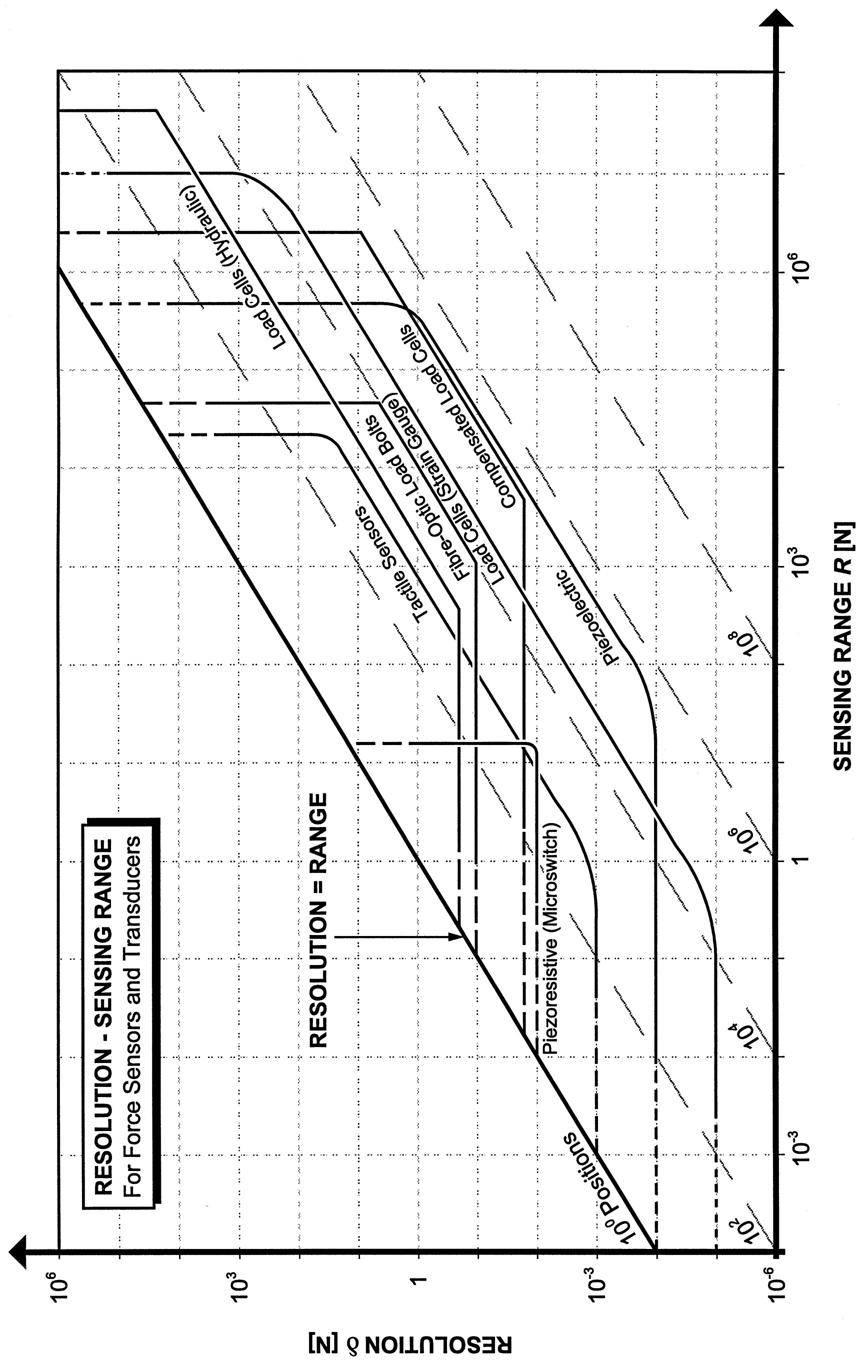

Fig. 5. Resolution versus sensing range for force sensors.

Resolution is controlled mainly by the quality of the measuring circuitry or electronic instrumentation. It is commonly expressed in bits or in percent of full scale. This is why the envelopes of performance in Fig. 5 tend to follow lines of constant number of positions. Fig. 5 shows that most force sensors can resolve 10^3–10^6 positions; this corresponds to approximately 10–20 bits.

2.4.2. *Sensing frequency — sensing range chart (Fig. 6)*

Fig. 6 allows for a comparison of sensing frequency and sensing range of each class of force sensors or transducers. Fig. 6 shows a decrease in sensing frequency with increasing sensing range for some sensor classes: a device of higher sensing capacity often comes with a lower maximum operating frequency. The sensing frequency is commonly dependent upon the natural frequency of the sensor and the noise levels within the associated electronic circuits. Piezoelectric force sensors have the highest operating frequency (>10 kHz), making them suitable for the measurement of dynamic force events. Conventional strain gauge-based load cells are limited to frequencies of about 200 Hz at low load; however, by using dynamically compensated load cells the frequency can be increased to about 1000 Hz. Hydraulic load cells contain no electrical components, and so the sensing frequency is governed by the viscosity of the oil and the inertia of the diaphragm chamber.

All force sensors, except piezoelectric sensors, are capable of static force measurements. For the piezoelectric case, the measurement signal decays with time due to the leakage of electrostatic charge. A typical lower frequency limit for piezoelectric force sensors is 0.0003–0.01 Hz, depending upon the discharge time constant.

2.5. *Temperature sensors*

2.5.1. *Resolution — operating temperature chart (Fig. 7)*

Fig. 7 shows the resolution δ versus operating temperature T for temperature sensors. The operating temperature is shown (rather than range) because a temperature sensor can only operate within a regime of absolute temperatures. An overall upper boundary exists for each class of sensor, which in many cases is set by the resolution equal to the operating temperature. A span of 4 orders of magnitude in operating temperature allows a large number of temperature sensors of different technologies to be shown and compared quantitatively.

Fig. 7 shows that the operating temperatures of many sensors are clustered between 70 and 1000 K. For temperatures above 1000 K, thermocouples, infra-red thermometers and pyrometers are feasible. Infra-red devices can be used in low temperature sensing: the Space Infrared Telescope Facility (SIRTF) detects infra-red radiation from a source at below 5 K. Such technologies are not readily available sensors and are excluded from Figs. 7 and 8. For temperatures below 70 K, only platinum resistance temperature detectors (RTD), thermocouples and cryogenic sensors based on resistors and diodes are viable. The lower limit of operating temperature for several sensors is determined by the temperature of practical applications: 77 K for liquid nitrogen environments, and the regime 253–273 K for food storage. These are not fundamental limits of the technologies, but are practical limits

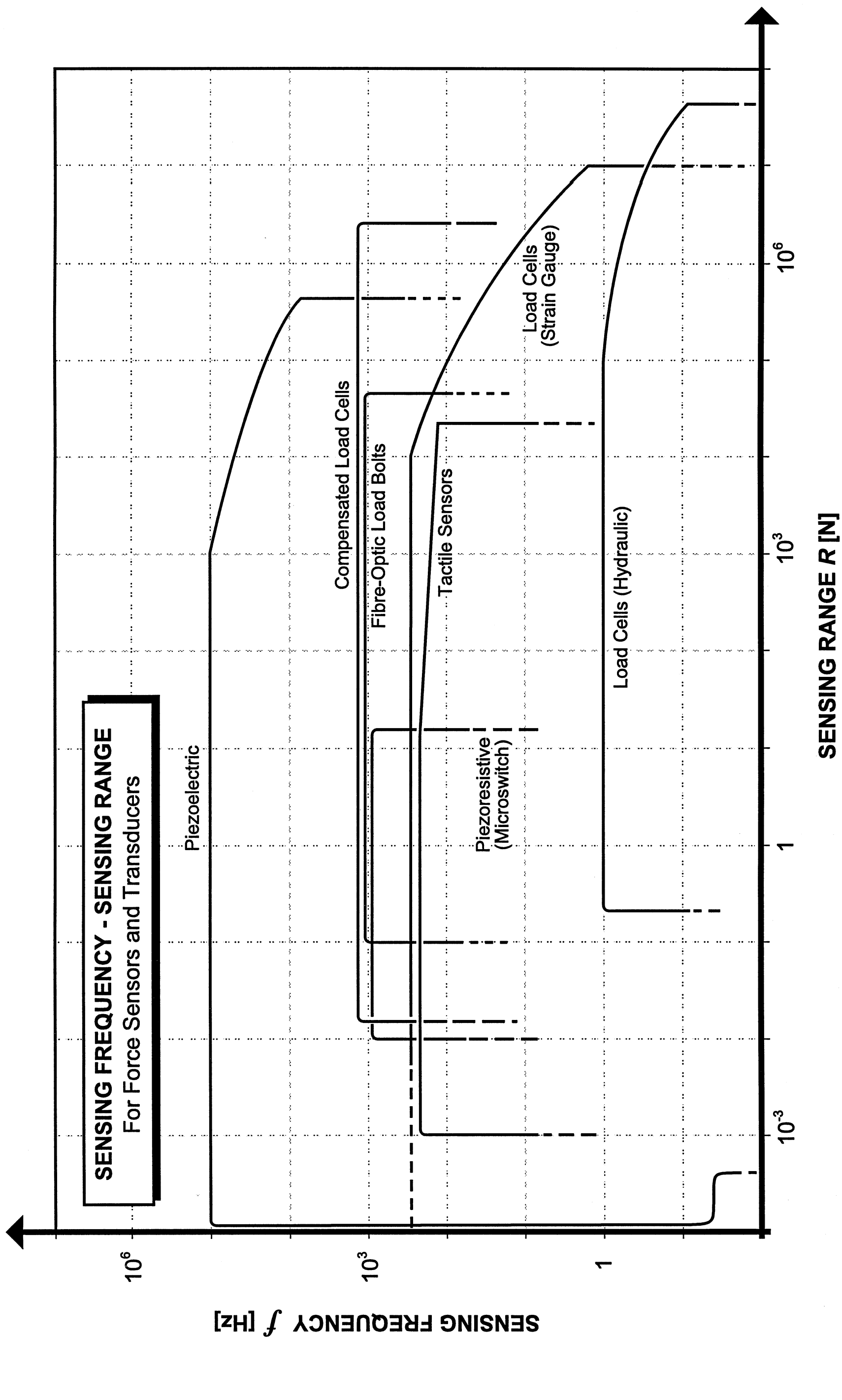

Fig. 6. Sensing frequency versus sensing range for force sensors.

