2. THE PIEZOELECTRIC ACCELEROMETER

2.1. INTRODUCTION

The aim of this chapter is to give a basic, and often theoretical insight into the operation and the characteristics of the piezoelectric accelerometer. Due to the nature of its operation the performance of the vibration preamplifier will need to be included to a small extent. However for a complete description of the operation and characteristics of preamplifiers, Chapter 3 "Vibration Preamplifiers" should be consulted. A summary of the complete Brüel & Kjær range of accelerometers can be found in Appendix H.

The piezoelectric accelerometer is widely accepted as the best available transducer for the absolute measurement of vibration. This is a direct result of these properties:

1. Usable over very wide frequency ranges.
2. Excellent linearity over a very wide dynamic range.
3. Acceleration signal can be electronically integrated to provide velocity and displacement data.
4. Vibration measurements are possible in a wide range of environmental conditions while still maintaining excellent accuracy.
5. Self-generating so no external power supply is required.
6. No moving parts hence extremely durable.
7. Extremely compact plus a high sensitivity to mass ratio.

In order to appreciate these advantages it is worth examining the characteristics of a few other types of vibration transducer and vibration measurement devices.

1. **Proximity probe.** A device measuring only relative vibration displacement. It has a response to static displacements and also a low electrical impedance output. However, the device is not self-generating and the high frequency performance is poor. In addition the vibrating surface must be electrically conductive.

2. **Capacitive probe.** A small, non-contact, vibration displacement transducer with a high sensitivity and a wide frequency range. The disadvantages are, however, that the vibrating surface must be electrically conductive, the probe's dynamic range is very limited and it is difficult to calibrate.

3. **Position potentiometer.** A low cost, low impedance device capable of measuring static displacements. However, the dynamic and frequency ranges are limited and the device only has a short working lifetime and low resolution.

4. **Piezoresistive transducer.** A vibration acceleration transducer which is capable of measuring static accelerations. The measuring frequency and dynamic ranges can be wide. The limited shock handling capacity means that this type of transducer is easily damaged. Viscous damping is often used to protect the transducer against shocks. However, this leads to a reduction in the operating temperature range and alters the phase characteristics.

5. **Moving coil.** A self-generating low impedance vibration velocity transducer. It is severely limited in its frequency range and dynamic range, is susceptible to magnetic fields and is affected by its orientation.

2.2. OPERATION OF AN ACCELEROMETER

Fig. 2.1 illustrates a simplified model of a Brüel & Kjær Delta Shear® accelerometer showing only the mechanical parts. The active elements of the accelerometer are the piezoelectric elements. These act as springs connecting the

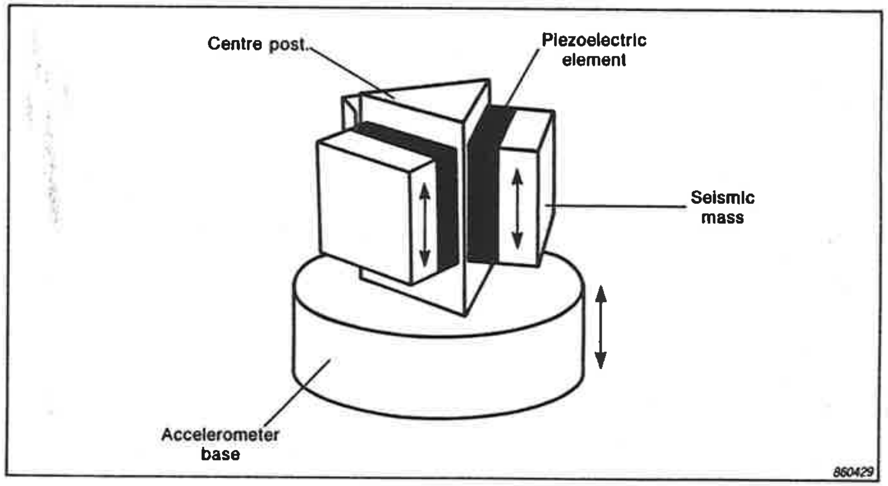

Fig. 2.1. Schematic of a Brüel & Kjær Delta Shear® piezoelectric accelerometer

base of the accelerometer to the seismic masses via the rigid triangular centre post. When the accelerometer is vibrated a force, equal to the product of the acceleration of a seismic mass and its mass, acts on each piezoelectric element. The piezoelectric elements produce a charge proportional to the applied force. The seismic masses are constant and consequently the elements produce a charge which is proportional to the acceleration of the seismic masses. As the seismic masses accelerate with the same magnitude and phase as the accelerometer base over a wide frequency range, the output of the accelerometer is proportional to the acceleration of the base and hence to the acceleration of the surface onto which the accelerometer is mounted.

The above model can be simplified as shown in Fig. 2.2.

2.2.1. Analytical Treatment of Accelerometer Operation

Fig. 2.2 shows a simplified model of the accelerometer described in the last section and referenced to an inertial system. The two masses are unsupported and connected by an ideal spring. Damping is neglected in this model because Brüel & Kjær accelerometers have very low damping factors.

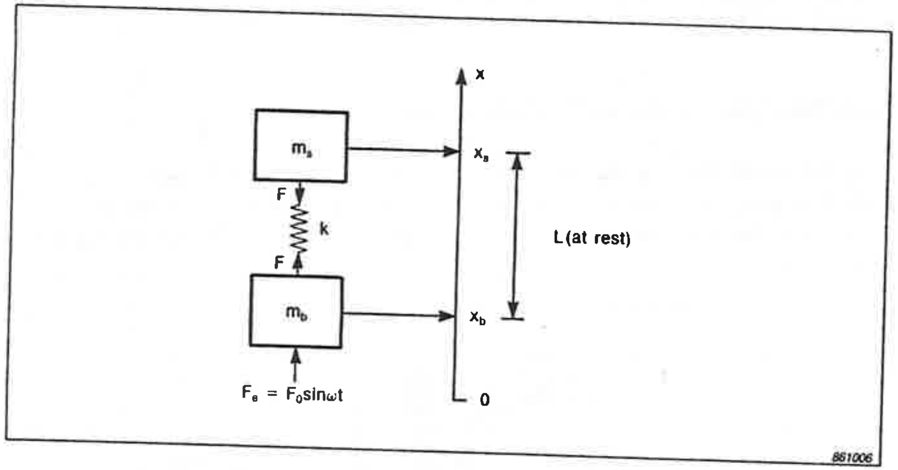

Fig. 2.2. Simplified model of an accelerometer

m_s = total seismic mass

m_b = mass of the accelerometer base

x_s = displacement of the seismic mass

x_b = displacement of the accelerometer base

L = distance between the seismic mass and the base when the accelerometer is at rest in the inertial system

k = equivalent stiffness of the piezoelectric elements

F_e = harmonic excitation force

F_0 = amplitude of excitation force

ω = excitation frequency (rad/s) = $2\pi f$

ω_n = natural resonance frequency of the accelerometer (rad/s)

ω_m = mounted resonance frequency of the accelerometer (rad/s)

f_m = mounted resonance frequency of the accelerometer (Hz)

f = excitation frequency (Hz)

The following expressions describe the forces present in the model

$F = k(x_s - x_b - L)$ (spring force)

$m_b\ddot{x}_b = F + F_e$ (force on base)

$m_s\ddot{x}_s = -F$ (force on seismic masses)

