situation must be decided upon by the ultimate use of the data obtained and the measuring equipment available. This and the following chapters will demonstrate the facilities provided by a wide range of instruments and discuss their application to practical problems.

6.2. SELECTION OF ACCELEROMETER

An accelerometer is an electromechanical transducer which produces at its output terminals, a voltage or charge that is proportional to the acceleration to which it is subjected. Piezoelectric accelerometers exhibit better all-round characteristics than any other type of vibration transducer and are more-or-less universally preferred for measurements covering a wide frequency range.

The heart of the accelerometer is its piezoelectric elements which are usually made from an artificially polarized ferroelectric ceramic. These piezoelectric elements have the property of producing an electrical charge which is directly proportional to strain and thus the applied force when loaded either in tension, compression or shear. In practical accelerometer designs the piezoelectric elements are arranged so that they are loaded by a mass or masses and a preloading spring or ring. When subjected to vibration the masses exert a varying force on the piezoelectric elements which is directly proportional to the vibratory acceleration. For frequencies lying well under the resonant frequency of the assembly, the acceleration of the masses will be the same as the acceleration of the base, and the output signal level will be proportional to the acceleration to which the accelerometer is subjected.

Two accelerometer configurations are in common use, the compression and the shear types which are shown in the schematic drawings in Fig.6.2.

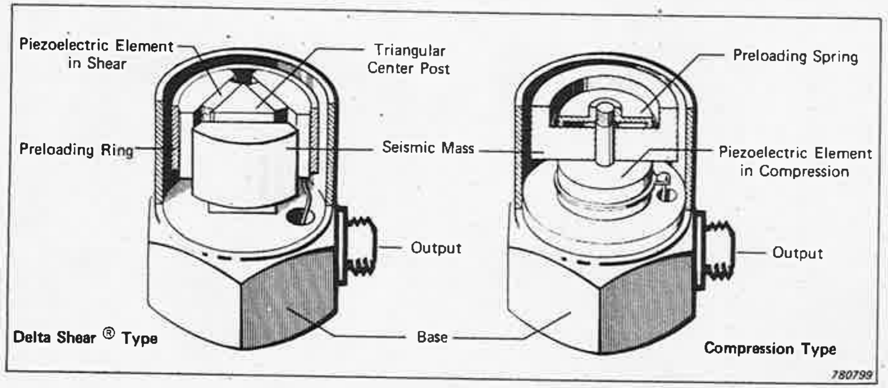


Fig.6.2. The two accelerometer configurations in common use

Accelerometer Type	Weight (gram)	Charge Sensitivity (pC/ms⁻²)*	Mounted Resonance Frequency (kHz)	Important Characteristics	Application Areas
4366 Δ 	28	~4,5	27	Delta Shear® Construction having good all-round characteristics and particularly low sensitivity to temperature transients and base strains	General shock and vibration measurements. Vibration testing and control.
4367 Δ 	13	~2	32		
4368 Δ 	30	~4,5	27		
4369 Δ 	14	~2	32		
4371 Δ 	11	1 ± 2%	35	Delta Shear® types as above. Also have Uni-Gain® sensitivity for simple system calibration and Interchangeability	
4370 Δ 	54	10 ± 2%	18		General vibration measurements. High sensitivity for low-level measurements
4375 Δ 	2 excl. cable	~0,3	60	Miniature size, low weight Delta Shear® type. High resonance frequency	High level and high freq. vibr. measurements. Ideal for delicate structures, panels etc. and in confined spaces
4374 Δ 	0,7 excl. cable	~0,1	75	Submiature size, low weight shear type. Very high resonant frequency	
8309 □ 	3 excl. cable	~0,004	180	Miniature size. Integral fixing stud. Integral cable.	Shock measurements up to 1 million ms⁻² High frequency vibr. measurements
4321 Δ 	55	1 ± 2%	40	Three Delta Shear® Uni-Gain® accelerometers combined in one unit	Vibration measurements in three mutually perpendicular directions
8305 □ 	40	~0,12	30	Quartz element for high stability. Laser calibrated to ± 0,5% accuracy	Reference standard for comparison calibration of accelerometers
8306 □ 	500	1000	1 kHz LP filter built in	Very High Uni-Gain® sensitivity. Built-in Preamp and LP filter. Requires 28V 2mA DC power supply	Ultra low-level (down to 0,000 002 g) and low freq. vibration measurements on large structures
8308 □ 	100	1 ± 2%	30	Robust-construction. Balanced Uni-Gain® output. Max. Temp. 400°C	Permanent vibration monitoring. High temp. vibr. measurements. Aeronautical, industrial and nuclear use. Used with preamp. Type 2634
8310 □ 	100 excl. cable	1 ± 20%	30	As Type 8308 but with integral high temp (800°C) cable.	