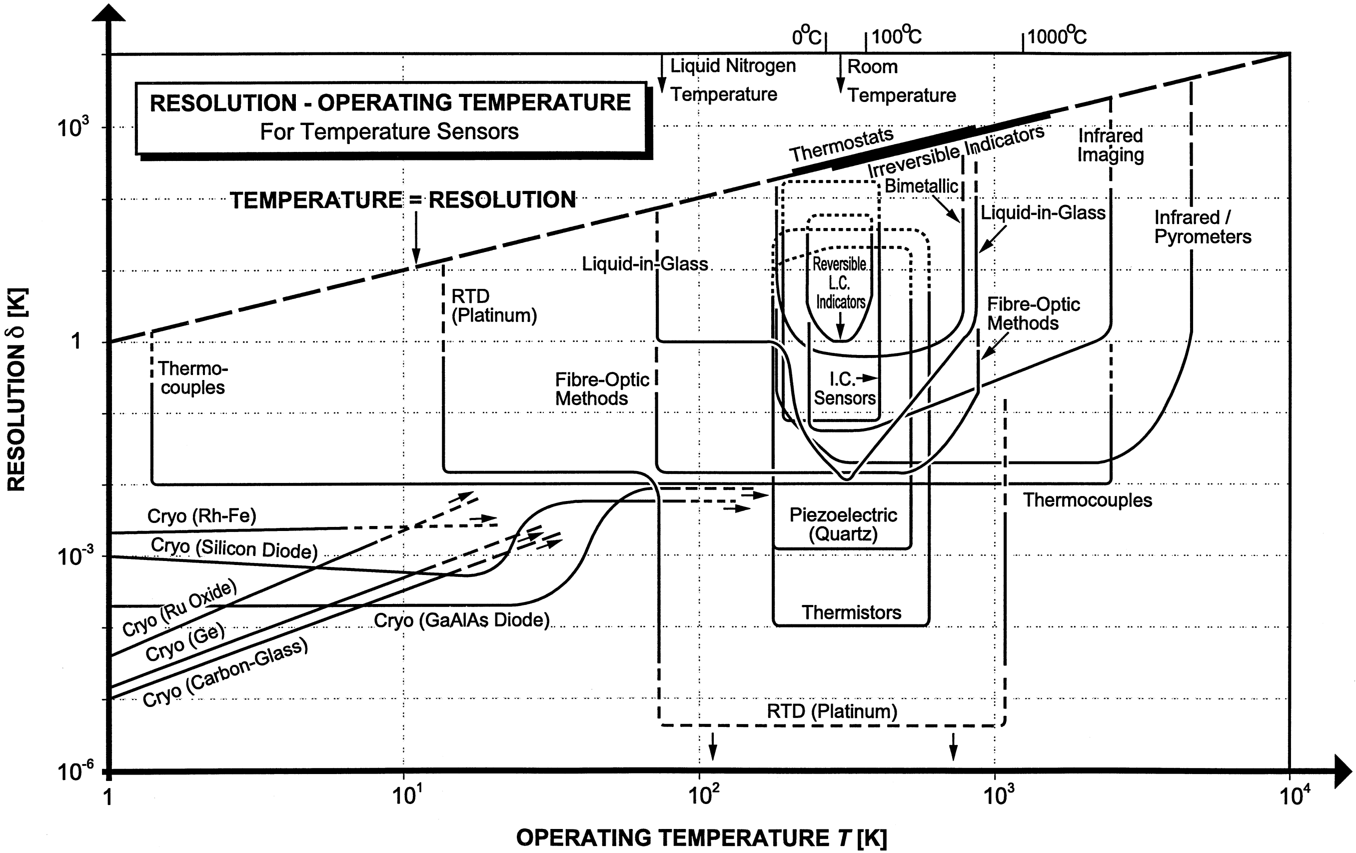

Fig. 7. Resolution versus operating temperature for temperature sensors.

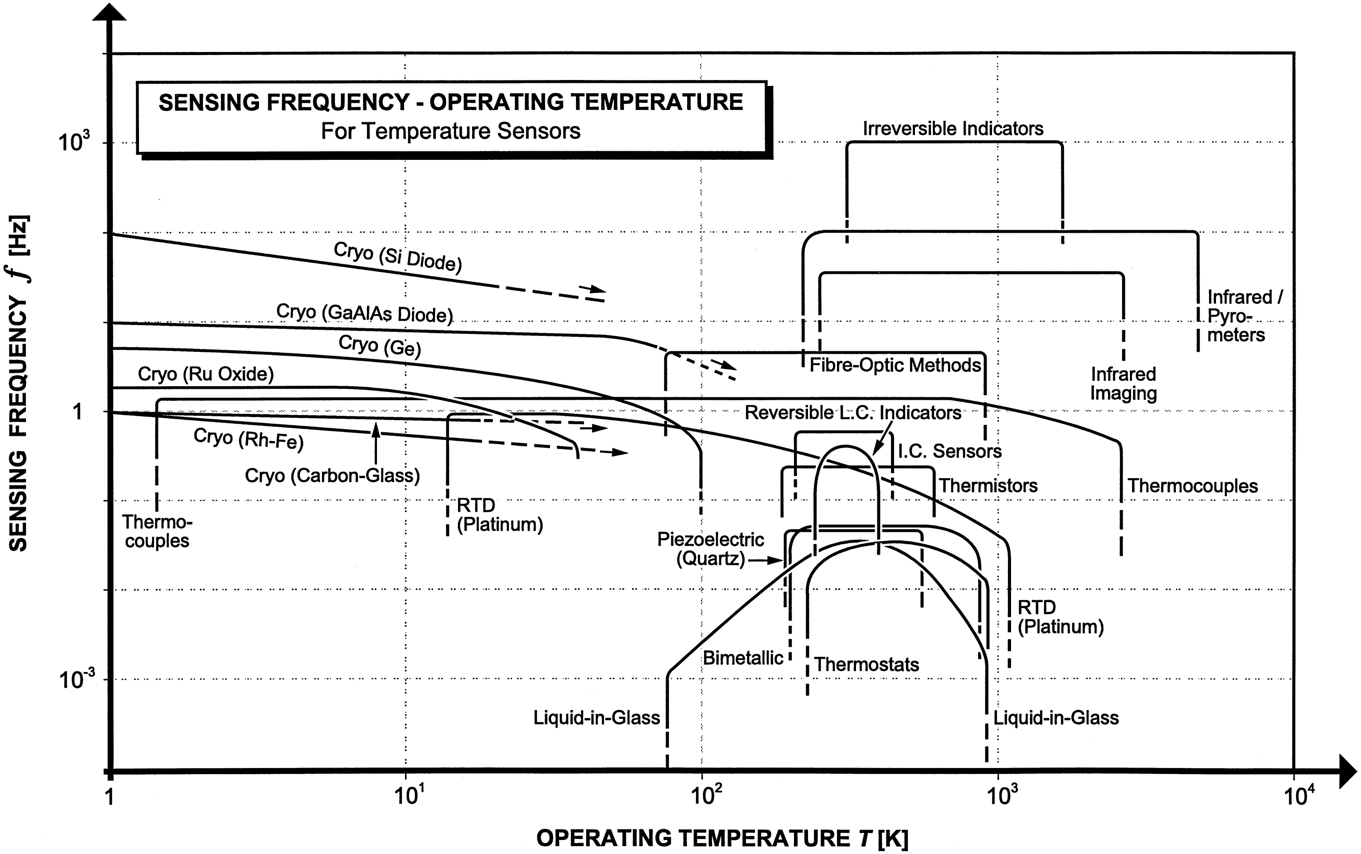

Fig. 8. Sensing frequency versus operating temperature for temperature sensors.

on available sensors for a particular market requirement. For liquid-in-glass thermometers, the lower temperature limit is set by the freezing point of the liquid used in the thermometer.

Temperature sensors can be divided into contacting and non-contacting types. For contacting sensors, the maximum operating temperature is limited by the decomposition temperature of the sensing element or housing. In applications requiring operating temperatures greater than 1000 K, sensors are predominantly non-contacting, with the exception of thermocouples (which can operate up to 2500 K). Infra-red sensors, though relatively expensive, are available for temperatures of up to 4700 K, far exceeding the range of contacting devices. They can also sample temperature over a surface that would otherwise require a large array of contacting thermal sensors (e.g. RTD or thermocouples). In applications requiring operating temperatures below 200 K, contact sensors are needed.

To avoid complicating the chart, the temperature regime of various cryogenic sensors are not shown for T greater than about 10 K in Figure 7.[8] Their resolutions at higher operating temperatures can be inferred by extending their performance lines, as indicated by the arrows. The resolution of cryogenic sensors depends largely upon their operating temperatures and varies by up to 1.5 orders of magnitude per order of magnitude change in temperature (see [4,5]).

Several sensors have a resolution of less than 0.01 K. Piezoelectric (quartz) temperature sensors and thermistors can achieve resolutions of 10^{-3} to 10^{-4} K; however, their operating temperatures are limited to about 200–570 K. Platinum RTD systems can achieve resolutions up to 10^{-4} K. Higher resolutions are possible with specialised instrumentation, and find application in thermometer calibration, and oceanographic research. Fig. 7 shows that some liquid-in-glass thermometers are capable of 0.01 K resolution at certain operating temperatures. These high-resolution glass thermometers are designed for specific applications, for example, bomb calorimetry where temperature change is used as a measure of the calorific value of fuel. A jump in resolution is evident for the platinum RTD at 70 K, below which the resolution deteriorates to about 0.01 K. The resolution of temperature sensors is usually controlled by the noise level and by the capability of the ancillary electronics.

Fig. 7 shows that thermocouples cover the widest range of operating temperatures, from cryogenic applications to high temperature sensing tasks (up to 2500 K). Integrated circuit (IC) sensors and reversible liquid crystal indicators have narrow operating ranges; however, they have additional benefits such as miniature size and low cost. Temperature switches or indicators that trigger at a pre-set temperature, such as thermostats and irreversible indicators, do not have a meaningful resolution: they exist on the line $\delta = T$ in Fig. 7.

2.5.2. Sensing frequency — operating temperature chart (Fig. 8)

Fig. 8 is a performance chart of sensing frequency versus operating temperature; the boundaries are the upper limit of sensing frequency of each class of temperature

[8] The ranges are typically from 1.4 to 300 K. The upper operating temperatures of ruthenium oxide and germanium resistor sensors are lower, however, typically 40 and 100 K, respectively.

sensor. Infra-red thermometers are non-contacting devices. They infer temperature by measuring the thermal radiation emitted by the target material and can respond to step changes in temperature within about 10^{-2} s.[9]

The sensing frequency of a contact thermometer is generally governed by its characteristic time constant, τ, given by mc/hA where m is the sensor mass, c is the specific heat capacity of the sensor, h is the heat transfer factor of the sensor–object interface, and A is the area of the heat transmitting surface. After a time of 5τ, thermal equilibrium is assumed to have been reached [6]. Accordingly, the maximum frequency may be estimated as $1/5\tau$. The upper limits of sensing frequency of most contact sensors in Fig. 8 are derived from their time constants in an environment of agitated water, which is significantly shorter than the values in air.

Liquid-in-glass thermometers are not designed to measure extreme temperature changes; therefore their response time is on the order of minutes. Piezoelectric temperature sensors have a relatively slow response as compared with commonly used contact sensors such as RTD, thermocouples and thermistors [6]; this is due to the difficulty of thermal coupling between the object of measurement and the oscillating piezoelectric crystal. Irreversible indicators (or change-of-state temperature sensors) consist of labels, pellets, crayons or lacquers. Some crayons or powders made of materials that indicate temperature by melting can a have response time on the order of milliseconds because their heat capacity is very low. The sensing frequencies of cryogenic sensors differ in accordance with the materials employed in their construction. Cryogenic sensors based on semiconductor junction devices (e.g. diodes) normally have faster thermal responses than other types.