The equation of motion for the model can be found

$$\ddot{x}_s - \ddot{x}_b = -\frac{F}{m_s} - \frac{F + F_e}{m_b} = -\frac{k}{\mu}(x_s - x_b - L) - \frac{F_e}{m_b} \qquad (1)$$

or

$$\mu\ddot{r} = -kr - \frac{\mu}{m_b}F_0\sin\omega t$$

Where

$$\frac{1}{\mu} = \frac{1}{m_s} + \frac{1}{m_b}$$

or

$$\mu = \frac{m_s m_b}{m_s + m_b}$$

μ is often referred to as the "reduced mass" and r is the relative displacement of the seismic mass to the base

$$r = x_s - x_b - L$$

When the accelerometer is in a free hanging position and is not being excited by external forces ($F_e = 0$) the equation of motion for its *free* vibration reduces to

$$\mu\ddot{r} = -kr$$

This simple differential equation can be solved by assuming that the displacement of m_s relative to m_b varies harmonically with an amplitude R. In other words

$$r = R\sin\omega t$$

$$-\mu R\omega^2\sin\omega t = -kR\sin\omega t$$

and therefore the *resonance frequency* of the accelerometer, ω_n, can be written directly as

$$\omega_n^2 = \frac{k}{\mu}$$

The implications of this result can be seen by rewriting this equation as follows

$$\omega_n^2 = k\left(\frac{1}{m_s} + \frac{1}{m_b}\right) \qquad (2)$$

If the accelerometer is now mounted wih perfect rigidity onto a structure which is heavier than the total weight of the accelerometer then m_b becomes much larger than m_s. The resonance frequency of the accelerometer becomes lower. Taken to the limit, if the accelerometer is mounted on an *infinitely* heavy structure ($m_b \to \infty$) then the last equation reduces to

$$\omega_m^2 = \frac{k}{m_s} \qquad (3)$$

This is the natural frequency of the seismic mass-spring system and is defined as the *mounted resonance frequency*, ω_m, of the accelerometer. The *mounted resonance frequency* is a *property* of the accelerometer seismic mass-spring system. Later it will be seen that this frequency is used to define the *useful operating frequency range* of an accelerometer.

In practice it is obviously not possible to mount the accelerometer on an infinitely heavy and stiff structure to measure its *mounted resonance frequency*. An approximation is achieved by mounting the accelerometer on a 180 g steel block and exciting the two together at a constant acceleration over a wide frequency range to measure the *mounted resonance frequency*. This is examined in Chapter 5.

The resonance frequency when mounted will change if the structure is not infinitely rigid or if the accelerometer mounting technique introduces an additional compliance between the base and the structure. The resonance will split up in two and the lowest resonance frequency will be lower than the mounted resonance frequency. This is examined in Chapter 4.

The forced vibration of the accelerometer must now be examined. The applied force on the accelerometer must be included in the analysis along with the natural resonance frequency, ω_n, previously defined. The equation of motion for the model (1) now becomes

$$\ddot{r} + \omega_n^2 r + \frac{F_0}{m_b}\sin\omega t = 0$$

and assuming again that the displacements of the masses vary sinusoidally then

$$-\omega^2 R\sin\omega t + \omega_n^2 R\sin\omega t + \frac{F_0}{m_b}\sin\omega t = 0$$

and therefore

$$R(\omega_n^2 - \omega^2) + \frac{F_0}{m_b} = 0$$

or

$$R = -\frac{F_0}{m_b(\omega_n^2 - \omega^2)}$$

At frequencies well below the natural resonance frequency of the accelerometer ($\omega << \omega_n$) the displacement, which is now called R_0, is expressed by

$$R_0 = -\frac{F_0}{m_b\omega_n^2}$$

The ratio of the displacement at low frequency, R_0, to the displacement at high frequency, R, can be expressed as follows

$$\frac{R}{R_o} = \frac{-\dfrac{F_0}{m_b(\omega_n^2 - \omega^2)}}{-\dfrac{F_o}{m_b\,\omega_n^2}}$$

and by denoting this ratio as A and rearranging the expression, then

$$A = \frac{1}{1 - \left(\dfrac{\omega}{\omega_n}\right)^2} \qquad (4)$$

This important result shows that the displacement between the base and the seismic masses increases when the forcing frequency becomes comparable to the natural resonance frequency of the accelerometer. Consequently the force on the piezoelectric elements and the electrical output from the accelerometer also increase. As the piezoelectric elements used in Brüel & Kjær accelerometers exhibit constant force sensitivity the increase in electrical output of an accelerometer near its resonance frequency is attributable entirely to the natural resonance of the accelerometer. The typical shape of a frequency response curve of an accelerometer (see Fig. 2.3) and amplitude measurement errors are related to this equation. This is covered in section 2.3.

The free hanging natural resonance frequency of the accelerometer depends heavily on the ratio of the total seismic mass to the mass of the rest of the transducer but primarily to that of the base. As a general rule the total seismic mass of an accelerometer is approximately the same as the mass of the base and this gives the relationship

$$\frac{\text{mounted resonance frequency}}{\text{free hanging resonance frequency}} \approx \frac{1}{\sqrt{2}}$$

2.3. Frequency Range

The relative change in electrical output from an accelerometer is shown in Fig. 2.3. A frequency response curve of this kind shows the variation in the accelerometer's electrical output when it is excited by a constant vibration level over a wide frequency range. To obtain such a frequency response curve the accelerometer is mounted onto a 180 g exciter head. Hence the approximation

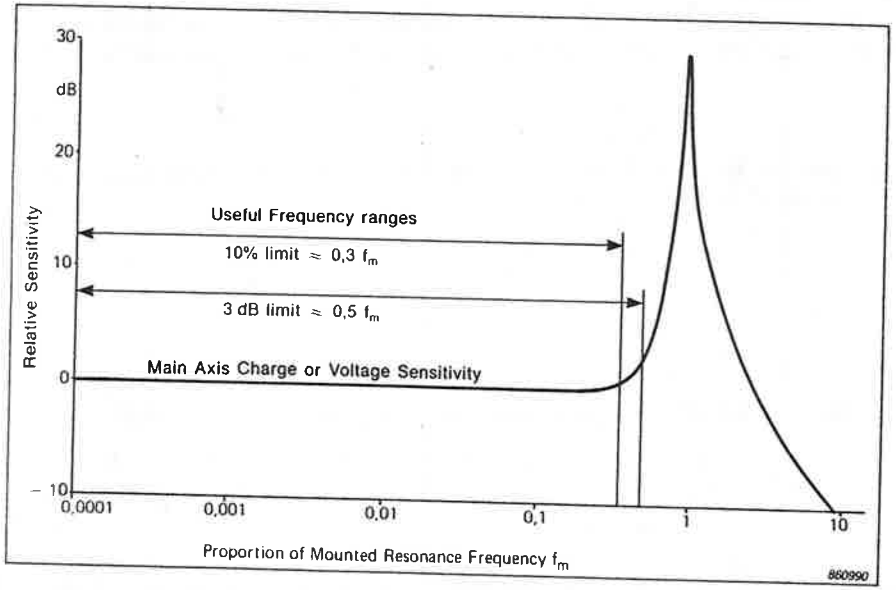

Fig. 2.3. Relative sensitivity of an accelerometer vs. frequency

to the *mounted resonance frequency* of the accelerometer can be found. This frequency response curve is related to equation (4) in the last section. However, the *mounted resonance frequency* can now be directly substituted into (4) to obtain

$$A = \frac{1}{1 - \left(\frac{\omega}{\omega_m}\right)^2} \qquad (5)$$

Equation (5) can be used to calculate the deviation between the measured and the actual vibration at any frequency and to define useful frequency ranges.

2.3.1. Upper Frequency Limit

Fig. 2.3 shows that the *mounted resonance frequency* determines the frequency range over which the accelerometer can be used while a constant electrical output for a constant vibration input is still maintained.

The higher the mounted resonance frequency, the wider the operating frequency range. However, in order to have a higher mounted resonance frequency it is necessary to have either stiffer piezoelectric elements or a lower total seismic mass. The stiffness of the piezoelectric elements is generally constant so a lower seismic mass is required. Such a lower mass would however exert less force on the piezoelectric element and the accelerometer would consequently be less sensitive. Therefore accelerometers possessing very high frequency performance are less sensitive. Conversely, high sensitivity accelerometers do not have very high frequency measurement capability.

Several useful frequency ranges can be defined from the frequency response curve of an accelerometer. They are:

5% Frequency Limit is the frequency at which there is a 5% deviation between the measured and the actual vibration level applied to the base of the accelerometer. The maximum vibration frequency which can be measured with this accuracy is approximately one fifth (0,22) of the mounted resonance frequency of the accelerometer.