*Multiply by 9.81 for sensitivity in pC/g

Δ Shear Types

□ Compression Types

791117

Fig.6.3. Main characteristics and application areas for B & K accelerometers

In general, it can be said that the shear configuration gives the best all-round results for general purpose accelerometers and the compression design is used for accelerometers which are aimed at particular applications.

The table in Fig.6.3 indicates the application and main characteristics of the B & K accelerometer range. At first glance there may seem to be a confusingly large range of accelerometers available. But it will be seen, after closer inspection, that they can be divided into two main groups. A group of general purpose types, with various sensitivities and a choice of top or side connectors, which will satisfy most needs, and a range of accelerometers which have their characteristics slanted towards a particular application.

When selecting an accelerometer for a particular application the accelerometer's parameters and the environmental conditions it is to be used under need to be considered as follows:

Frequency Range: The frequency response of an accelerometer has a characteristic shape as shown in Fig.6.4. Measurements are normally confined to using the linear portion of the response curve which at the high frequency end is limited by the accelerometer's natural resonance. As a rule of thumb the upper frequency limit for measurements can be set to one-third of the accelerometer's resonance frequency so that vibration components measured at this limit will be in error by no more than + 12% , 1 dB). Small, low mass accelerometers can have a resonant frequency as high as 180 kHz but for the more sensitive general purpose accelerometers resonant frequencies of 30 kHz (giving an upper frequency limit of 10 kHz) are typical.

It should be noted however that an accelerometer's useful frequency range is significantly higher, i.e. to 1/2 or 2/3 of its resonant frequency, where for example 3 dB linearity is acceptable. This may be the case where vibration measurements are being used to monitor the internal condition of machines because repeatability is there more important than linearity.

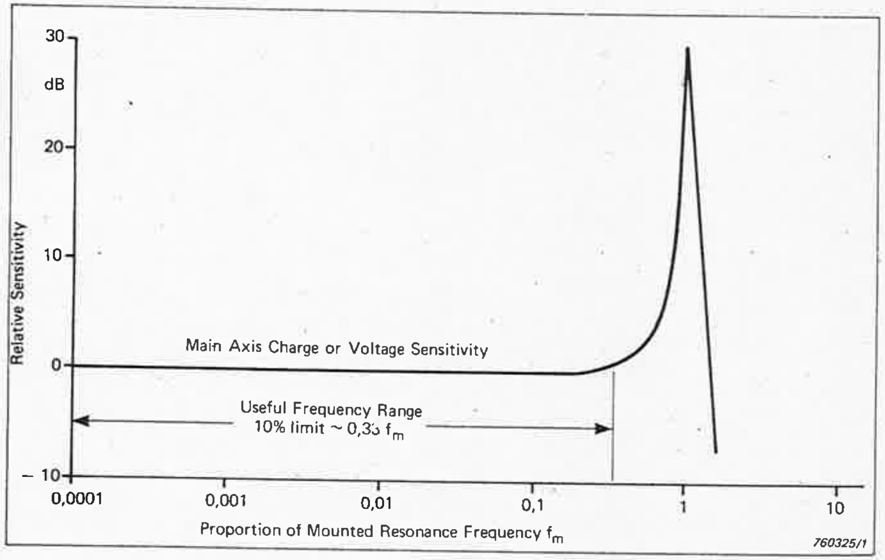


Fig.6.4. Frequency characteristic of a piezoelectric accelerometer

In practice the lower measuring frequency limit is determined by two factors. The first is the low-frequency cut-off of the associated preamplifier, but this is not normally a problem as the limit is usually well below 1 Hz. The second is the effect of ambient temperature fluctuations (temperature transients) to which the accelerometer is sensitive. With modern shear type accelerometers this effect is typically 20 dB lower than for corresponding compression types which thus allows measurement down to well below 1 Hz for normal environments.

Sensitivity, Mass and Dynamic Range: Ideally, the higher the transducer sensitivity the better, but a compromise has to be made because high sensitivity normally entails a large piezoelectric assembly and consequently a relatively large, heavy unit with low resonant frequency. In normal circumstances the sensitivity is not too critical a factor as modern preamplifiers are designed to accept these low-level signals.