3. Case studies

The performance charts described above, and documented in Appendices A–D, can be used for the selection of a sensor once the requirements of a particular application are known. We shall consider the following case studies to illustrate the selection procedure

1. selection of a displacement and a force sensor in order to determine the force versus deflection response of a biological specimen (a butterfly femur),
2. selection of an accelerometer for air-bag deployment and to measure the vibration level in a plate,
3. selection of a thermometer for medical use.

3.1. The mechanical testing of a miniature bone (butterfly femur)

A typical butterfly femur is a tubular structure of polysaccharide chitin, of length 5 mm and diameter 0.5 mm; the femur can support a maximum force of about 1 N.

[9] Note that some ultra high speed pyrometers developed for temperature measurements of high speed rotating turbine blades can have a response time of < 100 μs.

In a compression test on a butterfly femur, an axial shortening of about 1 mm is expected during the test, and we specify a resolution of 10^3 positions in both force and displacement, corresponding to 1 μm displacement resolution and 1 mN force resolution. The force sensor is placed in series with the femur, and must be sufficiently stiff to displace through less than 1 μm (the displacement resolution) at the maximum force of 1 N; this gives a minimum stiffness of 1 MN m^{-1}. In contrast, the displacement sensor is placed in parallel with the femur, and it must be sufficiently compliant to displace through the full range of 1 mm at a force of less than 1 mN, giving a maximum stiffness of 1 N m^{-1}. It is assumed that the test is carried out over 1 s, at a sensing frequency of 1 kHz for both load and displacement.

3.1.1. Selection of a displacement sensor

The optimal displacement sensor is selected by matching the required range, resolution and sensing frequency to that of available sensors using the charts of Figs. 1 and 2. In addition, the stiffness of the sensor must be less than 1 N m^{-1}. This places an additional restriction on suitable contact sensors (but no additional restriction on non-contacting sensors). The stiffness of the main types of contact sensors is plotted against displacement range in Fig. 9, and the stiffness constraint for the butterfly femur has been added to the figure. It is deduced that the contacting sensors, except for some types of LVDT, are too stiff to allow their use.

Table 4a shows the results of assessing the main types of displacement sensor against the requirements for testing a butterfly femur. Note that five classes of sensor pass all stages of the assessment: capacitive and capacitance micrometry, eddy current sensors, LVDT, and laser triangulation. A final selection among these may be made on the basis of cost, drift and linearity; see Table 4b for notes on these additional considerations. The final selection is an LVDT or a capacitive sensor, on the basis of low cost.

3.1.2. Selection of a force sensor

An appropriate force sensor for measurement of axial load in a butterfly femur is selected with the aid of the performance charts for force, as given in Figs. 5 and 6. In addition, the required force sensor must have a minimum stiffness of 1MN m^{-1}. The significance of this stiffness constraint is determined from a chart of stiffness of force sensor versus sensing range (see Fig. 10). Piezoresistive load cells have insufficient stiffness, while the other main types of force sensor pass this test. An assessment of the practicality of the various force sensors for the butterfly femur application is given in Table 5a (also see Table 5b for notes on the additional considerations): it is concluded that the piezoelectric sensor is the preferred choice.

3.2. An accelerometer for air-bag deployment

Increasing safety requirements in road transport give rise to a need for crash detection and safety devices. One form of crash detection which may be required in

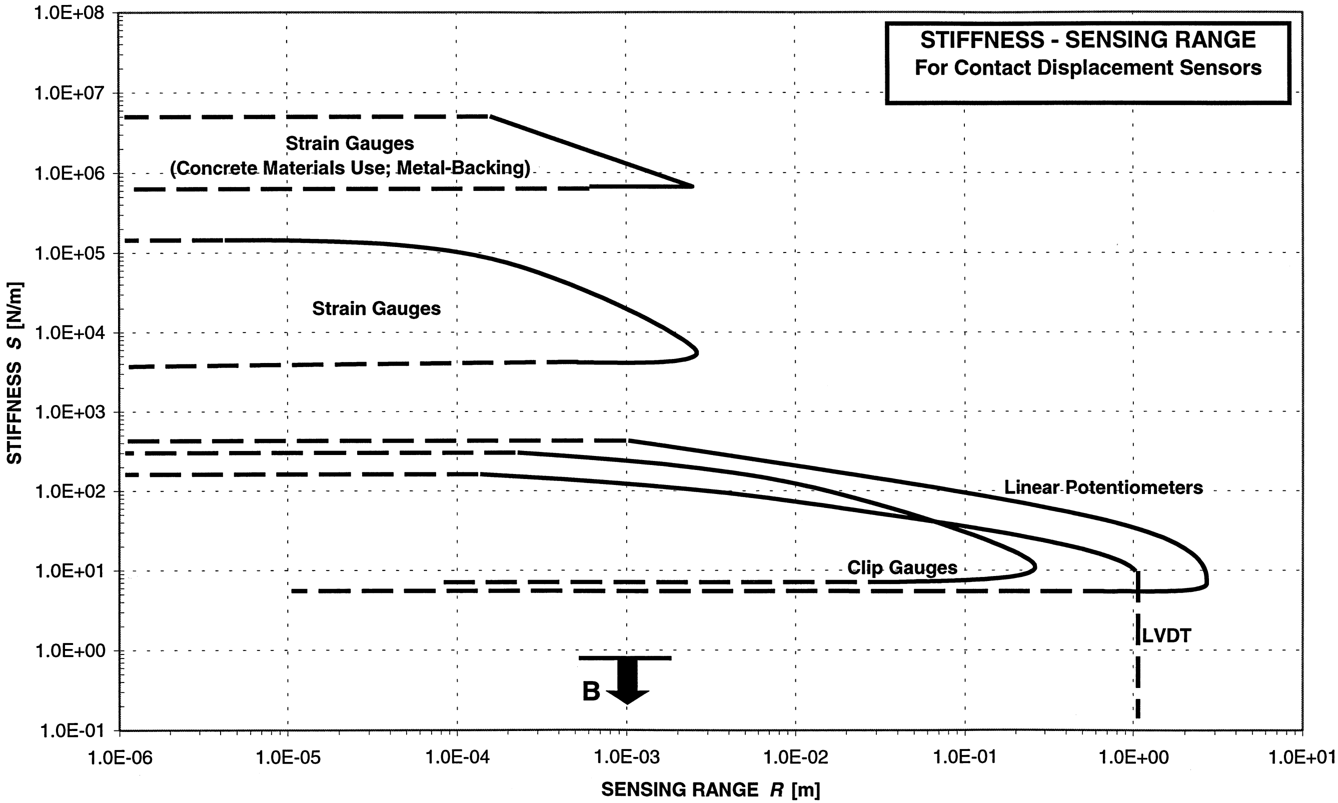

Fig. 9. Stiffness versus sensing range for displacement sensors (the downwards arrow labelled B shows the constraint on stiffness for the application of a butterfly femur).

Table 4
Assessment of displacement sensors for butterfly femur study
(a)

Sensor	Range — resolution	Range — frequency	Range — stiffness	Cost, drift and linearity
AFM/STM				
Video extensometers	✓		✓	
Strain gauges	✓[a]	✓[a]		
Capacitive	✓	✓	✓	Cost highly variable
Capacitance micrometry	✓[a]	✓[a]	✓[a]	high cost
Clip gauges	✓[a]			
Linear potentiometers		✓[a]		
Eddy current/inductive	✓	✓	✓	Cost highly variable
LVDT	✓	✓	✓	Low cost
Laser triangulation	✓	✓	✓	Good linearity, low drift, moderate to high cost
Magnetostrictive		✓	✓	
Optical linear encoders	✓		✓	
Ultrasonic			✓	
Fibre-optic/photoelectric		✓	✓	

(b) Drift, linearity and cost data for displacement sensors

Sensor class	Drift (%FS[b]/K)	Linearity (%FS[b])	Cost (US$)
AFM/STM	N/A	$< \pm 0.001$	$> 15{,}000$
Capacitive	± 0.02–0.1	± 0.1–1	Wide range
Capacitance micrometry	$< \pm 0.002$	$< \pm 0.02$	> 5000
Eddy current	± 0.01–0.05	± 0.1–1	Wide range
Inductive	± 0.06–0.4	± 0.2–2	< 1000
Laser triangulation	± 0.002–0.05	± 0.03–0.5	1000–8000
Linear encoders (optical)	$\pm 5\times10^{-6}$–2×10^{-3} (depending on the materials of scale and mounting substrate)	± 0.0001–0.001	Wide range
Linear potentiometers	± 0.01–0.04	± 0.1–1	< 1000
LVDT	± 0.005–0.01	± 0.1–0.5	< 1000
Magnetostrictive	$< \pm 5\times10^{-4}$	$< \pm 0.05$	> 1000
Photoelectric and fibre-optic	$< \pm 0.1$	± 0.1–1	Wide range
Ultrasonic	± 0.02–0.1	± 0.2–0.5	< 5000
Strain gauges	± 2–65 $\mu\epsilon$/K for Cu–Ni, Ni–Cr and some type p or type n Si sensing elements)	± 0.1–1	< 1000
Clip gauges	Depending on the strain gauge used and built-in circuitry	± 0.1–0.3	Wide range
Video extensometers	N/A	$< \pm 1$	> 1000

[a] Sensor is close to its performance limits.
[b] FS, full scale reading.