10% Frequency Limit is the frequency at which there is a 10% deviation between the measured and the actual vibration level applied to the base of the accelerometer. The maximum vibration frequency which can be measured with this accuracy is approximately one third (0,30) times the mounted resonance frequency of the accelerometer.

3 dB Frequency Limit is the frequency at which there is a 3 dB difference between the measured and the actual vibration level applied to the base of the accelerometer. The maximum vibration frequency which can be measured with this accuracy is approximately one half (0,54) times the mounted resonance frequency of the accelerometer.

2.3.2. Lower Frequency Limit

Piezolelectric accelerometers are not capable of a true DC response. The piezoelectric elements will only produce a charge when acted upon by *dynamic* forces. The actual low frequency limit is determined by the preamplifier to which the accelerometer is connected as it is the preamplifier which determines the rate at which the charge leaks away from the accelerometer. Measurements of vibrations at frequencies down to 0,003 Hz are possible with Brüel & Kjær accelerometers and preamplifiers.

Applications requiring a low frequency limit in the order of fractions of a hertz are very rare and consequently the lack of a true DC response is seldom a drawback.

Chapter 3, "Vibration Preamplifiers", should be consulted for a description of the low frequency performance of preamplifiers. Environmental effects associated with low frequency measurements are covered in Chapter 4 "Accelerometer Performance in Practice".

2.4. PIEZOELECTRIC MATERIALS

A piezoelectric material is one which develops an electrical charge when subjected to a force. Materials which exhibit this property are intrinsic piezoelectric monocrystals such as quartz and Rochelle salt, and artificially polarized ferroelectric ceramics which are mixtures of different compounds such as barium titanate, lead zirconate and lead metaniobate.

The process by which the ceramics are polarized is analogous to the process by which a piece of soft iron can be magnetised by a magnetic field . A high voltage surge is applied across two ends of the material. The domains within the molecular structure of the material become aligned in such a way that an external force causes deformations of the domains and charges of opposite polarity to form on opposite ends of the material. Fig. 2.4. shows a simplified illustration of this effect. When a piezoelectric accelerometer is vibrated forces proportional to the applied acceleration act on the piezoelectric elements and the charge generated by them is picked up by the contact. It is the extremely linear relationship between the applied force and the developed charge, over a very wide dynamic and frequency range, which results in the excellent characteristics of the piezoelectric accelerometer. The sensitivity of a piezoelectric material is given in pC/N.

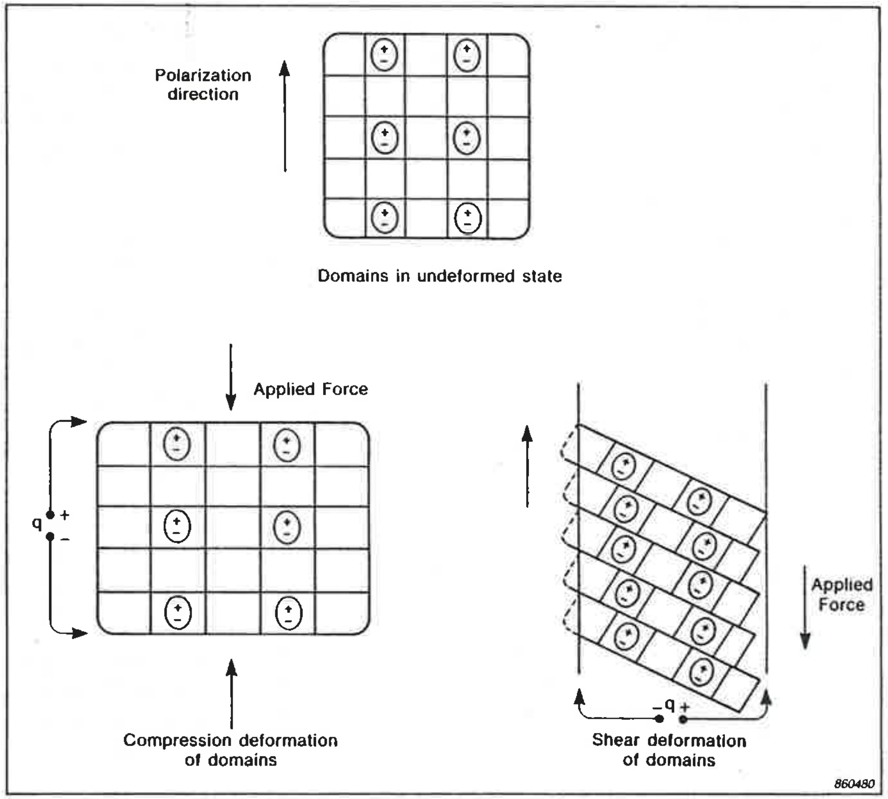

Fig. 2.4. Simple model of the piezoelectric effect within an artificially polarized ceramic. The charge q is collected between the indicated surfaces

The piezoelectric element can undergo both compression and shear deformation as illustrated in Fig. 2.4. In both cases a charge is developed along the surfaces on which the forces act.

In compression deformation the charge is picked up in the polarization direction. This has the distinct disadvantage that non-vibration inputs, such as temperature fluctuations, cause charge to be developed in the polarization direction. This charge is also picked-up along with the vibration induced charge and the accelerometer output is no longer only related to the vibration input. However, when using shear deformation, the charge is picked up in a direction perpendicular to the polarization direction and the extra charge caused by the temperature fluctuations is not picked up. This is one of the reasons why shear mode accelerometer designs give better performance than compression designs. The influence of temperature fluctuations is discussed in further detail in section 4.2.2.

Ferroelectric ceramics may be produced in any desired shape and their composition may be varied to give them special properties for different applications. With piezoelectric monocrystalline materials such as quartz this is not the case as their composition is fixed and their shape is restricted by the size of crystal from which they are cut. Because of this accelerometers which use monocrystalline elements generally have a lower sensitivity and internal capacitance than those with ferroelectric ceramic elements.

Piezoelectric materials used in Brüel & Kjær accelerometers are designated PZ 23, PZ 27, PZ 45 and PZ 100. These have the following properties:

1. PZ 23 belongs to the lead titanate, lead zirconate family of ferroelectric ceramics and is artificially polarized. It may be used at temperatures up to 250°C (482°F). Due to its high sensitivity (approx. 300 pC/N) and other good all round properties it is used in most Brüel & Kjær accelerometers.
2. PZ 27 is an artificially polarized lead zirconate titanate element very similar to PZ 23. It is suitable for use in miniature accelerometers.
3. PZ 45 is a specially formulated artificially polarized ferroelectric ceramic which has a particularly flat temperature response and may be used at temperatures of up to 400°C (752°F). It is used in Brüel & Kjær differential, high temperature and high shock accelerometers.
4. PZ 100 is a carefully selected and prepared quartz crystal. It may be used at temperatures up to 250°C (482°F) and has excellent stability with low temperature transient sensitivity. It is used in the Brüel & Kjær Standard Reference Accelerometer Type 8305 and in the force transducers.

The type of the piezoelectric element used in any particular Brüel & Kjær accelerometer can be found in the accelerometer Product Data.

2.5. PRACTICAL ACCELEROMETER DESIGNS

Three different mechanical constructions are used in the design of Brüel & Kjær accelerometers. The first two designs, Planar Shear and Delta Shear® are shown in Fig. 2.5. A Compression Design (see Fig. 2.6) is also in use. Due to its superior performance the Delta Shear® design is used in nearly all Brüel & Kjær accelerometers.

1. **Delta Shear® Design**. Three piezoelectric elements and three masses are arranged in a triangular configuration around a triangular centre post. They are held in place using a high tensile clamping ring. No adhesives or bolts are required to hold the assembly together and this ensures optimum performance and reliability. The ring prestresses the piezoelectric elements to give a high degree of linearity. The charge is collected between the housing and the clamping ring.