Accelerometer mass becomes important when measuring on light test objects. The accelerometer should load the structural member as little as possible; additional mass can significantly change the vibration levels and frequencies present at the measuring point and invalidate the measured results. An approximate indication of the change in structural response due to loading can be found using the following equations:

$$a_s = \frac{a_m(m_s + m_a)}{m_s} \quad \text{and} \quad f_s = f_m \sqrt{\frac{m_s + m_a}{m_s}} \qquad (6.1)$$

where:

a_m = acceleration measured with accelerometer mounted
a_s = acceleration without accelerometer
f_m = resonance frequency measured with accelerometer mounted
f_s = resonance frequency without accelerometer
m_a = accelerometer mass
m_s = effective mass of that "part" of the structure to which the accelerometer is mounted.

As a general rule, the accelerometer mass should be no greater than one-tenth of the effective (dynamic) mass of the part of the structure to which the accelerometer is mounted.

When it is wished to measure abnormally low or high acceleration levels, the dynamic range of the accelerometer should be considered. Theoretically the output of a piezoelectric accelerometer is linear down to zero acceleration but in practice the lower dynamic limit is determined by electrical noise from connecting cables and amplifier circuitry. This limit is normally below 0,01 ms^{-2} with general purpose instruments measuring over a wide band. Significantly lower levels may be measured when using a filter for frequency analysis.

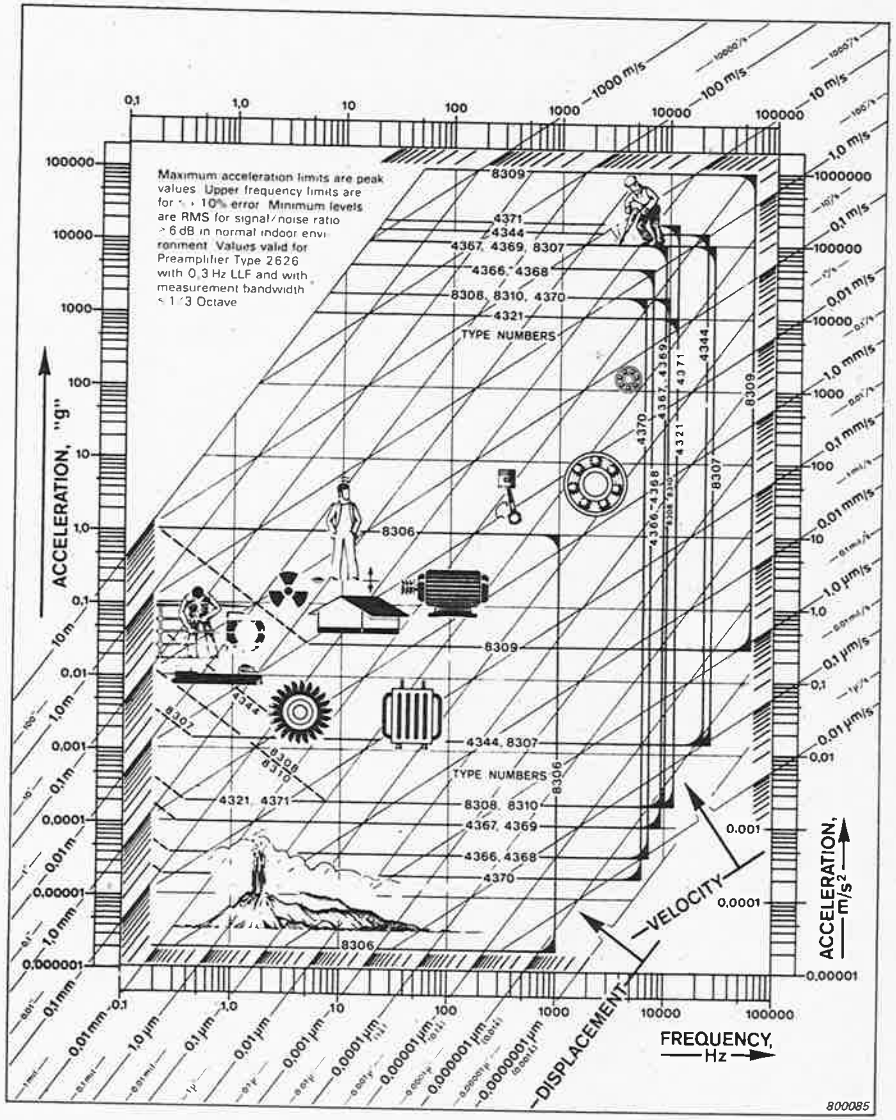

Maximum acceleration limits are peak values. Upper frequency limits are for < + 10% error. Minimum levels are RMS for signal/noise ratio > 6 dB in normal indoor environment. Values valid for Preamplifier Type 2626 with 0,3 Hz LLF and with measurement bandwidth < 1/3 Octave