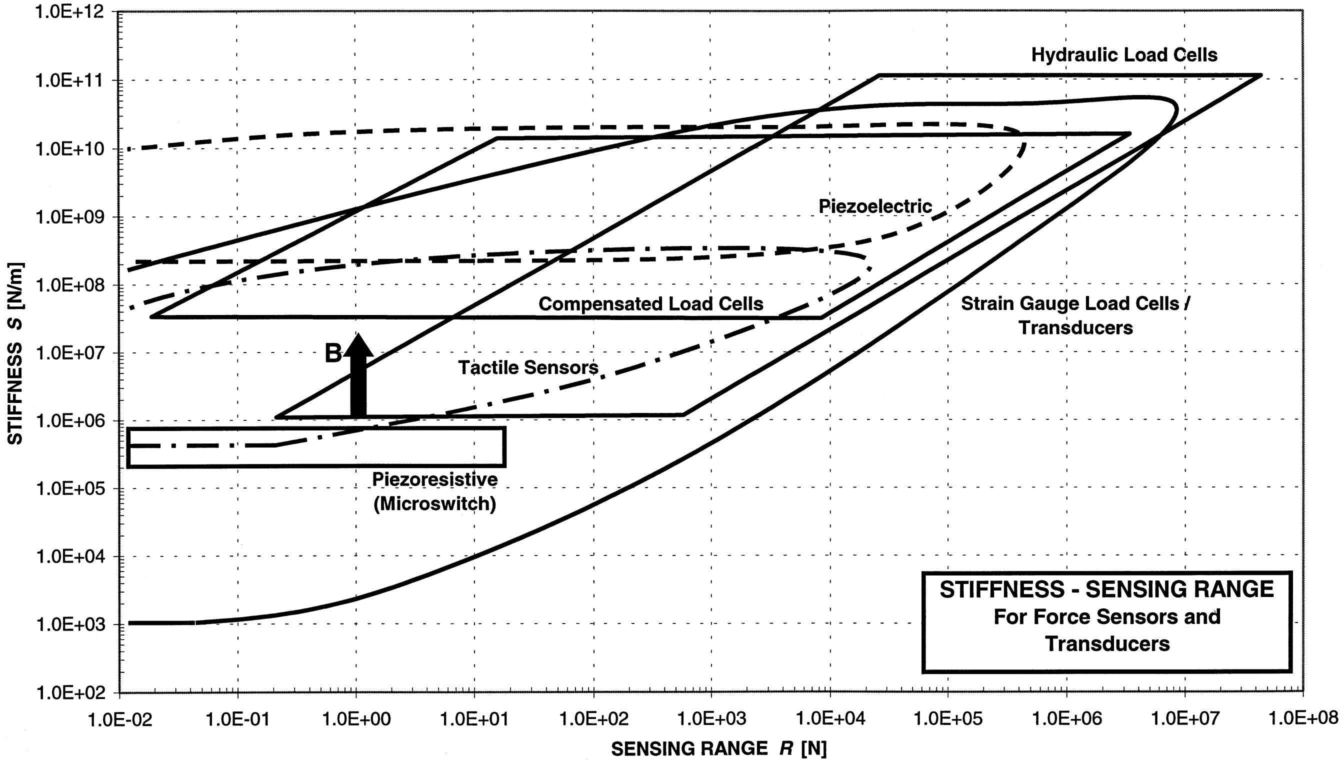

Fig. 10. Stiffness versus sensing range for force sensors (the upwards arrow labelled B shows the constraint on stiffness for the application of a butterfly femur).

Table 5
Assessment of force sensors for butterfly femur study
(a)

Sensor	Range — resolution	Range — frequency	Range — stiffness	Cost, drift and linearity
Piezoresistive		✓		
Tactile sensors	✓[a]		✓	
Fibre-optic load bolts		✓	✓	
Piezoelectric	✓	✓	✓	Low to moderate cost
Compensated load cells		✓	✓	High cost
Strain gauge load cells	✓		✓	Cost highly variable
Hydraulic load cells			✓	

(b) Drift, linearity and cost data for force sensors and transducers

Sensor class	Drift (%FS[b]/K)	Linearity (%FS[b])	Cost (US$)
Fibre-optic load bolts	±0.01–0.1	±0.1–1	> 1000
Hydraulic load cells	High	< ±0.25	> 5000
Strain gauge load cells	±0.002–0.02	±0.03–1	Wide range
Compensated load cells	< ±0.003	±0.1–1	> 5000
Piezoelectric	±0.02–0.2	< ±1	< 2000
Piezoresistive (microswitch)	~±0.2	~±0.5	< 50
Tactile sensors	< ±0.4	< ±5	Wide range

[a] Sensor is close to its performance limits.
[b] FS, full scale reading.

future is the sensing of contact or proximity of a moving vehicle with other bodies. A second form, which is currently in use, is the detection of severe crash conditions for the purpose of deploying safety devices such as airbags or seat-belt locks. In this case study we consider the selection of a sensor which is to detect crash conditions in order to deploy an air-bag. An accelerometer is required to sense the extreme deceleration of the vehicle.

3.2.1. Selection parameters

In a typical car crash, the driver experiences accelerations in the range 5–30 g (1 $g = 9.81$ m s^{-2}). A 30 g acceleration sustained for an interval of 0.2 s leads to severe injuries. A crash sensor is required to detect the instant at which the acceleration reaches 6 g, but must have a wider range than this: we shall specify 10 g. The resolution of the measurement needs to be no better than 0.1 g. However, it is required that the crash is detected within the first few milliseconds of the 6 g acceleration being reached, and thus a sensing frequency of at least 1 kHz and preferably close to 10 kHz is required (i.e. a response time of 0.1–1 ms). The sensor is required for high volume automotive production, and a maximum cost of US$20 per sensor is set.

3.2.2. Selection of an accelerometer

Fig. 3 shows that all classes of commercially available accelerometers are well within their operating range and resolution for the application of automobile crash detection. Each class of accelerometer has a broad range of operation, and includes devices which can operate at high acceleration and with sufficient resolution. However, the sensing frequency requirement (see Fig. 4) is beyond the scope of servo-accelerometers, and close to the practical limit of operation of strain-gauge-based devices. This leaves capacitive, piezoelectric and piezoresistive devices. Table 6 (size, mass and cost for accelerometers)[10] shows that capacitive and piezoelectric devices are available at sufficiently low cost. If low cost piezoresistive sensors could be produced, they would also be competitive for this application.

3.3. An accelerometer for measuring the free vibration of a plate

Measurement of the displacement and acceleration of vibrating plate structures has applications in noise-cancellation, aero-elastic flutter detection, and the study of acoustic devices such as musical instruments and loudspeakers. Consider the problem of measuring the local acceleration of an isotropic elastic plate of modulus E, thickness h and density ρ, vibrating with amplitude u and frequency f (angular frequency $\omega = 2\pi f$). An accelerometer is fixed to the plate, and must be capable of detecting an acceleration of maximum magnitude $u\omega^2$, with 10^3 positions of resolution. As well as satisfying the range, resolution and frequency requirements, it is desirable that the mass m of the accelerometer should cause negligible disturbance to the vibration; consequently, the mechanical impedance of the accelerometer, given by $Z_a = \omega m$ should be much less than the impedance $Z_p = 8\sqrt{D\rho h}$ of the plate, where D is the flexural rigidity given by $Eh^3/12(1-\nu^2)$ and ν is Poisson's ratio. Thus we require:

$$fm \ll \frac{2}{\pi\sqrt{3}}\sqrt{\frac{E\rho}{1-\upsilon^2}}h^2 \tag{1}$$

Table 6
Size, mass and cost data for accelerometers

Sensor class	Size (m)	Mass (kg)	Cost (US$)
Capacitive	1×10^{-2}–3×10^{-2}	7.5×10^{-4}–1.5×10^{-2}	10–550
Force-balance (servo)	2×10^{-2}–7×10^{-2}	1×10^{-2}–2×10^{-1}	High
Piezoelectric	5×10^{-3}–6.2×10^{-2}	1×10^{-4}–1	20–1000
Piezoresistive	1×10^{-2}–3×10^{-2}	4×10^{-4}–2.8×10^{-2}	100–650
Strain gauge-based	1×10^{-2}–5.5×10^{-2}	2×10^{-3}–2.8×10^{-1}	200–800

[10] Size here is the longest dimension or diameter of the accelerometer or chip carrier (for micromachined sensors packaged as a chip component). Cost does not include external electronics such as meters, signal conditioners, power supplies or data acquisition/analyzing instruments, etc.

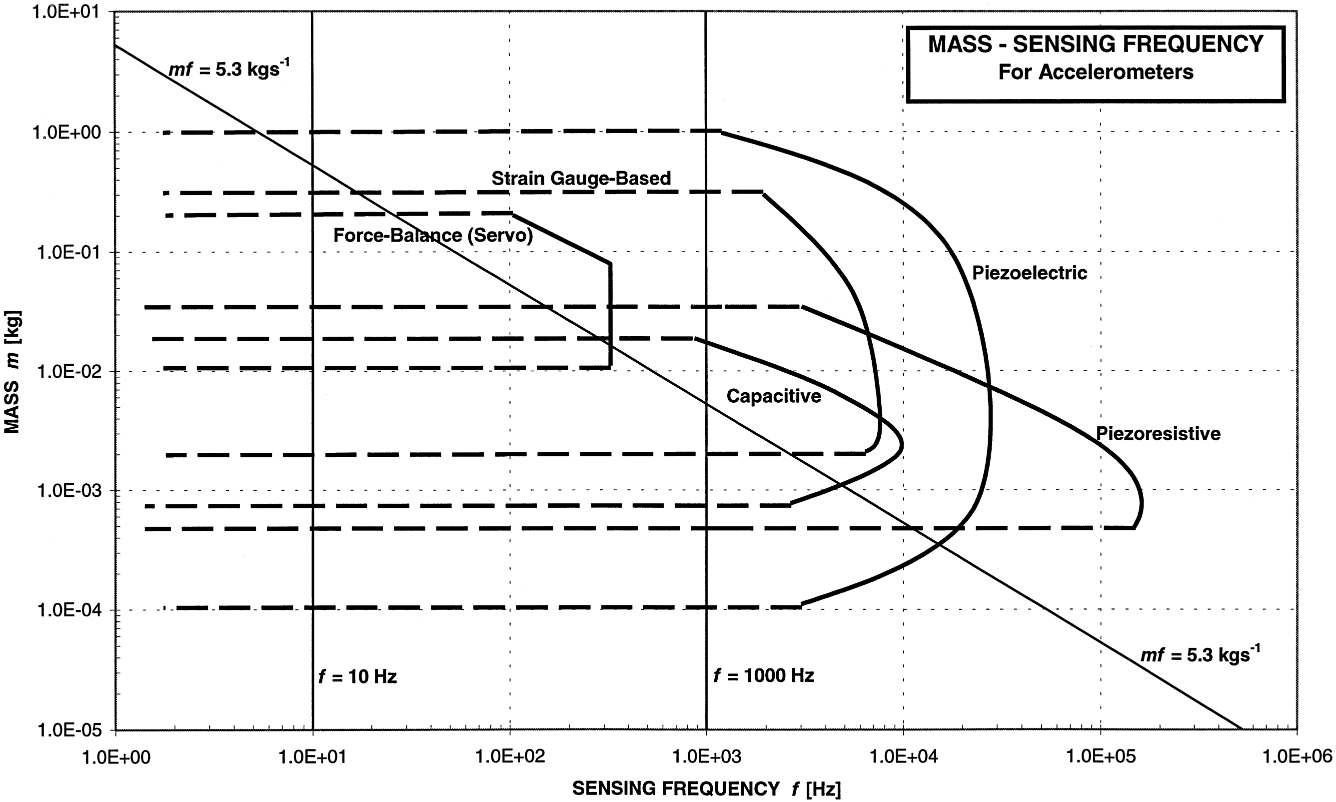

Fig. 11. Mass of accelerometer versus sensing frequency (with constraints displayed for a plate vibrometer).

3.3.1. Example

For illustrative purposes, we consider a large aluminium plate of thickness $h = 1$ mm; then the impedance constraint (1) becomes $fm \ll 5.3$ kg s^{-1}. For vibrations in the frequency range 10 Hz–1 kHz with amplitude 1 mm the maximum acceleration to be sensed is 400 *g* with resolution 0.4 *g*. Consider first the range and resolution requirements (Fig. 3) and the frequency requirements (Fig. 4). Fig. 3 shows that piezoelectric, strain-gauge and piezoresistive devices lie well within their capabilities. Capacitive devices are also possible, but are at their upper limit of range. When the plate oscillates at 1 kHz, a sensing frequency of at least 2 kHz is required to capture acceleration data. From Fig. 4, it is evident that both capacitive and strain-gauge-based accelerometers are close to their limits of performance.