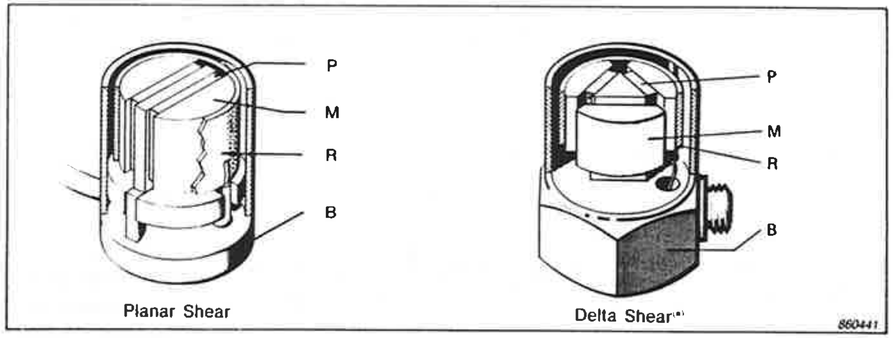

Fig. 2.5. Planar Shear and Delta Shear® designs. M=Seismic Mass, P=Piezoelectric Element, R=Clamping Ring and B=Base

The Delta Shear® design gives a high sensitivity-to-mass ratio compared to other designs and has a relatively high resonance frequency and high isolation from base strains and temperature transients. The excellent overall characteristics of this design make it ideal for both general purpose accelerometers and more specialized types.

2. **Planar Shear**. In this design the piezoelectric element undergoes shear deformation as in the Delta Shear® design. Two rectangular slices of piezoelectric material are arranged on each side of a rectangular centre post. Two masses are formed as shown in Fig. 2.5 and held in position using a high tensile strength clamping ring performing the same function as in the Delta Shear® design. The base and piezoelectric elements are effectively isolated from each other thus giving excellent immunity to base bending and temperature fluctuations.

3. **Centre Mounted Compression Design**. This traditional, simple construction gives a moderately high sensitivity-to-mass ratio. The piezoelectric element-mass-spring system is mounted on a cylindrical centre post attached to the base of the accelerometer. However, because the base and centre post effectively act as a spring in parallel with the piezoelectric elements, any dynamic changes in the base such as bending or thermal expansions can cause stresses in the piezoelectric elements and hence erroneous outputs. Even though Brüel & Kjær employ very thick bases to minimize these effects in compression designs, bending and stretching forces can still be transmitted to the piezoelectric elements. This will result in an erroneous non-vibration related output at the frequency of the vibration. In the previous section it was seen that temperature fluctuations can also produce charge in the piezoelectrics which are picked up in Compression Designs.

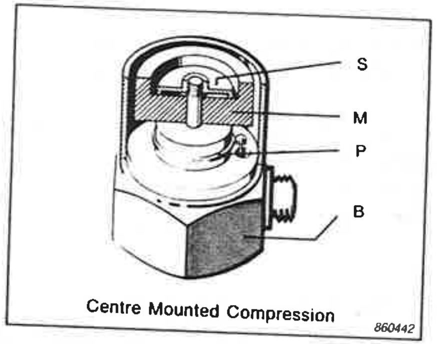

Fig. 2.6. Traditional Compression Design. M=Seismic Mass, P=Piezoelectric Element, B=Base, and S=Spring

For the reasons mentioned above Brüel & Kjær only produce compression design accelerometers for high level measurements (i.e. shock measurements) where the erroneous output is small compared with the vibration signal. A compression design is also used for the Standard Reference Accelerometer which is used in the controlled environment of accelerometer calibration. Here the addition of a beryllium disc strengthens the base and minimizes the effect of base bending. This accelerometer is inversely mounted in order to measure more accurately the vibration at the base of the accelerometer which is mounted onto it.

2.5.1. Line-drive Accelerometers

These accelerometers contain a built-in preamplifier. A line-drive accelerometer is shown in Fig. 2.7. The accelerometer part of this design is identical to the Delta Shear* construction mentioned above. The electronic part utilizes thick film micro-circuitry techniques to produce a preamplifier with excellent performance characteristics. Chapter 3 includes a description of the operation of the preamplifier section.

Line-drive accelerometers require an external power supply for their operation. The built-in preamplifier is supplied by a constant voltage and the vibration signal is transmitted back to the external supply unit in the form of the modulated power supply current. This system is also described in Chapter 3.

Built-in preamplifiers do however introduce temperature and shock limitations. To overcome this Brüel & Kjær also produce a separate line-drive preamplifier for use with accelerometers.

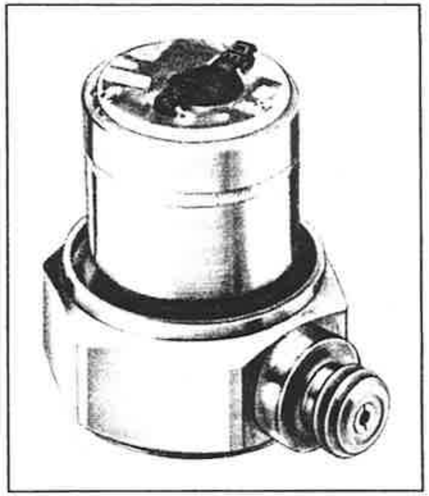

Fig. 2.7. A Brüel & Kjær line-drive accelerometer with its housing removed to reveal the built-in electronics

2.5.2. Other designs

Other designs of accelerometer exist, based around the compression and shear deformation principles. Brüel & Kjær only use the designs mentioned above as these, and in particular the Delta Shear(R) design, give the most uncompromising performance available. The following general designs may still be found elsewhere;

Annular Shear Designs where the piezoelectric elements and masses are formed into rings and simply glued together.

Isolated Shear (Bolted Shear) is similar to the planar shear design except the piezoelectric elements are secured using a bolt.

2.6. ACCELEROMETER SENSITIVITY

So far it has been seen that an accelerometer is a self-generating device whose electrical output is proportional to the applied acceleration. In order to assess the accelerometer's role as a measurement device, the relationship between its input (acceleration) and output (charge or voltage) is now examined in more detail.

2.6.1. Charge and Voltage Sensitivity

The piezoelectric accelerometer can be regarded as either a charge source or a voltage source. The piezoelectric element acts as a capacitor C_a in parallel with a very high internal leakage resistance, R_a, which, for practical purposes, can be ignored. It may be treated either as an ideal charge source, Q_a in parallel with C_a and the cable capacitance C_c or as voltage source V_a in series with C_a and loaded by C_c, as shown in Fig. 2.8. The equivalent circuits for both models are shown in Fig. 2.8. Both models can be used independently according to which model yields the easiest calculations.

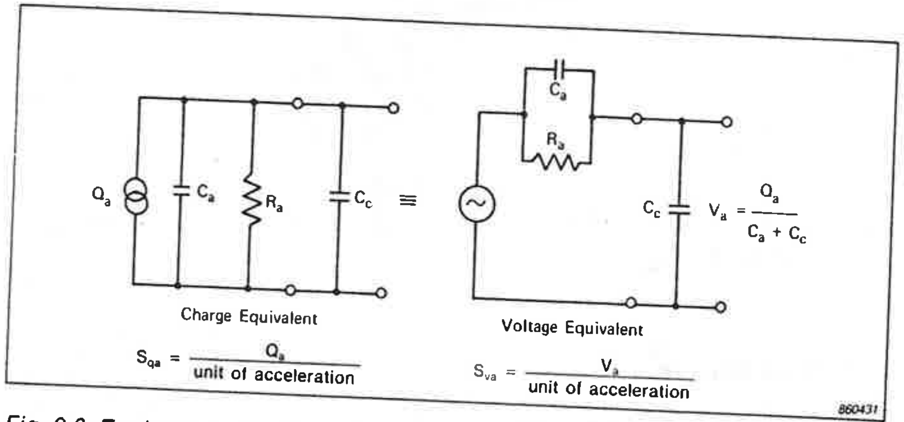

Fig. 2.8. Equivalent electrical circuits for piezoelectric accelerometer and connection cable

The choice of accelerometer preamplifier depends on whether we want to detect charge or voltage as the electrical output from the accelerometer.