Fig.6.5. Measuring range nomogram for B & K accelerometers under the specific conditions stated

The upper dynamic limit is determined by the accelerometer's structural strength. General purpose accelerometers are linear up to 50 to 100 kms^{-2} (5000 to 10000 g) which is well into the range of mechanical shocks. For very high shock measurements the shock accelerometer (Type 8309) shown in Fig.6.3 can be used up to 10^6 ms^{-2} (100000 g).

A typical example of how the various factors limit the operating range of B & K accelerometer types under specific conditions is shown in the nomogram, Fig.6.5.

Transverse Response: The transverse sensitivity of an accelerometer is its sensitivity to accelerations in a plane perpendicular to the main accelerometer axis as shown in Fig.6.6. It is normally expressed in percent of the main axis sensitivity and should be as low as possible. The transverse sensitivity varies according to which direction is considered, the direction of minimum sensitivity is marked on most B & K accelerometer types with a red paint spot. Measurement of the maximum transverse sensitivity is part of the indi-

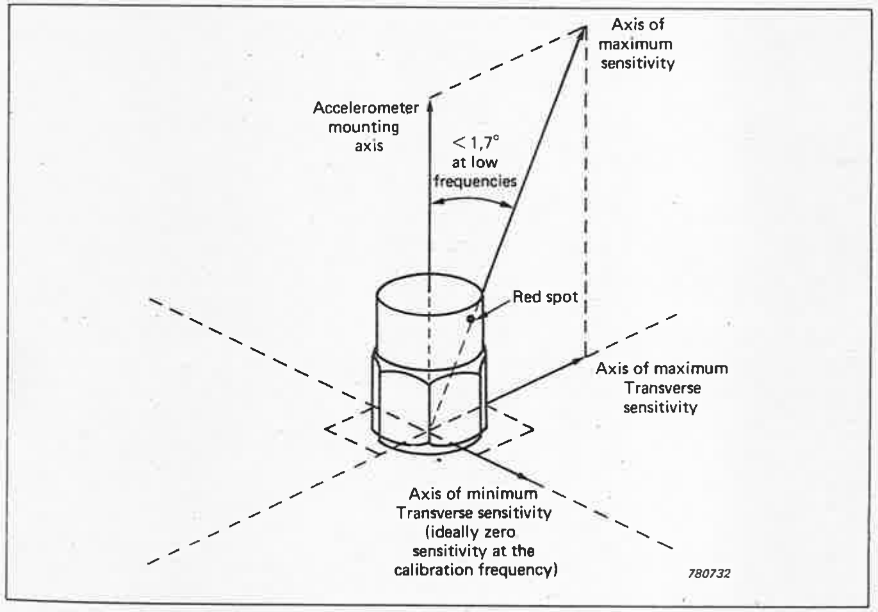


Fig.6.6. Vectorial representation of transverse sensitivity

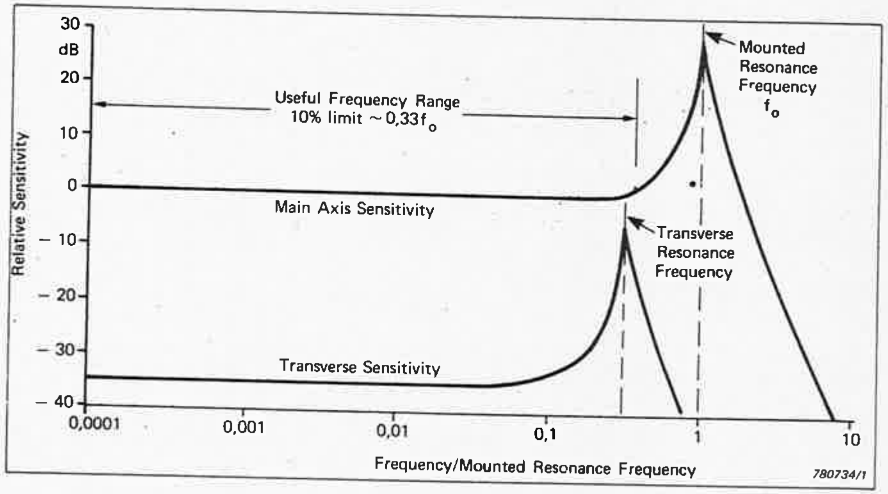


Fig.6.7. The relative response of an accelerometer to main axis and transverse axis vibration

vidual calibration procedure for many accelerometer types and is always less than 3 to 4% according to type. It should be noted that the transverse sensitivity is typically less than 1% of the main axis sensitivity.