Next, consider the mechanical impedance requirement. Fig. 11 shows mass versus sensing frequency for various classes of contacting accelerometers. The constraint-line $fm = 5.3$ kg s^{-1} is shown; at least one order of magnitude offset from this line is desirable, giving $fm \ll 5.3$ kg s^{-1}. The optimal choice of accelerometer, using the criterion of minimum disturbance to the measured stimulus, is that which minimises the product fm (i.e. lies towards the lower left of Fig. 11). Using this constraint alone, a low mass piezoelectric accelerometer would the optimum choice; some piezoresistive and capacitive accelerometers give tolerable performance, especially towards the low frequency end of the 10 Hz–1 kHz range. At the 1 kHz frequency the mass of accelerometer used is to be less than 0.53×10^{-3} kg, which places capacitive devices on their lower limit of mass, but cost must also be taken into account. A plot of cost versus mass of accelerometer is given in Fig. 12, from which it is deduced that the cheapest accelerometer of acceptable performance is a capacitive device. The final selection is to use a low mass capacitive or piezoresistive device, recognising that this task is at the limits of readily available capacitive accelerometers.

3.4. A thermometer for medical use

It is instructive to use the performance charts for temperature sensors in order to explore possible replacement thermometers to the traditional liquid-in-glass construction for measuring body temperature: liquid-in-glass thermometers are fragile, have a slow response time (frequency response of less than 0.03 Hz) and cannot be heat-sterilised without causing damage. Their continued use is due to their low cost, long term stability and acceptable accuracy (about 0.1 K).

The ideal thermometer for the measurement of body temperature will sense temperatures between 308 and 315 K, with a resolution of less than 0.1 K and a frequency response faster than 0.1 Hz. On examination of Figs. 7 an 8, potential sensors are thermistors, infra-red pyrometers and the thermocouple. IC sensors are barely acceptable as their resolution is at best 0.1 K. The infra-red pyrometer has a fast response (a sensing frequency on the order of 3 Hz is achievable) and such thermometers are now available, measuring the temperature within the auditory canal. Contacting thermistors have also been developed recently for the measurement of body temperature.

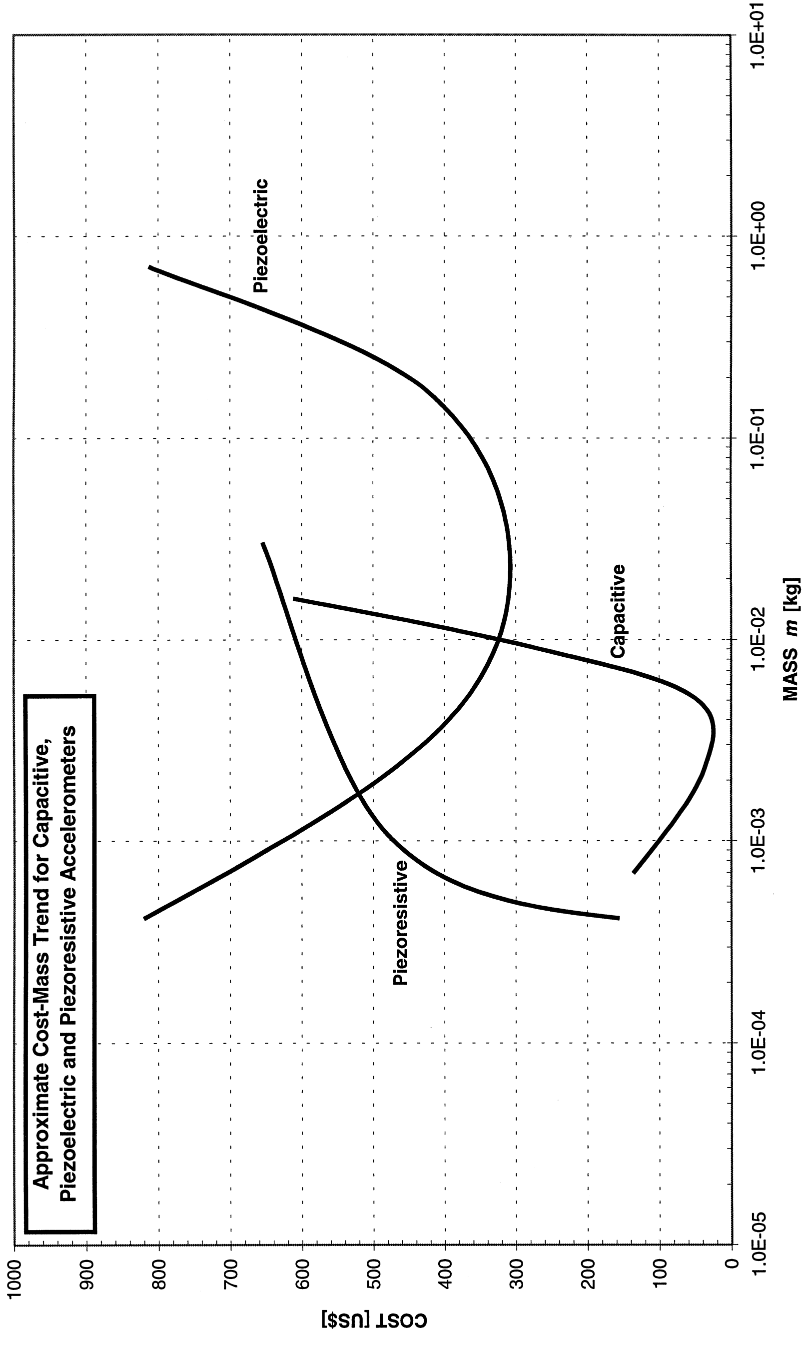

Fig. 12. Cost versus mass for accelerometers.

4. Concluding remarks

A wide array of sensors have evolved to allow measurement of strain, distance, displacement, velocity, acceleration, force and temperature, each specialised for a particular set of requirements. Fundamental theoretical limits on range, resolution, precision and sensing frequency constrain the performance of some sensors, but for many others the limits appear to be practical rather than fundamental. The enormous diversity both of sensor type and of performance creates the need for methods to enable comparison and selection, allowing the choice of a sensor to meet a given set of sensing requirements. A way of achieving these goals is described in this paper, which presents performance charts to guide the selection process, and a number of case-studies that display the utility of the method. Typically, several competing technologies exist, and the final choice is guided by detailed distinctions of cost or availability. The value of the charts lies in their ability to provide an overview of sensor performance and to direct attention to the sensor type best suited for a given need.

Acknowledgements

The support of the EPSRC is gratefully acknowledged.

Appendix A. Displacement sensors and transducers

A brief description is given below of each class of displacement sensors, including proximity switches.

A1. AFM/STM

Atomic force microscopy (AFM) operates by measuring the attractive or repulsive forces between the sample and a small probe tip (of dimension ~3 μm) mounted at the end of a cantilever beam (of length ~100 μm) (see, for example [7]). Atomic forces on the probe tip cause the cantilever beam to bend, and the topology of the sample surface is measured by the reflection of a laser beam off the cantilever and onto a position-sensitive photo diode. In scanning tunnelling microscopy (STM), the probe tip is lowered until a tunnelling current flows between the probe tip and the sample surface (with a spacing of less than 1 nm). Distances on the order of 0.1 nm can be resolved by monitoring the tunnelling current.

A2. Capacitive sensors (displacement and proximity)

Capacitive sensing is a non-contact technology suitable for detecting the position of metals, non-metals, solids and liquids. The device consists if a capacitor, with the sensor as one plate and the target as the other plate. In analog sensing, a change in the spacing of the capacitor plates results in a change in the measured capacitance; in discrete sensing, the proximity of the sensed object leads to a change in the dielectric constant.

A3. Capacitance micrometry

Capacitance micrometry adopts the same operating principle as capacitive sensing. However, instead of using the target as one of the plate electrodes, the capacitance micrometry technique has two sensor plates — one is secured to a fixed reference, while the other one is secured to the moving target. The spacing of these two sensor plates can be measured to better than 0.1 nm, with a range up to 1.25 mm, a sensing frequency of up to 5 kHz and a linearity error of down to 0.02% (see [8]).

A4. Eddy current sensors

Eddy current sensing is a non-contact technology suitable for detecting electrically conductive objects. These sensors employ a "dual-coil" configuration and are designed to generate an electromagnetic field. One coil is used as a reference, while the other is for the sensing of eddy currents induced in the conductive target. Eddy currents generated within the target produce a magnetic field which opposes that of the sensing coil, thus resulting in an imbalance with respect to the reference coil ([6]). The closer the target to the sensing coil, the greater is the change in the magnetic impedance.

A5. Inductive sensors (displacement and proximity)

Inductive sensors operate on the principle that the inductance of a coil is modified by bringing it into proximity with a ferromagnetic object (the target). An external circuit monitors the coil inductance which decays non-linearly as the distance to the target increases. Inductive displacement sensors can operate over a similar range to that of eddy current sensors, but have coarser resolution and lower sensing frequency.

A6. Laser triangulation

This technique is based on an active optical measuring module that incorporates a light emitting diode (LED) and a detector such as a position sensitive detector (PSD) or a charge coupled device (CCD). The near infra-red LED projects a narrow-angle beam (usually visible class 2 laser) onto the target. The diffuse reflection of the light is then focused on the PSD or CCD by a lens and the position of the object is determined by the principle of triangulation. The PSD (or CCD) element supplies a position dependent, analog output voltage proportional to the measuring distance between sensor and target. Long operating distance (750 mm max.) and small beam spot diameter (~10–30 μm) make this a highly accurate and versatile displacement measuring technique.

A7. Linear encoders (optical)

Optical linear encoders operate by sliding a photoelectronic read-head along a scale with regular gradations. Light emitted from the read-head either passes through or reflects off the scale and through an identical phase grating. This produces sinusoidal interference fringes at the detection plane within the read-head. Photodetectors on the detection plane convert these fringes into electrical signals. Alternatively, an interferometric technique is capable of capturing the $\pm$1st order laser diffracted signals reflected from the scale, and can be used to achieve sub-nanometre position resolution. Optical linear encoders use gratings on various carriers (such as glass, glass ceramic, solid steel or steel tape) as their measuring standard. The accuracy and thermal stability of the encoder can be optimised by the choice of carrier (see [9–13]).

A8. Linear potentiometers

Linear potentiometers rely upon the principle that the resistance along a wire is proportional to its length. Thus, the position of a wiper contact on the wire is a measurement of the wire resistance.