The charge sensitivity, S_{qa}, of a piezoelectric accelerometer is calibrated in terms of charge (measured in pC) per unit of acceleration:

$$S_{qa} = \frac{pC}{ms^{-2}} = \frac{pC_{RMS}}{ms^{-2}_{RMS}} = \frac{pC_{peak}}{ms^{-2}_{peak}}$$

Likewise, the voltage sensitivity can be expressed in terms of voltage per unit of acceleration:

$$S_{va} = \frac{mV}{ms^{-2}} = \frac{mV_{RMS}}{ms^{-2}_{RMS}} = \frac{mV_{peak}}{ms^{-2}_{peak}}$$

It can be seen from the simplified diagrams that the voltage produced by the accelerometer is divided between the accelerometer capacitance and the cable capacitance. Hence a change in the cable capacitance, caused either by a different type of cable and/or a change in the cable length, will cause a change in the voltage sensitivity. A sensitivity recalibration will therefore be required. This is a major disadvantage of using voltage preamplification and is examined in greater detail in Chapter 3. Charge amplifiers are used nearly all the time nowadays.

At low and medium frequencies, within the useful operating frequency range of an accelerometer, the voltage sensitivity is independent of frequency. This also applies to the charge sensitivity of accelerometers using PZ 45 and PZ 100 piezoelectric materials, but not to those using PZ 23 and PZ 27 piezoelectric materials. Instead, this piezoelectric material has been designed so that both the charge sensitivity and capacitance decrease by approximately 2,5% per decade increase in frequency. The effect of this decrease is to partially offset the output rise at resonance. Therefore, the maximum deviation between the measured and actual accelerations over the useful operating frequency range of accelerometers employing PZ 23 with medium to high resonance frequencies is only ± 5% of the acceleration applied to the base of the accelerometer, as indicated in Fig. 2.9.

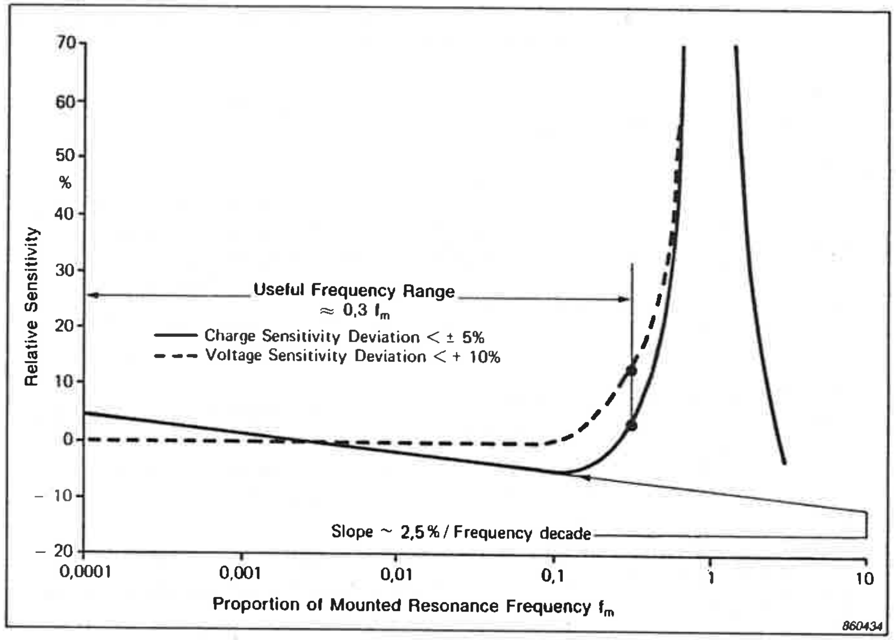

Fig. 2.9. Charge and voltage sensitivity versus frequency for an accelerometer using PZ 23 piezoelectric material

2.6.2. Uni-Gain® Sensitivity

Almost every Brüel & Kjær accelerometer is of the Uni-Gain® design. This means that their measured sensitivities have been adjusted to within 2% of a convenient value such as 1; 3,16; 10 or 31,6 pC/ms^{-2}. With Uni-Gain® accelerometers one accelerometer can be replaced by another of the same type without further adjustment of any instrument setting. Because the values above are 10 dB apart relative to each other, the calibration of measurement systems and set-ups is very easy. For example, if one accelerometer is exchanged for another of a different type, only fixed gain changes of 10 dB are required on the measurement instrumentation.

Uni-Gain® sensitivities are achieved in Brüel & Kjær accelerometers by carefully adjusting the mass of the seismic elements.

2.6.3. Linearity and Dynamic Range

Linearity is a fundamental requirement of any measuring system. The ouput from the system must be linearly related to the input over as wide a frequency and dynamic range as is required. The excellent linearity of Brüel & Kjær accelerometers is illustrated in Fig. 2.10.

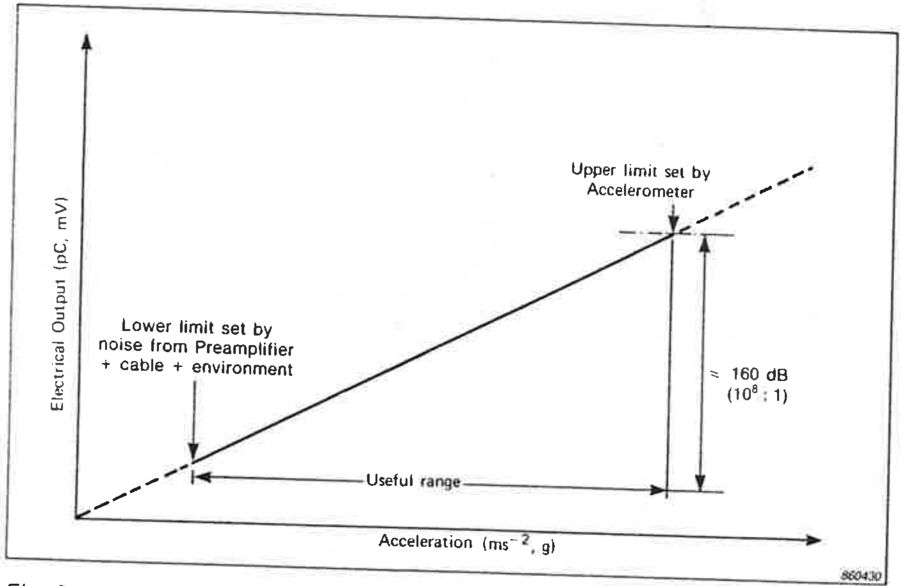

Fig. 2.10. Accelerometer output versus acceleration for piezoelectric accelerometers demonstrating the linearity and wide dynamic range

The piezoelectric accelerometer is an extremely linear device over a very wide dynamic range because of the linear performance of the piezoelectric elements over a wide dynamic range. In theory the accelerometer is linear down to zero acceleration. However a practical lower limit is determined by the noise inherent in the measurement system. This noise can have several sources of origin and these are discussed in Chapters 3 and 4.

When an accelerometer is taken beyond its maximum acceleration limit the performance becomes increasingly non-linear. At levels far in excess of the maximum limit the preloading ring might begin to slip down the piezoelectric elements and eventually short-circuit with the base, thus rendering the accelerometer useless. In practice this will never happen unless the accelerometer is subjected to shock levels well outside its specified operating range.