Piezoelectric accelerometers also exhibit transverse resonance as indicated in Fig.6.7. Where high levels of high frequency transverse vibration are present at the measuring position this may result in erroneous results and in this case measurements should be made to establish the level and frequency content of transverse vibrations.

Transient Response: Shocks are sudden releases of energy often characterised by having a high level, short duration and a very wide frequency content.

The overall linearity of the measuring system can be limited at low and high frequencies by phenomena known as Zero Shift and Ringing respectively. These effects are shown graphically in Fig.6.8.

"Zero Shift" is caused both by phase non-linearities in the preamplifier and by the piezoelectric element of the accelerometer retaining charge after being subjected to very high level shocks.

"Ringing" occurs when the accelerometer resonance frequency is excited by high frequency components.

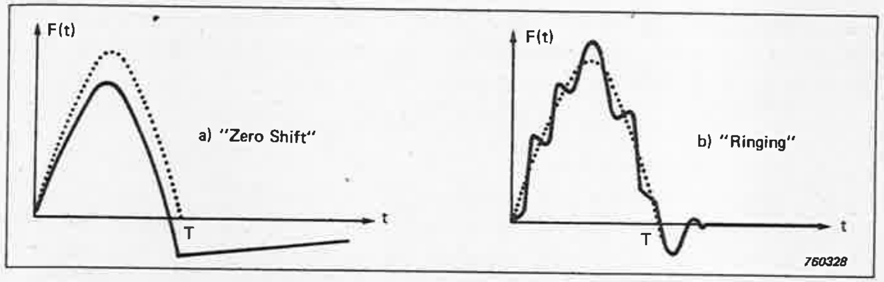


Fig.6.8. Vibration measurement system response to half sine wave pulse of length T.
a) "Zero Shift" limits the low-frequency response of the system.
b) "Ringing" limits the high frequency response of the system

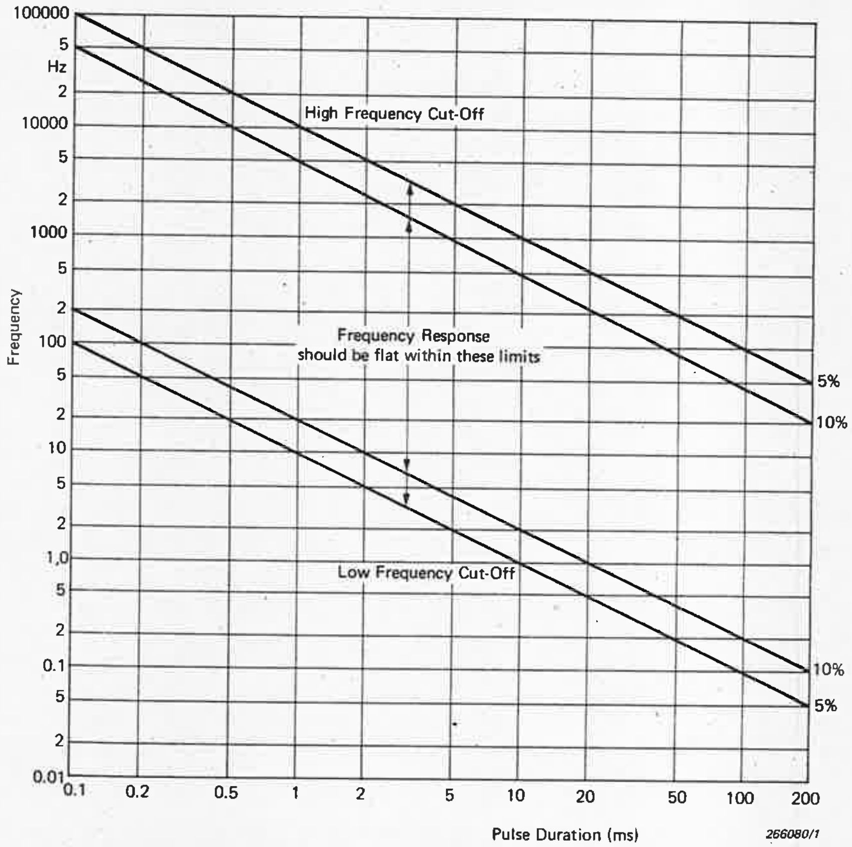


Fig.6.9. Vibration system —3 dB lower and upper limiting frequencies vs pulse duration T for acceleration measurements on transient vibrations keeping amplitude errors less than 5 and 10% respectively