A9. LVDT

A linear variable differential transformer (LVDT) is a transformer with a mechanically actuated ferromagnetic core. Its coil configuration consists of a central primary driven by an excitation signal (sine wave) and two external secondaries for induction purposes. The flux coupling between the coils and the out-of-balance voltage of the transformer is a measure of the position of the core [6]. The maximum operating frequency is typically about one-tenth of the carrier (excitation) frequency which can be as high as 100 kHz.

A10. Magnetic field sensors (proximity)

The presence of magnetic fields can be detected using magnetically actuated proximity sensors. The operation of these sensors can be based on several different techniques, namely: (1) reed switching, relying upon the alignment between a pair of contacts and the magnetic flux, (2) interruption of the magnetic flux between a magnet and a Hall probe, (3) evaluation of the change in polarity of the magnetic field, and (4) a change in the inductance and reversible permeability of a core-coil configuration due to a variation in the superimposed magnetic field (see [6,14]).

A11. Magnetostrictive sensors

The magnetostrictive effect is the tendency of some materials to strain in the presence of a magnetic field. Magnetostrictive sensors measure the relative position of a permanent ring magnet along the axis of a magnetostrictive waveguide, up to 7.5 m in length (see [6,15]).

A12. Photoelectric and fibre-optic sensors (displacement and proximity)

These optical sensors operate either by the time-of-flight approach or by sensing a change in the amount of light that is reflected by the target. An infra-red or near infra-red LED or a diode laser transmitter provides the light source, and a photodiode or phototransistor is used as the light receiver. Fibre-optic sensors permit the attachment of fibre-optic cables that can be mounted in locations that would otherwise be inaccessible to other types of photoelectric sensors. Photoelectric and fibre-optic sensors are extremely versatile. For example, a pulsed laser distance sensor is able to sense objects 1 km away, while other fibre-optic sensing systems are capable of sub-nanometre resolution.

A13. Ultrasonic sensors (displacement and proximity)

Ultrasonic sensing relies upon the time of flight for a high-frequency sound wave ($>$ 20 kHz) to strike the target and echo back to the sensor. Piezoelectric transducers are used to generate and receive the ultrasonic waves. These sensors require the measured object to have adequate acoustic reflectivity; they have an inherent blind zone located at the sensing face, and consequently they have a minimum sensing distance.

A14. Strain gauges and clip gauges

A strain gauge is a resistive sensor consisting of a fine wire, a photographically etched foil or a semiconductor element bonded to an insulating base. When strained, the wire, foil or semiconductor element experiences a change in resistance proportional to the strain; this resistance change is measured using a bridge circuit. A variation in ambient temperature introduces an error of 10 to several thousand microstrain per K. Consequently, the interface circuits and gauges require temperature-compensating networks. Clip gauges (extensometers) are strain gauges that adopt a bending-beam mechanism to achieve a displacement measurement of larger range (up to 250 mm) than that of the individual strain gauge (about 0.1 mm).

A15. Video extensometers

Non-contacting video extensometers utilise digital image processing technology to determine the displacement of a target. The system uses a CCD camera which sends displacement data to an image processing system, in which image processing algorithms are used to provide high resolution, sub-pixel results (see [16,17]).

Appendix B. Accelerometers

Typically, accelerometers use the mass of an element to convert acceleration into a force, in accordance with Newton's second law. Such an accelerometer contains an inertial mass, a spring-like support system, a force or displacement sensing element and a damping element[11] [6]. The movement of the inertial mass lags behind that of the accelerometer's housing, which is fastened to the object under study. The imposed acceleration gives rise to a relative displacement of the inertial mass with respect to the housing, or to a force on the force-sensing element (e.g. piezoelectric materials) by the inertial mass. In the following sub-sections a brief description is given for the main types of accelerometers in use today.

B1. Capacitive accelerometers

Capacitive accelerometers operate by detecting the change in the spacing of two capacitor plates; one is stationary and connected to the housing, while the other one is attached to the inertial mass. Most capacitive accelerometers adopt differential techniques to provide a reliable compensation for drift. Temperature calibration is required to maintain accurate measurements over the operating range of temperature, typically 223–393 K.

Recently, capacitive accelerometers have been manufactured by surface micromachining: a technique for building electromechanical structures in silicon. Combined with onboard signal conditioning circuits, acceleration sensing systems can be economically built on a single piece of silicon, typically smaller than 1 mm^2 [18]. The first commercially successful applications for surface micromachined accelerometers were automotive airbags.[12] Surface micromachined accelerometers are low in cost and small in size. The all-in-one package design minimises the problems of noise and non-linearity; however their accuracy and resolution are generally below that of other classes of accelerometers (see [19]).

B2. Force-balance (servo) accelerometers

Force-balance or servo accelerometers, used predominately in inertial navigation systems, are closed-loop devices in which the deflection signal is used as feedback in a servo system that moves the inertia mass back to the equilibrium position.[13] The acceleration is determined via the motor drive current. By null-balancing of the displacement of the inertial mass, geometric non-linearity errors are minimised. In addition, closed-loop accelerometers usually have higher resolution, accuracy and stability than open-loop types [2]: these attributes are controlled by the feedback electronics rather than the characteristics of the sensing element as in open-loop designs. For vibration sensing, servo accelerometers are generally designed for accelerations of less than ± 90 g and at frequencies of less than 300 Hz.

[11] Gas or oil damping to protect accelerometers from high shoock or excess acceleration loads.

[12] Examples of such devices are the ADXL family or accelerometers from Analog Devices, Inc. used in Ford Motor Company's model year 2000 Taurus airbag system.

[13] Accelerometers based on technologies other than the force-balance (servo) principle are open-loop devices in which the output due to deflection of the sensing element is read directly.

B3. Piezoelectric (PE) accelerometers

Piezoelectric (PE) Accelerometers contain a piezoelectric crystal, such as quartz or PZT, sandwiched between the seismic mass and the sensor housing. The acceleration of the inertial mass generates a force on the crystal, and thereby induces a charge, which is detected by a charge amplifier [2,20]. Alternatively, integral miniature accelerometers can be fabricated by depositing a thin piezoelectric film of lead titanate, onto a micromachined silicon structure. Although PE accelerometers do not have a DC response, they have a wide frequency range, typically from 0.1 Hz up to about 20 kHz. They also possess good off-axis noise rejection and linearity (see [6,21,22]).

B4. Piezoresistive and strain gauge-based accelerometers

These accelerometers use strain gauges as the sensing elements to measure strain in mass-supporting springs. The strain scales with the displacement of the mass and, thereby, with the acceleration. Piezoresistive accelerometers are made by the etching of semiconducting silicon gauges with high gauge factors ($\sim$100). Most contemporary piezoresistive accelerometers are manufactured from a single piece of silicon ($\sim$1 mm^2), and this miniaturisation allows for natural frequencies in excess of 1 MHz [2]. With integrated circuit technology it is possible to produce a fully integrated conditioned accelerometer to achieve amplification and temperature compensation, giving improved stability and reliability [23].

Accelerometers adopting metal wire or foil/film gauges are termed strain gauge-based accelerometers in this study. Due to the low gauge factors (typically $\sim$2 for metal wire/foil strain gauges) and comparatively large size, strain gauge-based accelerometers have a much lower sensing frequency and a narrower sensing range compared to piezoresistive types.

Appendix C. Force sensors and transducers

C1. Fibre-optic load bolts

This technique is based on drilling a hole of about 0.5 mm diameter through the neutral axis of a bolt or stud, and inserting a miniature, high-precision fibre-optic strain gauge. The fibre-optic strain gauge, typically uses Fabry–Perot interferometry based on white-light. The gauge consists of two semi-reflective mirrors facing each other and deposited on the tips of two optical fibres. When the gauge (i.e. bolt) is strained, the air gap between the mirrors, called the Fabry–Perot cavity length, varies; and as a result, the interference between the reflective lights from the two mirrors changes. This alteration in optical interference is detected by a photodetector and subsequently related to the magnitude of applied load or force [24,25]. Fibre-optic load bolts are immune to electromagnetic and radio frequency interference (EMI/RFI), and insensitive to off-axis and torsion loads. Their operating temperature can be as high as 533 K. Because of the excellent flexibility in size, they are capable of non-invasive in-situ measurements in hazardous environments and obscure locations.

C2. Load cells (hydraulic)

Hydraulic load cells are force-balance devices, measuring force as a change in pressure of the internal fluid. Most hydraulic cells have a rolling diaphragm structure: a force on the loading head of the cell is transferred to a piston that in turn compresses a fluid confined within an chamber. This pressure is indicated by using a tube gauge or transmitted for remote readout and data acquisition via various electrical transducers. Since hydraulic load cells do not require a power supply, they are ideal for use in hazardous areas and remote locations. Common applications for them include tank weighing, rock/soil anchoring and concrete pre- and post-tensioning. However, they are sensitive to temperature changes, and typically have an accuracy of about 0.25% full scale.

C3. Load cells (strain gauge-based)

Strain gauge load cells dominate the weighing industry due to their versatility, high accuracy and low cost. They contain metal foil strain gauges which are bonded onto a beam or shell structural member that deforms under force. Multiple gauges and resistors are often arranged in a bridge circuit configuration, to compensate for gauge mismatch, temperature effects and off centre loading. Some cells are fatigue-rated for use in long term structural fatigue tests.[14] The spring elements in strain gauge load cells can respond to an axial force, bending moments or torques, with little cross-talk between channels (less than 1%). Accuracy is 0.03–1% full scale, with a compensated temperature range of 253–343 K.

C4. Compensated load cells

Dynamically compensated (or integrated accelerometer) load cells are fatigue-rated and are less affected by inertial loading effects: they are compensated for the loads associated with their own acceleration. They have a built-in accelerometer and are calibrated for the known mass of moving parts. The major advantage of servo-hydraulic machines adopting these cells is that high frequency operation ($\sim$1000 Hz) can be achieved while maintaining accurate closed-loop load control[15] [16].

C5. Piezoelectric (PE) force sensors

The piezoelectric effect can be used in both passive and active force sensors. The operating principle behind active types is that the resonant frequency of an oscillat-

[14] Fatigue rating is a distinct specification which guarantees a load cell which has a service life of 100 million fully reversed loading cycles at full rated capacity.

[15] Servohydraulic test machines are closed-loop systems that compare live feedback signals to an input command signal to maintain accurate control of preset conditions.

ing quartz crystal is affected by mechanical loading (see [6,26]). In passive PE force sensors, an applied stress is converted directly into an electrical signal using the piezoelectric effect. The sensor comprises a thin quartz crystal disc sandwiched between two parallel plates. Multi-component force measurement is possible by stacking multiple quartz discs; each quartz disc is cut in a particular crystallographic direction to respond independently to each component of the measured force. Most PE force sensors have a high stiffness ($\sim 3.5\times 10^{8}$–2.3×10^{10} N/m) and are small in size (of diameter about 10 mm). These characteristics provide for a high frequency response, permitting the accurate capture of short-duration impulse force data.