2.6.4. Transverse Sensitivity

When an accelerometer has acceleration applied at right angles to its mounting axis, there will still be some output from the accelerometer. On the accelerometer calibration chart the transverse sensitivity is quoted as a percentage of the main axis sensitivity. Ideally the transverse sensitivity of an accelerometer should be zero, but in practice minute irregularities in the piezoelectric element and in metal parts prevent this. At Brüel & Kjær particular attention is paid to selection of homogenous piezoelectric ceramics and to careful machining, polishing and lining up of accelerometer parts. Thus with proper handling and

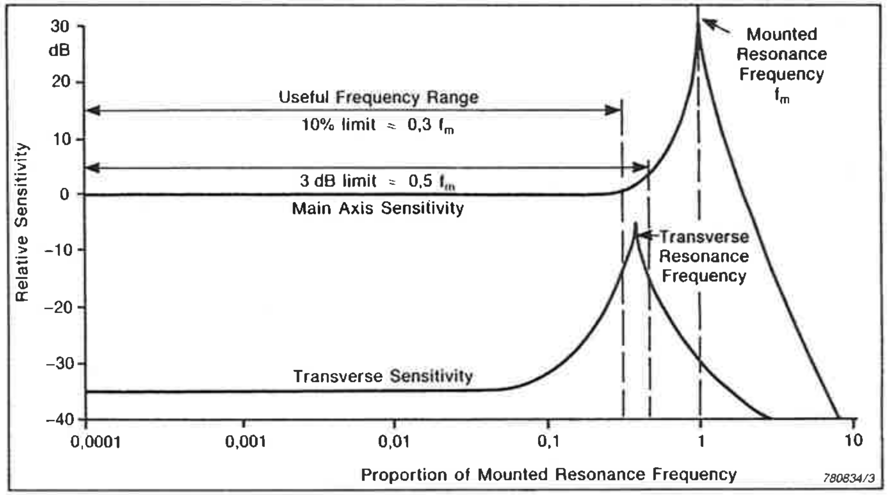

Fig. 2.11. The relative response of an accelerometer to main axis and transverse axis vibrations

mounting on a flat, clean surface, the maximum transverse sensitivity of most Brüel & Kjær accelerometers can be kept below 4% of the main axis sensitivity at 30 Hz (see Fig. 2.11).

At frequencies less than one sixth of the main axis mounted resonance frequency transverse sensitivity can be kept below 10%. At frequencies just over one third of the main axis mounted resonance frequency it is difficult to specify exact values of transverse sensitivity as transverse resonance occurs. This is indicated in Fig. 2.11.

As illustrated in Fig. 2.12, transverse sensitivity can be regarded as the result of the maximum charge and voltage sensitivity axis of the accelerometer not being quite aligned with the mounting axis. Because of this there are directions of maximum and minimum transverse sensitivity which are at right angles to one another and to the main sensitivity axis. It is therefore the maximum value of transverse sensitivity which is specified on the accelerometer calibration chart. The direction of minimum sensitivity is marked by a red dot on the accelerometer housing. This is a unique feature of Brüel & Kjær accelerometers.

It should be noted that the Delta Shear* design, having constant stiffness in all transverse directions, has only one transverse resonance. Other shear designs may have two or more transverse resonances.

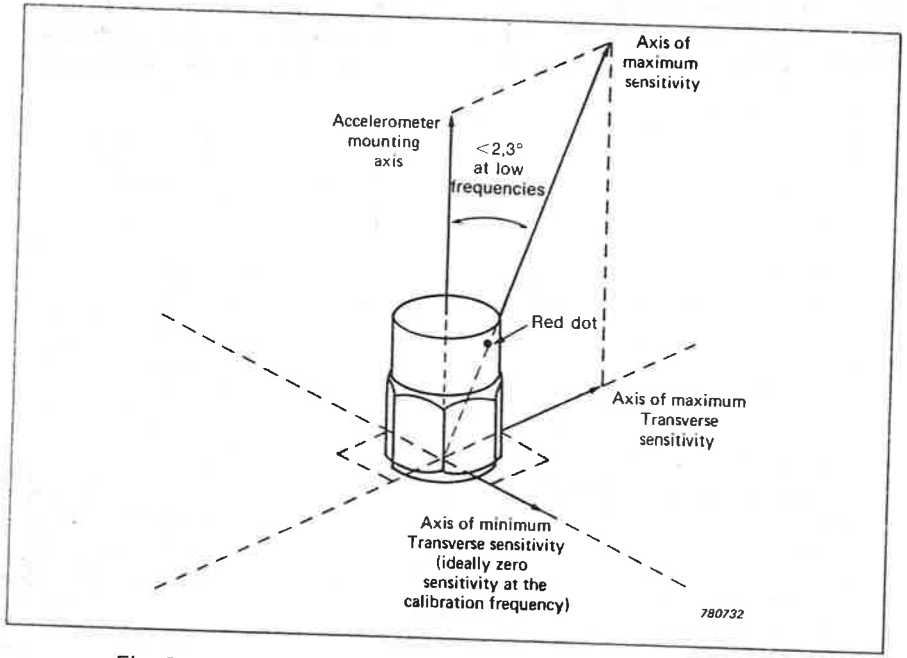

Fig. 2.12. Vectorial representation of transverse sensitivity

As the transverse resonance is just outside the useful operating frequency range of an accelerometer and with a peak amplitude just below the main axis sensitivity, it is important that transverse vibrations and shocks are kept well below the specified main axis continuous vibration limits. Similarly, dropping or banging accelerometers can subject them to large transverse shocks well outside practical design limits and permanent damage can be caused to the piezoelectric elements inside the accelerometer.

The following precautions can be taken against severe transverse vibrations:

1. Align the red dot in the direction of maximum transverse acceleration.

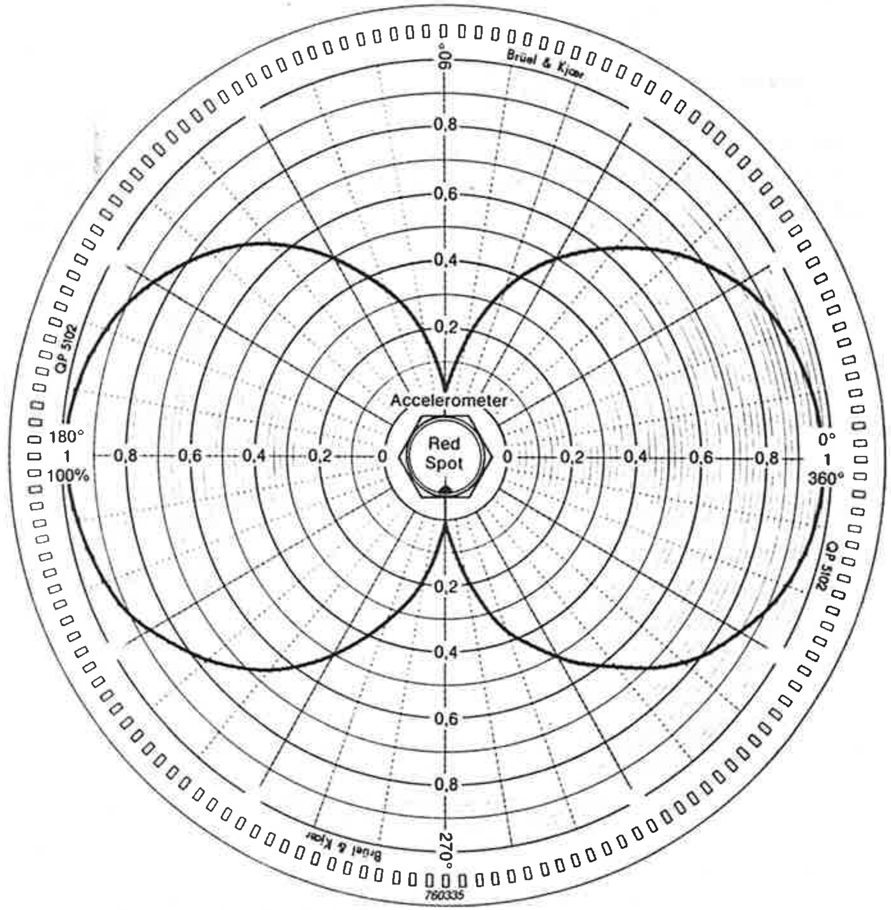

Fig. 2.13. Chart for determining the accelerometer transverse sensitivity in any direction when the maximum transverse sensitivity is known

2. Use a mechanical filter to filter off vibrations in directions other than the main axis.

3. Use the chart in Fig. 2.13 to calculate the sensitivity to vibrations in any direction from the maximum transverse sensitivity.