To avoid significant measuring errors due to these effects, the frequency response of the measuring system should be limited as shown in Fig.6.9 which is based on measuring errors of less than 5% or 10%.

6.2.1. Environmental Conditions

Temperature: Typical general purpose accelerometers can tolerate temperatures up to 250°C. At higher temperatures the piezoelectric ceramic will begin to depolarise causing a permanent loss in sensitivity. Up to temperature excesses of 50°C above the specified limit the loss is gradual so that after recalibration the accelerometer is still usable. At even higher temperatures the Curie point is reached which results in complete destruction of the piezoelectric element. Special high temperature accelerometers can be used in temperatures up to 400°C.

All piezoelectric materials are temperature dependent so that changes in the ambient temperature result in changes in sensitivity. For this reason B & K accelerometers are delivered with a sensitivity versus temperature calibration curve so that corrections can be made when working in temperatures significantly higher or lower than the calibration temperature of approximately 20°C. A curve plotting the variation in sensitivity with temperature is shown in Fig.6.10.

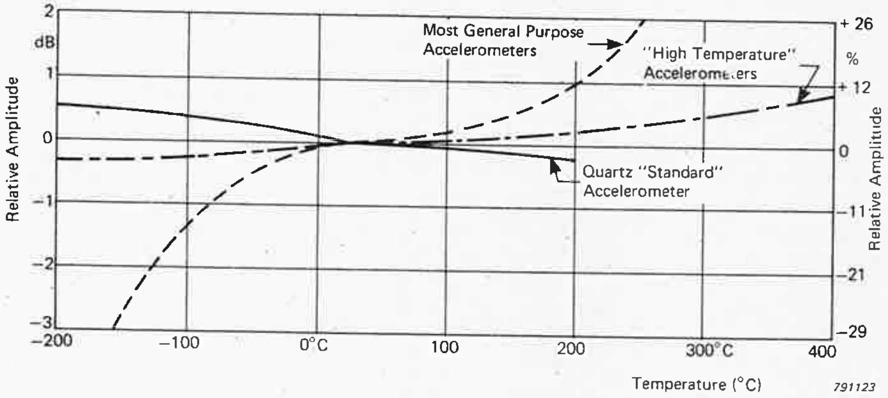


Fig.6.10. Typical charge sensitivity versus temperature characteristic for piezoelectric accelerometers

When accelerometers are to be attached to surfaces at a higher temperature than their design maximum a heat sink and mica washer can be inserted between the base and the surface to reduce heat transmission as shown in Fig.6.11.

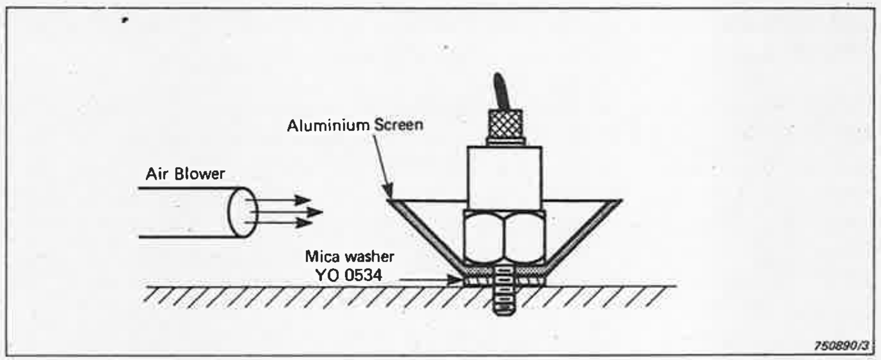


Fig.6.11. The use of a mica washer and heat sink will enable accelerometer to be used on surfaces at temperatures rather higher than the accelerometer's design maximum

Temperature Transients: Piezoelectric accelerometers also exhibit a varying output when subjected to small temperature fluctuations called temperature transients in the measuring environment. This is normally only a problem where very low level or low frequency vibrations are being measured. Modern shear type accelerometers have a very low sensitivity to temperature transients.