C6. Piezoresistive (PR) force sensors

Piezoresistive force sensors contain piezoresistive micro-machined silicon sensing elements and operate on the principle that the resistance of silicon-implanted piezoresistors will increase with an imposed strain. Applications for PR force sensors include medical pumps, robotic end-effectors and contact sensing. Piezoresistors have higher temperature sensitivity than wire/foil strain gauges; hence the operating temperature range for force sensors adopting piezoresistors is typically limited to 233–353 K (see [27]).

C7. Tactile sensors

In tactile sensing, a contact force distribution or deflection profile is measured, using a closely spaced array of force, displacement or proximity sensors. Most tactile sensing systems adopt grid-based configuration endowing the sensor array with skin-like properties. They are extremely thin (down to 0.1 mm), flexible and have a wide range of shapes, sizes and spatial resolution (i.e. sensor spacing). The touch surface of a tactile sensing system is usually made of an elastomeric pad or flexible membrane. Sensors embedded inside can be based on various technologies such as piezoelectric, piezoresistive, strain gauging, optical, ultrasonic, electromagnetic and capacitive.

Tactile sensing systems are designed to detect either qualitative force/pressure information (i.e. whether the contact force reaches a certain limit) or quantitative force/pressure information (i.e. magnitude of the contact force). A typical system has about 100 sensor elements in one square centimetre. Therefore, in order to sample all sensing locations in a short duration of time, tactile sensing systems require a high-speed data acquisition and analysis unit. Tactile sensors have numerous applications in robotics and medical areas (see [20,28]).

Appendix D. Temperature sensors

D1. Bimetallic thermometers

The differential expansion of the two components of a bimetallic strip induces bending of the strip, and to a temperature indication via an indicator needle on a dial, or via the activation of a switch. Typically, the nickel–iron alloy Invar, possessing a very low thermal expansion coefficient, is used as one strip, with brass, iron or nickel alloys as the other strip [29]. Bimetallic thermometers generally have an accuracy of several degrees kelvin.

D2. Cryogenic temperature sensors

Commercially available cryogenic temperature sensors include various types of resistors, capacitors, thermocouples, and semiconductor junction devices such as diodes or transistors; the basis of choice depends upon the required accuracy and operating environment. The most commonly used cryogenic thermometers are diodes and resistors. Diode sensors are based on the forward voltage drop at constant current through a temperature-sensitive semiconductor pn-junction; resistive sensors rely upon temperature dependence of electrical resistance (see [4,5,29–32]).

D3. Fibre-optic temperature sensors

Fibre-optic sensors are remote sensors suitable for temperature sensing in hazardous environments (for example in strong electromagnetic fields). The operation is based on several different techniques, as follows:

1. fluoroptic (range of 73–723 K). A rare-earth phosphor compound located at the fibre-end emits a fluorescent signal in response to light excitation; the frequency content of the response pulse is a function of temperature (see [6,33,34]);
2. Interferometric (range of 223–923 K). These sensors rely upon optical methods such as Fabry–Perot gauging, intensity modulation and Raman scattering (see [6,25,35–37]);
3. Light absorption (range of 73–573 K). A semiconductor crystal placed at the fibre changes its light-absorption capacity with temperature (see [38]).

D4. Integrated-circuit (IC) temperature sensors

IC sensors rely upon the fact that the characteristic of a semiconductor pn-junction in a diode depends upon temperature. If the junction is biased by a constant current, the resulting voltage is a measure of the junction temperature, with a linear response for temperatures in the range 218–423 K. IC sensors are attractive devices for many applications due to their miniature size, the inherent low cost of a monolithic integrated circuit ($1–10), and the elimination of external support circuitry. IC temperature sensors are often employed in the silicon substrate in monolithic sensors to compensate for the temperature dependence of sensing elements (see [6,19,29,39]).

D5. Infra-red thermometers/pyrometers and infra-red imaging

Infra-red thermometers (or pyrometers) consist of optical systems and wavelength-characterised radiation detectors. They infer temperature by measuring the thermal radiation emitted by a target material in the 0.7 to 20 μm wavelength range (i.e. infra-red). As the temperature increases, the amount of infra-red radiation and its average frequency increase. Infra-red thermometers take into account the emissivity of the object surface being measured and the thermal radiation of surrounding heat sources at some other temperatures. The emissivity of a given material varies with temperature and localised conditions such as oxidation and surface finish. Infra-red thermometers are non-contacting devices and therefore are suited to the measurement of moving objects or inaccessible surfaces and for sensing in hazardous environments. Although more expensive than other types of sensors, infra-red thermometers have faster responses[16] and higher maximum operating temperatures (up to 4723 K) than contact thermometers. Their accuracy is typically ±0.2–1% of the full-scale reading.

Infra-red imaging devices (or thermal imagers) are infra-red thermometers that incorporate real-time imaging, i.e. a camera to display thermal profiles and temperature measurements as a multi-colour visual image. The sensor employs a high-speed scanner and/or multiple radiation detectors to produce thermograms (heat pictures) of machinery, buildings, electrical installations, biological objects and so on (see [29,40–42]).

D6. Irreversible temperature indicators

Irreversible temperature indicators, also known as change-of-state temperature sensors, consist of labels, pellets, crayons and lacquers whose physical state changes when a critical temperature is reached. The transformation is irreversible and leads to a change in sensor's appearance, usually in the form of colour change or to melting of the indicator. The accuracy is lower than other sensor classes, typically ±1–2% of the target temperature. Some crayons or pellets made of temperature melt materials can have a response time on the order of milliseconds. Irreversible temperature indicators are predominantly used to check whether a temperature limit has been exceeded, in the food preservation industry for example.

D7. Liquid crystal temperature indicators (reversible)

The molecular order of a liquid crystal can be modified by temperature changes, with corresponding changes in its optical properties such as colour. Typical multi-temperature liquid crystal strips have 7–16 temperature indicating levels in 1–10° increments. The response time is typically 0.5–2 s.

D8. Liquid-in-glass thermometers

Mercury-in-glass and organic liquid-in-glass thermometers rely upon the principle that the liquid expands with increasing temperature. Liquid-in-glass thermometers

[16] Typically up to 100 Hz; some ultra high speed pyrometers developed for temperature measurements of high speed rotating turbine blades can rach 10 kHz.

can be used in the temperature range 73–923 K. Despite their limited precision and accuracy ($\sim\pm0.03$–0.5 K), their simplicity, long term stability and low cost (\$1–300) allow them to find widespread industrial and medical application. Most liquid-in-glass thermometers have graduation intervals of 0.01–1 K. Thermometers with high precision (i.e. fine graduation intervals) and limited sensing range exist for specific laboratory applications, for example, bomb calorimetry and solidification point detection.

D9. Piezoelectric (quartz) temperature sensors

Many modes of oscillation can be obtained in quartz depending on the crystallographic orientation (i.e. angle of cut). By selecting a temperature-dependent mode, a temperature sensor based on variation of the frequency of a quartz oscillator can be constructed. The probe crystals of quartz temperature sensors can be cut so as to exhibit either linear or non-linear frequency–temperature response (see [43–46]). The operating temperature range is from 193–513 K with an accuracy of ±0.02–0.075 K. The sensing frequency is typically slower than thermoresistive and thermoelectric sensors because of the difficulty of thermal coupling between the measuring object and the sensor's oscillating plate [6].

D10. Resistance temperature detectors (RTD)

The resistivities of all metals and most alloys are temperature-dependent. Resistance temperature detectors (RTD) make use of metals which possess a positive temperature coefficient and display a linear change in resistance with temperature. Although virtually all metals can be used as the RTD sensing element, platinum is used almost exclusively because of its linear response, long-term stability, corrosion resistance and wide temperature range of operation. RTD require an external current source in order to detect the change in resistance; the current must be sufficiently small for self-heating to be negligible. Platinum RTD can be used in the temperature range 13–1333 K. The accuracy achievable is largely dependent upon the calibration method and the bridge circuits used to measure the resistance (see [6,29,47–49]).

D11. Thermistors

Thermistors exploit a temperature-dependent resistance change in a semiconductor, with either a positive temperature coefficient (PTC), or, more commonly a negative temperature coefficient (NTC). NTC thermistors are mainly metal-oxides. Their resistance decreases non-linearly with the increase in temperature, so they are often used in matched pairs to offset non-linearities. PTC thermistors are fabricated of semiconductive doped ferroelectric ceramics (e.g. La, Nb, Mn, Fe or Cr doped barium titanate). The dramatic increase in resistivity of the doped material when approaching its Curie temperature is used for current control and temperature switching. Compared to RTD, thermistors can produce much larger changes in resistance with small changes in temperature. This makes them suitable for applications requiring a high output signal over a relatively narrow temperature range. Thermistors require an external current source, and therefore the issue of self-heating arises. To achieve good reproducibility, the operating range is usually limited to 193–573 K with an accuracy of ±0.001 K (calibrated standards) to 0.1K (see [6,50,51]).

D12. Thermocouples

Thermocouples consist of two wires made of different metals and employ a hot junction and a cold junction. According to the Seebeck effect, an electromotive force (emf) is induced when the measuring junction (hot) is at a different temperature from that of the reference junction (cold). A number of metallic pairs are commonly used for practical thermocouples (see, for example [29,48,52–55]). Thermocouples are probably the most-widely-used temperature sensors due to their wide operating temperature range (1–2500 K), stability, simplicity, low cost and lack of requirement for an external power supply. Their accuracy is typically ±0.1–1% of the full-scale reading.

D13. Thermostats (electro-mechanical)

Thermostats are temperature switches used to control system temperatures or to act as a safety shut-off for protection against overheating. The two most common electro-mechanical thermostat types are bimetallic and gas/vapour actuated. Upon reaching a temperature trip point, the sensing element (bimetallic or gas/vapour) in the thermostat actuates a switch. Some thermostats can be adjusted to trigger at a series of temperature points or to have multiple temperature set-point differentials (i.e. hysteresis).

Appendix E. Issue of accuracy

Accuracy is the largest expected error between actual and ideal output signals. It is expressed in terms of "inaccuracy", which is an estimate of the range of values within which the true value lies. Most sensors have a systematic accuracy expressed in terms of absolute or relative value. Absolute accuracy is specified by the worst-case error in output, relative to an absolute, external standard, whereas relative accuracy is specified by the worst-case error expressed as a proportion or percentage of the full scale. The accuracy rating of a sensor is governed by several factors such as nonlinearity, calibration procedure and repeatability errors [6]. Fig. E1 shows that the ratio between the accuracy and sensing range of individual sensors is typically in the range 1:100–1:1000. For most displacement, acceleration and force sensors, the ratio of accuracy to range lies between 0.1 and 1%. For temperature sensors, accuracy is plotted against operating temperature (as in Fig. 7). In general accuracy lies in the range 10^{-2} to 10 K for all operating temperatures.