Example. At 60° to the maximum sensitivity axis of 0° the chart indicates a transverse sensitivity factor of 0,5. (This could also have been calculated from the cosine of the angle). Therefore an accelerometer having a maximum transverse sensitivity of 2% will have a transverse sensitivity at 60° of:

$$0,5 \times 2\% = 1\%$$

2.7. PHASE RESPONSE

The phase shift of an accelerometer corresponds to the time delay between the mechanical input and the resulting electrical output. If the phase is not constant at all frequencies in the operating range, the phase relationship between various frequency components of a vibration signal will be altered with respect to each other, resulting in an electrical output that is a distorted representation of the mechanical input.

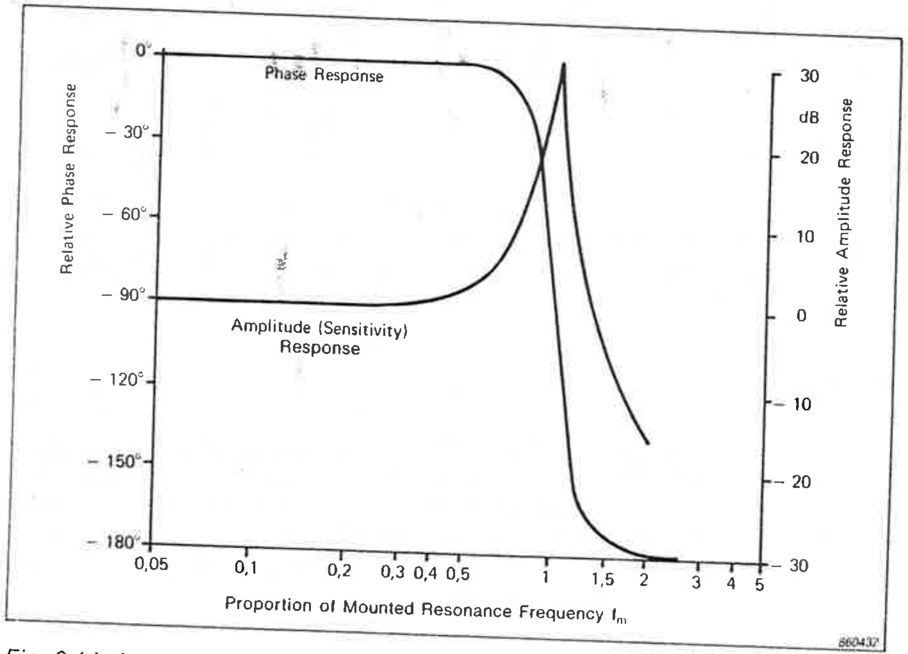

Fig. 2.14. Accelerometer amplitude and phase response as a function of frequency

The sensitivity and phase responses of an accelerometer are shown in Fig. 2.14. At frequencies below the mounted resonance the phase shift introduced is insignificant. At frequencies very close to the resonance, the motion of the seismic masses lags that of the base and phase distortion is introduced. However, with Brüel & Kjær accelerometers small resonance damping factors ensure that the frequency range over which resonance occurs is relatively narrow, and therefore the accelerometer may be operated well beyond its rated useful frequency range without introducing phase distortion.

Nevertheless, it is also necessary to consider the phase linearity of the charge or voltage preamplifier used, especially if integration networks and other filters are in use. This is especially important when measuring transient vibrations and mechanical shocks.

2.8. TRANSIENT RESPONSE

When measuring transient vibrations and shocks particular attention must be paid to the overall linearity of the system as otherwise the reproduced transients will be distorted. Piezoelectric accelerometers are extremely linear transducers and will reproduce a wide range of transients without problem. The accelerometer is the least frequent source of error when poor measurements are made of transients. More often it is the preamplifier and any associated filters and integration networks which cause the problem. However, to ensure the accuracy of the measurement it is necessary to consider the following transient phenomena.

2.8.1. Leakage Effects

In Fig. 2.15, a distortion has taken place in the waveform of a quasi-static acceleration pulse, such as might be encountered during a rocket launch or in a fast elevator. The distortion is caused by the accelerometer and preamplifier combination operating in the incorrect frequency range and can be explained as follows:

When the accelerometer is subjected to a quasi-static acceleration a charge is developed on the piezoelectric elements. By virtue of the elements capacitance, this charge is stored in the element and prevented from "leaking away" by the very high leakage resistance of the accelerometer. However, due to the finite leakage time constant of the accelerometer and the input impedance and lower limiting frequency setting on the preamplifier, some charge leaks away and this results in a negative slope waveform as seen between points A and B. When the acceleration stops, the charge changes a corresponding amount and drops below the zero level to point C before rising back up to the zero level

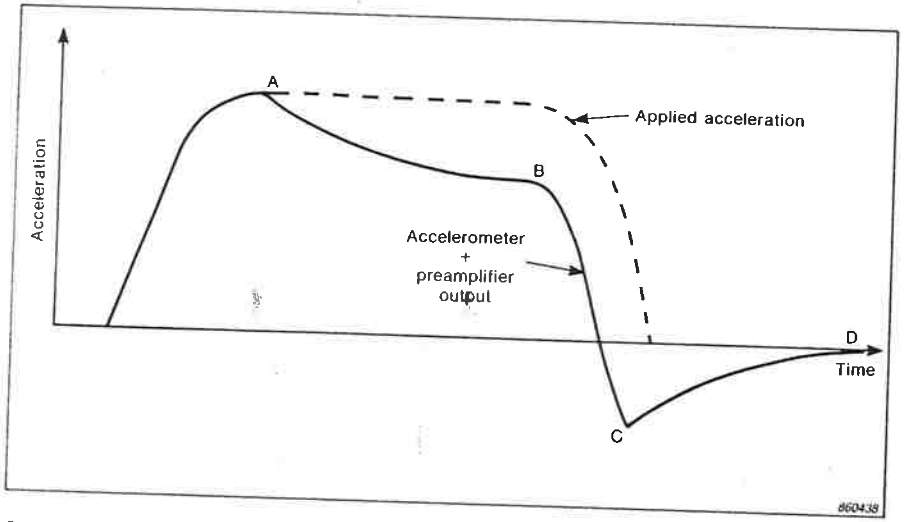

Fig. 2.15. The distortion of a waveform of a quasi-static acceleration input caused by "leakage" associated with the accelerometer and preamplifier

again at point D. The rate of exponential change between A and B and between C and D is the same and is determined by the time constant set by the accelerometer and preamplifier.

This effect causes errors in the measurement of the peak amplitude of the acceleration and is caused by the accelerometer being used with the wrong Lower Limiting Frequency on the preamplifier. Measurement errors of peak amplitude due to leakage may be kept to within 5% by ensuring that the –3dB Lower Limiting Frequency of the preamplifier is less than 0,008/T, where T is the period of a *square wave* transient. For measurements on half-sine transients the Lower Limiting Frequency must be less than 0,05/T.

The frequency bandwidth of the entire measurement system required to measure such transients with specified accuracies can be found from Fig. 2.16 which also includes the upper frequency requirement because transient signals have higher frequency components which must also be reproduced without distortion.

The distortion of the waveform of transients, and in particular quasi-static vibrations, caused by using the accelerometer with the incorrect frequency range can appear similar to the distortion produced by other phenomena such as zero shift (see section 2.8.3). It must be understood that the causes, and hence solutions, of the problems are different.