Cable Noise: Since piezoelectric accelerometers have a high output impedance problems can sometimes arise with noise signals induced into the connecting cable to the preamplifier. These spurious signals can result from ground loops, triboelectric noise, or electromagnetic noise.

Ground loop currents can flow in the shield of accelerometer cables because of slight differences in the electrical potential of grounding points when the accelerometer and the measuring equipment are grounded separately. The loop is broken by electrically isolating the accelerometer base from the mounting surface by means of an isolating stud (max. temperature 250°C) and mica washer.

Triboelectric noise can be generated by the accelerometer cable due to local capacity and charge changes between the conductor and shield as the cable vibrates. This problem is avoided by using a proper internally graphited accelerometer cable and fixing it to avoid cable movements as much as possible.

Electromagnetic noise can be a problem when the accelerometer cable lies in the vicinity of running electrical machinery. Double shielded cable helps to reduce this problem but in severe cases a balanced accelerometer and differential preamplifier should be used. The latter is standard practice with permanent vibration monitoring equipment on industrial machinery.

Base Strains: When an accelerometer is mounted on a surface which is undergoing dynamic deformations a spurious output will be generated as a result of strain being transmitted to the sensing element. Accelerometers have thick stiff bases to minimise this effect. Note that Delta Shear® types have a particularly low sensitivity to base strains because the piezoelectric element is mounted on a centre post rather than directly to the accelerometer base, and this does not so directly result in shear deformation of the elements.

Nuclear Radiation: Most general purpose accelerometer types may be used under gamma radiation rates of 10 k Rad/h up to an accumulated dose of 2 M Rad without significant changes in characteristics. Types intended for permanent installation on machines and equipment may also be used in heavy neutron radiation at rates of 1 M Rad/h up to accumulated doses of 100 M Rad. Special mineral insulated "hardline" cables are necessary in this case.

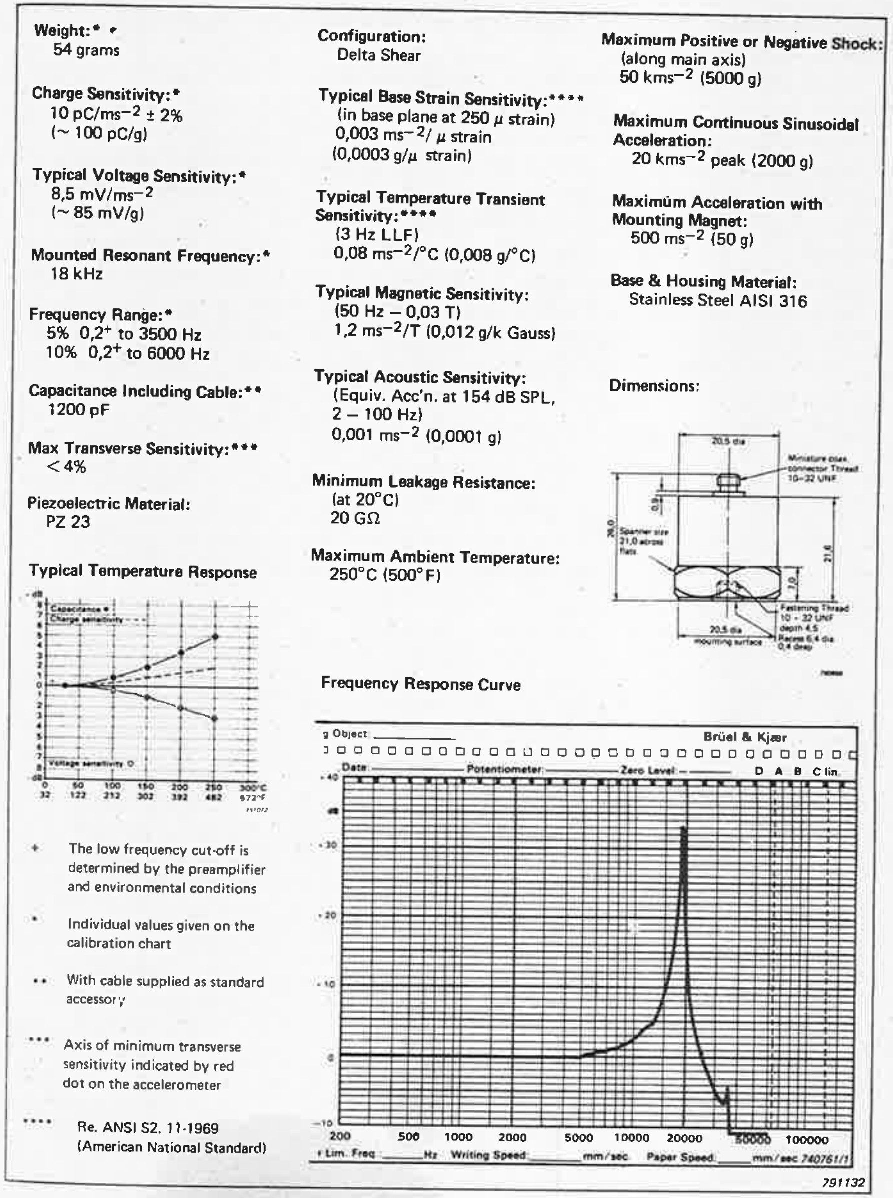
Magnetic Fields: The magnetic sensitivity of piezoelectric accelerometers is very low, normally less than 10 ms^{-2} /T with a 50 Hz alternating field and least favourable orientation of the accelerometer.