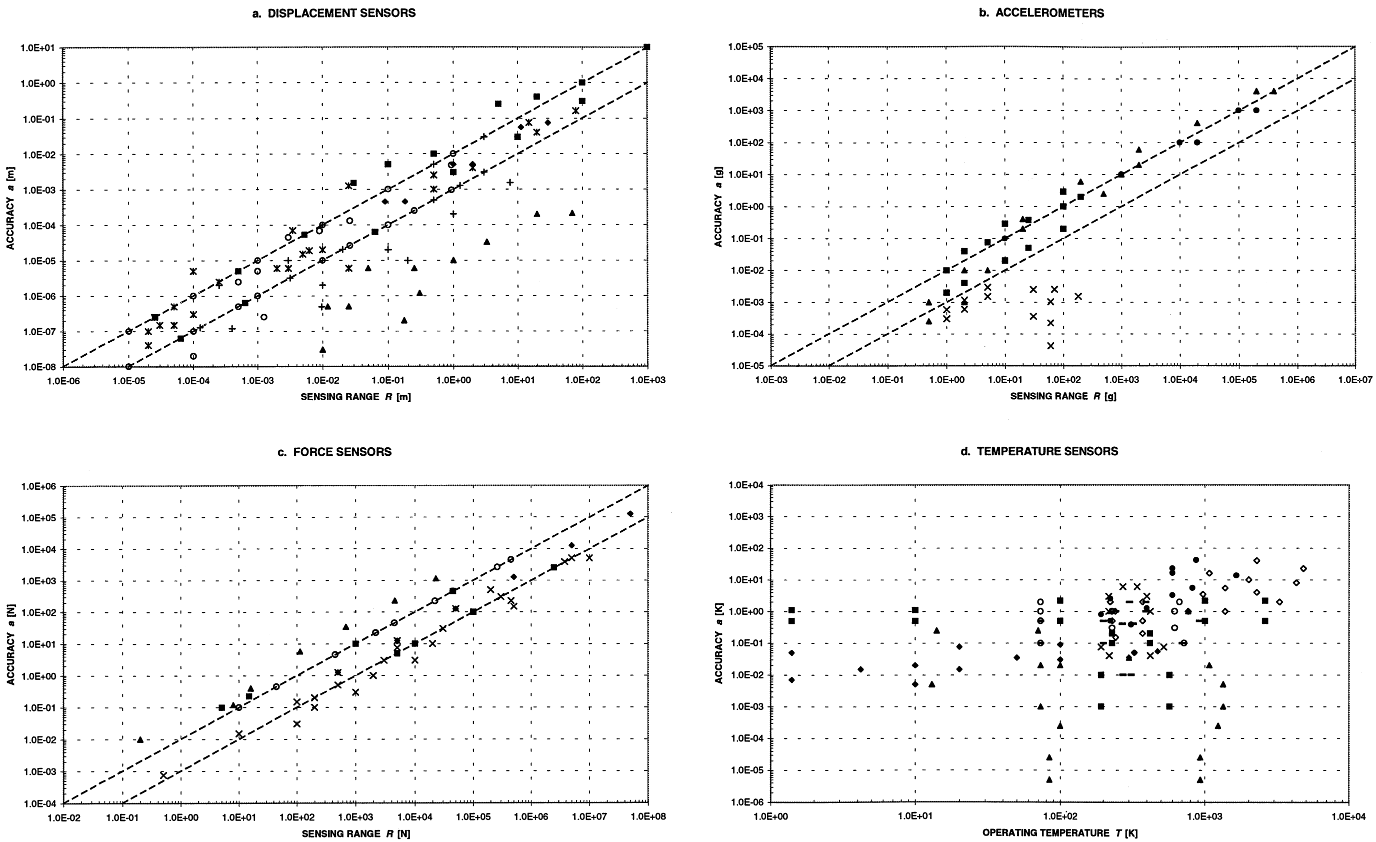

Fig. E1. Accuracy versus sensing range (or operating temperature) for displacement, acceleration, force and temperature sensors.

References

[1] Huber JE, Fleck NA, Ashby MF. The selection of mechanical actuators based on performance indices. Proc R Soc Lond 1997;453:2185–205.
[2] Wilson J. A practical approach to vibration detection and measurement, part 1, 2 and 3. Sensors, 1999; 16(2–4).
[3] Shock and vibration measurement echnology. 30700 Rancho Viejo Rd., San Juan Capistrano (CA 92675): Endevco Co, 1987.
[4] Holmes DS, Courts SS. Resolution and accuracy of cryogenic temperature measurements. AN 1005: Lake Shore Cryotronics, Inc, 1990.
[5] Courts SS, Holmes DS, Swinehart PR, Dodrill BC. Cryogenic thermometry — an overview. In: Applications of cryogenic technology, vol. 10. New York: Plenum Press, 1991. p. 55–69.
[6] Fraden J. Handbook of modern sensors: physics, designs and applications. 2nd ed. New York: AIP Press, 1997.
[7] Binnig G, Quate CF, Gerber CH. Atomic force microscope. Phys Rev Lett 1986;56(9):930–3.
[8] Product catalog: nanosensors. 90 Merrick Av., East Meadow (NY 11554): Queensgate Instruments, Inc., NanoPosition Div.
[9] Linear encoders — the debate heats up. Industrial Technology, October 1996.
[10] Product catalog: linear encoders. One Precision Way, Jamestown (NY 14707): Acu-Rite, Inc.
[11] Product catalog: linear encoders. 623 Cooper Court, Schaumburg (IL 60173): Renishaw, Inc.
[12] Product catalog: nanoscales. 461 Boston St., Topsfield (MA 01983): Optra, Inc.
[13] Product catalog: linear encoders. 8 Erie Drive, Natick (MA 01760-1313): MicroE Systems Co.
[14] Product catalog: factory automation. 1600 Enterprise Parkway, Twinsburg (OH 44087): Pepperl+-Fuchs, Inc.
[15] Product catalog: temposonics. 3001 Sheldon Drive, Cary (NC 27513): MTS Systems Co.
[16] Product catalog: material-testing systems. 100 Royall St., Canton (MA 02010-1089): Instron Co.
[17] Product catalog: video extensometers. Fraunhoferstr. 23h, 80469 Muenchen (Germany): DOLI Elektronik GmbH.
[18] Doscher J. Innovations in acceleration sensing using surface micro machining. Analog Devices, Inc., 1988.
[19] Product catalog: accelerometers & IC temperature sensors. One Technology Way, PO Box 9106, Norwood (MA 02062-9106): Analog Devices, Inc.
[20] De Silva CW. Control sensors and actuators. NJ: Prentice-Hall, 1989.
[21] W-14 machinery monitoring. 21 Firstfield Rd., Gaithersburg (MD 20878): Wilcoxon Research, Inc.
[22] Product catalog: piezoelectric sensors. 3425 Walden Av., Depew (NY 14043): PCB Piezotronics, Inc.
[23] Sill R. Testing techniques involved with the development of high shock acceleration sensors. Endevco Co., TP 284.
[24] Belleville C, Duplain G. White-light interferometric multimode fiber-optic strain sensor. Optics Letters 1993;18(1):78–80.
[25] Choquet P, Juneau F, Dadoun F. New generation of fiber-optic sensors for dam monitoring. In: Proc. 9th International Conference on Dam Safety and Monitoring, Hubei, 19–22 October 1999.
[26] Benes E, Gröschl M, Burger W, Schmid M. Sensors based on piezoelectric resonators. Sensors and Actuatorsz 1995;48:1–21.
[27] Product catalog: piezoresistive microswitch force sensors. 101 Columbia Rd., Morristown (NJ 07962): Honeywell, Inc.
[28] Product catalog: industrial, medical and flexiforce force-sensing systems. 307 West First St., South Boston (MA 02127-1309): Tekscan, Inc.
[29] Schooley JF. Thermometry. FL: CRC Press, 1986.
[30] Rubin LG, Brandt BL, Sample HH. Cryogenic thermometry: a review of recent progress, II. Cryogenics 1982;22:491–503.
[31] Holmes DS, Courts SS. Cryogenic instrumentation. In: Handbook of cryogenic engineering. Philadelphia: Taylor & Francis, 1998. p. 203–57.
[32] Temperature measurement and control. 575 McCorkle Blvd., Westerville (OH 43082-9803): Lake Shore Cryotronics, Inc.

[33] Wickersheim KA, Sun MH. Fluoroptic thermometry. Med Electronics 1987; February: 84–91.
[34] Product catalog: fluoroptic thermometers. 2775 Northwestern Parkway, Santa Clara (CA 95051-0941): Luxtron Co.
[35] Udd E. Fiber optic sensors. New York: Wiley, 1991.
[36] Culshaw B. Smart structures and materials. Boston: Artech House, 1996.
[37] Product catalog: fiber-optic transducers. 2014 Jean-Talon Nord. — suite 125, Sainte-Foy (Quebec G1N-4N6): FISO Technologies, Inc.
[38] Product catalog: fiber-optic thermometers. 240-500 St-Jean-Baptiste (Quebec G2E-5R9): Nortech Fibronic, Inc.
[39] Product catalog: analog- temperature sensors. 2900 Semiconductor Drive, Santa Clara (CA 95051): National Semiconductors Co.
[40] Omega Engineering, Inc. Transactions, vols. 1 & 3: non-contact temperature and force-related measurements. Omega Press LLC, 1998.
[41] Industrial advantage. 625 East Bunker Court, Vernon Hills (IL 60061-1844): Cole-Parmer Instrument Company.
[42] Product catalog: non-contact temperature measurement. 2525 Pearl Buck Rd., Bristol (PA 19007): Land Instruments International Ltd., Land Infrared Div.
[43] Hammond DL, Benjaminson A. Linear quartz thermometer. Instrum Control Syst 1962;38:115.
[44] Ueda T, Kohsaka F, Iino T, Yamazaki D. Temperature sensor utilizing quartz tuning fork resonator. In Proc. 40th Ann. Freq. Control Symp., Philadelphia, 1986, p. 224–9.
[45] Product catalog: quartz-based transducers. 1020 W. Atherton Dr., Salt Lake City (UT 84123): Quartzdyne, Inc.
[46] Product catalog: quartz-based sensors. 3000 Hanover St., Palo Alto (CA 94304-1185): Hewlett-Packard Company.
[47] Taylor HR. Data acquisition for sensor systems. London: Chapman & Hall, 1997.
[48] Product catalog: force and temperature measurements. One Omega Drive, PO Box 4047, Stamford (CT 06907-0047): Omega Engineering, Inc.
[49] Product catalog: temperature metrology. 100 Brickstone Square, Andover (MA 01810): ASL, Inc.
[50] Moseley PT, Crocker AJ. Sensor materials. Bristol: IOP Publishing, 1996.
[51] Product catalog: thermistors. 808 U.S. Highway 1, Edison (NJ 08817-4695): Thermometrics, Inc.
[52] British Standards Institution. International thermocouple reference tables. BS 4937: Parts 1–4, London: BSI, 1973 (confirmed 1981).
[53] British Standards Institution. International thermocouple reference tables. BS 4937: Parts 5–7, Equivalent to IEC 584.1, London: BSI, 1974 (confirmed 1981).
[54] Benedict RP. Fundamentals of temperature, pressure, and flow measurements. 3rd ed. New York: John Wiley & Sons, 1984.
[55] Product catalog: temperature sensors. 244 Oakland Drive, Danville (VA 24540): EDL, Inc.