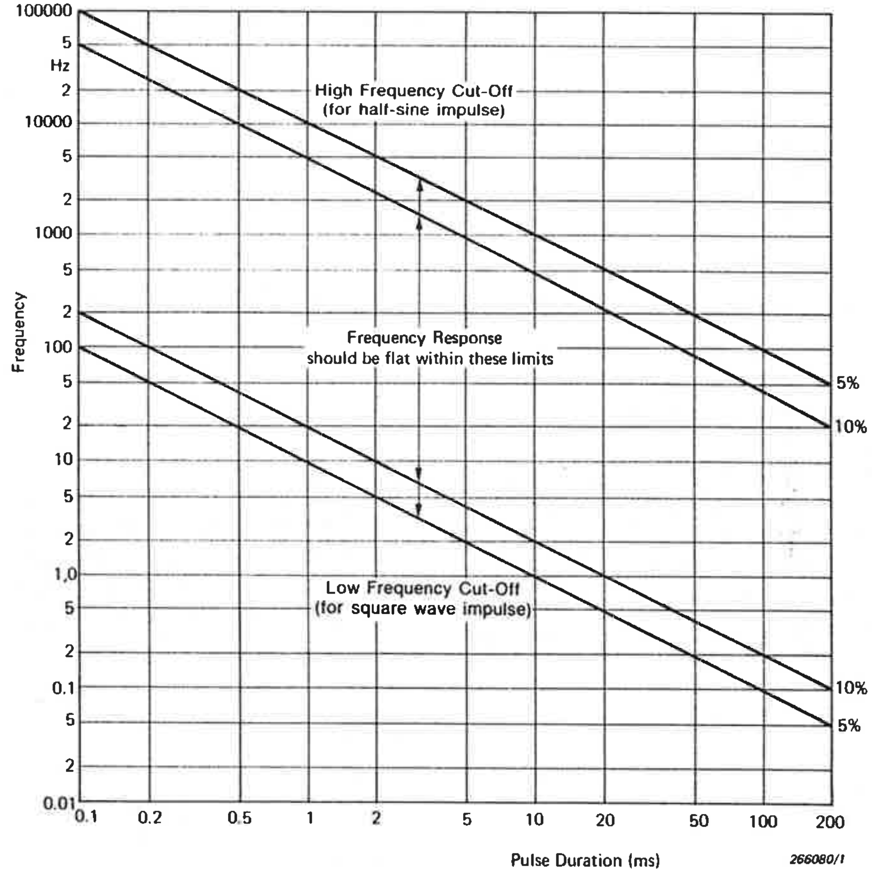

Fig. 2.16. Vibration system –3dB lower and upper limiting frequencies required for acceleration measurements of pulses of duration T keeping amplitude measurement errors less than 5 and 10% respectively

2.8.2. "Ringing"

This term is used to describe the distortion produced by an accelerometer which is being used to measure transient vibrations outside its useful frequency range. An example of the resulting distorted signal is shown in Fig. 2.17. The resonance of the accelerometer is excited with high frequency vibration components and this should be avoided. A first warning of ringing might be given by an overload indication on the preamplifier.

"Ringing" causes errors in the measurement of peak vibration amplitude. For 5% peak measurement error the accelerometer mounted resonance frequency should not be less than 10/T where T is the length of the transient in seconds.

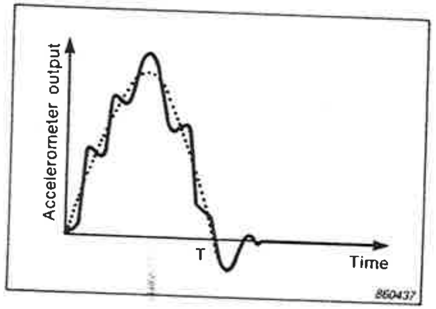

Fig. 2.17. Waveform distortion due to "ringing"

The accelerometer resonance can be damped to reduce the ringing and make optimum use of the measurement system dynamic range and bandwidth. This may be achieved using a mechanical filter for mounting the accelerometer (see section 4.5) or by applying the accelerometer signal to a preamplifier incorporating a low-pass filter. In the latter case the filter must have a high frequency attenuation slope of 12 dB/octave and a −3 dB upper limiting frequency f_u corresponding to approximately half the accelerometer mounted resonance frequency f_m (i.e. $f_u = 0,5\ f_m$). This gives the system response shown in Fig. 2.18, enabling a half-sine wave transient of duration $T = 1/f_m$ to be measured with less than 10% amplitude error.

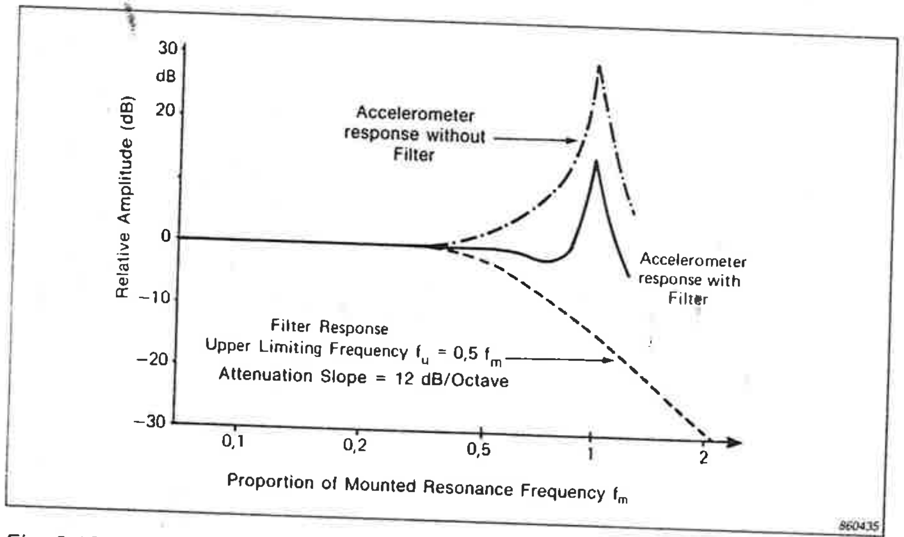

Fig. 2.18. Low pass filter or preamplifier response required to damp mounted resonance frequency f_m of accelerometer for measurement of half sine type shock pulses of duration $T=1/f_m$ seconds with less than 10% amplitude error

2.8.3. Zero Shift

Consider the accelerometer output signals in Fig. 2.19 resulting from two identical half sine pulses. In both cases distortion of the waveform has been introduced by the accelerometer. The measurement dynamic levels were very close to the maximum acceleration limit of the accelerometer.

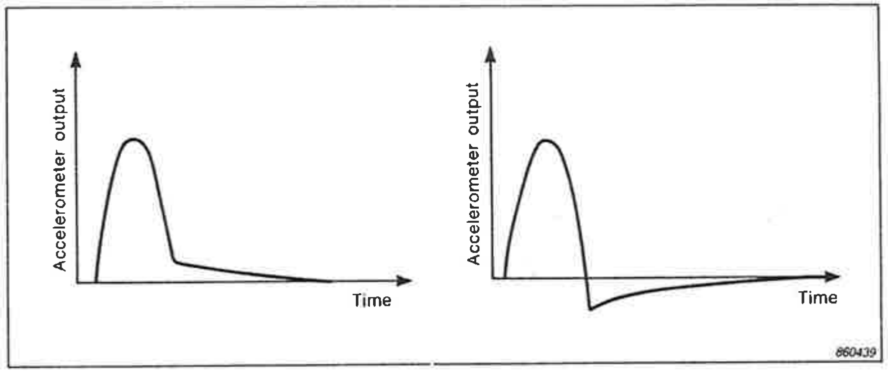

Fig. 2.19. Accelerometer and preamplifier output resulting from a half-sine pulse of such a high level that "zero shift" has been introduced

If the piezoelectric elements are not considered to be perfectly elastic materials, then when the force on the element is suddenly decreased the molecular domains may not all return to the state they were in before the shear force was applied. Therefore, when the force is removed the elements still produce a charge which slowly decays with time as the preamplifier output returns to zero at a rate determined by its Lower Limiting Frequency. This phenomenon occurs randomly and with random sign.

The time taken for the zero shift to disappear may be a factor of 1000 times longer than the length of the original pulse. Therefore, large errors result if integration networks are used.

A mechanical filter can often guard against zero shift effects.

REMEMBER: Zero shift, "Leakage" and "Ringing" are only problems when the accelerometer is used outside its useful operating ranges.