Humidity: Most accelerometers are sealed, either by epoxy bonding or welding and are therefore impervious to moisture. However, cable connectors only offer superficial protection. For short term exposure the transducer socket and cable plug can be dipped in silicone grease before the connector is assembled. For exposure to high humidity or direct immersion the whole assembled connector should be encapsulated in an acid-free RTV silicone rubber compound. In wet environments standard Teflon insulated accelerometer cables should always be used.

Corrosive Substances: Most accelerometers are encased in stainless steel, titanium or beryllium and therefore have a high resistance to most of the corrosive substances encountered.

Acoustic Noise: The noise levels present in machinery are not normally sufficient to cause any significant error in vibration measurements. It may be expected that the acoustically induced vibration in the structure on which the accelerometer is mounted will be far greater than the airborne excitation of the accelerometer.

This concludes the list of environmental factors which need to be considered when selecting and using piezoelectric accelerometers. To illustrate the sort of figures to be expected, the full specifications of a typical general purpose accelerometer, B & K Type 4370, are tabulated in Fig. 6.12.



Weight:* •
54 grams

Charge Sensitivity:*
10 pC/ms^{-2} ± 2%
(~ 100 pC/g)

Typical Voltage Sensitivity:*
8,5 mV/ms^{-2}
(~ 85 mV/g)

Mounted Resonant Frequency:*
18 kHz

Frequency Range:*
5% 0,2⁺ to 3500 Hz
10% 0,2⁺ to 6000 Hz

Capacitance Including Cable:**
1200 pF

Max Transverse Sensitivity:***
< 4%

Piezoelectric Material:
PZ 23

Typical Temperature Response

\+ The low frequency cut-off is determined by the preamplifier and environmental conditions

* Individual values given on the calibration chart

** With cable supplied as standard accessory

*** Axis of minimum transverse sensitivity indicated by red dot on the accelerometer

**** Re. ANSI S2. 11-1969 (American National Standard)

Configuration:
Delta Shear

Typical Base Strain Sensitivity:****
(in base plane at 250 μ strain)
0,003 ms^{-2}/ μ strain
(0,0003 g/μ strain)

Typical Temperature Transient Sensitivity:****
(3 Hz LLF)
0,08 ms^{-2}/°C (0,008 g/°C)

Typical Magnetic Sensitivity:
(50 Hz – 0,03 T)
1,2 ms^{-2}/T (0,012 g/k Gauss)

Typical Acoustic Sensitivity:
(Equiv. Acc'n. at 154 dB SPL, 2 – 100 Hz)
0,001 ms^{-2} (0,0001 g)

Minimum Leakage Resistance:
(at 20°C)
20 GΩ

Maximum Ambient Temperature:
250°C (500°F)

Maximum Positive or Negative Shock:
(along main axis)
50 kms^{-2} (5000 g)

Maximum Continuous Sinusoidal Acceleration:
20 kms^{-2} peak (2000 g)

Maximum Acceleration with Mounting Magnet:
500 ms^{-2} (50 g)

Base & Housing Material:
Stainless Steel AISI 316

Dimensions:

Frequency Response Curve

Fig. 6.12. Specifications of B & K accelerometer Type 4370