4320

INSTRUCTIONS AND APPLICATIONS

Triaxial Accelerometer Set Type 4320

The Triaxial Accelerometer is virtually three accelerometers mounted in one housing. It indicates the vibration in three mutually perpendicular directions. Principal application areas are, balancing of machinery, vibration testing, multidirectional shock testing and others where the direction of vibration is not known or where measurements in more than one direction are of interest.

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BB 4320

Accelerometer Set

Type 4320

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0. Introduction

The accelerometer is an electromechanical transducer which produces at its output terminals an e.m.f. proportional to the acceleration to which the transducer is subjected. The output signal can be electronically processed and read on a meter or some other suitable indicating device.

The Triaxial Accelerometer is virtually three accelerometers mounted in one housing. It indicates the vibration in three mutually perpendicular directions Principal application areas are, balancing of machinery, vibration testing, multidirectional shock testing and others where the direction of vibration is not known or where measurements in more than one direction are of interest.

The accelerometer is small, light and of rugged construction, suitable for most vibration measurements, both in the laboratory and in field environments. Versatility in use has been a prime goal and special care has been taken to ensure a wide frequency range, high sensitivity and good temperature characteristics. Furthermore, the accelerometer has low transverse sensitivity, negligible mounting error and low sensitivity to severe environmental conditions, such as humidity, high temperature, corrosive atmospheres and magnetic fields. The acoustical sensitivity and influence of cable whip are also minimized.

For absolute measurements it is necessary to know the sensitivity of the vibration transducer employed. Each accelerometer is supplied with individual calibration data and frequency response curves, all taken as part of the production test procedure. The aim has been to supply the maximum amount of information on the calibration sheet to ensure a completely predictable performance of the accelerometer.

The Triaxial Accelerometer has type number 4340 when on its own in the production and calibration stages. When it is sold it is accompanied by certain accessories such as connecting cable, mounting studs etc., and is available only as Accelerometer Set Type 4320. See Specifications at the end of this book.

1. Description

Construction.

The Accelerometer Type 4340 is of the piezoelectric compression type with a construction indicated schematically in Fig. 1.1.

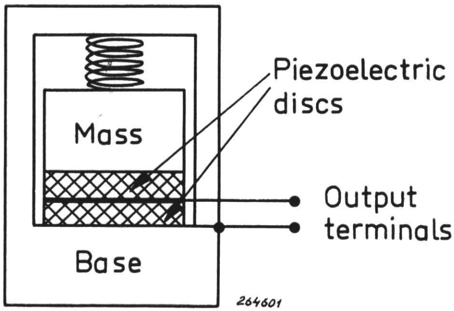


Fig. 1.1. Schematic drawing of a piezoelectric accelerometer.

Each transducing element consists of two piezoelectric*) discs on which is resting a heavy mass. The mass is preloaded by a stiff spring and the whole assembly is mounted in a metal housing with a thick base. When the accelerometer is subjected to vibration, the mass will exert a variable force on the piezoelectric discs. This force is exactly proportional to the acceleration of the mass. Due to the piezoelectric effect a variable potential will be developed across the two discs, which is proportional to the force and therefore to the acceleration of the mass. For frequencies much lower than the resonance frequency of the mass and the stiffness of the whole accelerometer system the acceleration of the mass will be virtually the same as the acceleration of the whole transducer, and the potential produced will therefore be proportional to the acceleration to which the transducer is subjected. This potential can be picked up from the output terminals of the accelerometer and used for determination of the vibration amplitude, waveform and frequency.
Although the accelerometer has been designed especially with multidirectional measurement in mind, it is also a versatile general purpose accelerometer which can successfully meet the requirements of most vibration laboratories.

*) Lead Zirconium Titanate.

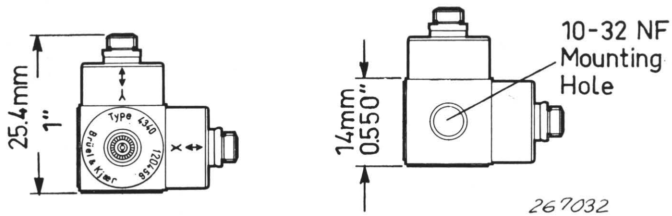


Fig. 1.2. Physical dimensions of the triaxial accelerometer.

Physical Dimensions.
It is generally true that an accelerometer should be as light as possible in order not to influence the vibration of the specimen on which it is mounted. For measurements on heavy machinery etc. this causes no problem but for lighter structures, such as for example a thin metal plate, the transducer weight is important.
The resonance frequency of a vibrating single degree of freedom system is

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m_0}}$$

where m_0 is the effective lumped mass and k is the lumped stiffness restraining the mass.
It is easily seen that adding another mass, e.g. an accelerometer, will result in a change in resonance frequency according to the formula

$$\frac{f_1}{f_0} = \sqrt{\frac{m_0}{m_1 + m_0}}$$

where f_1 is the new resonance frequency and m_1 is the added mass.
Thus any mass added to a vibrating structure will influence the vibration to some extent, but provided the added mass is small the influence is often negligible. A 10 % increase in mass will reduce the resonance frequency by about 5 %.
The sensitivity of a piezoelectric accelerometer is directly proportional to the mass acting on the piezoelectric disc. This limits the extent to which the accelerometer weight may be reduced without loosing too much of the sensitivity. For many applications it is also important that any strain developed in the material on which the accelerometer is fixed is not transmitted to the piezoelectric element as this would show up in the output signal, indicating an acceleration which actually is not present. It is therefore necessary to make the accelerometer base thick, in order to isolate the piezoelectric disc from such strain. The requirements to high sensitivity, low strain sensitivity

and good high frequency response are conflicting with requirements to small physical dimensions and weight, so that for general purpose accelerometers some useful compromise must be found.
The Triaxial Accelerometer Type 4340 has a titanium base and a total weight of 35 grammes (1.23 oz). Fig. 1.2 gives its physical dimensions.

Environmental Sensitivity.
Accelerometers are often used to measure vibration in the field or on specimens subjected to severe environmental tests. It is therefore important that their sensitivity to environmental changes is as small as possible. The factors that may influence accelerometer performance are primarily temperature, humidity and rapidly varying ambient pressure (Sound). The temperature effect is to reduce the voltage sensitivity of the accelerometer at higher temperature, but if the accelerometer has undergone a suitable temperature cycling process in the production stages, the sensitivity will revert to its normal value when the temperature is brought back to normal again. Beyond a certain temperature (the Curie point) the piezoelectric element is permanently damaged.

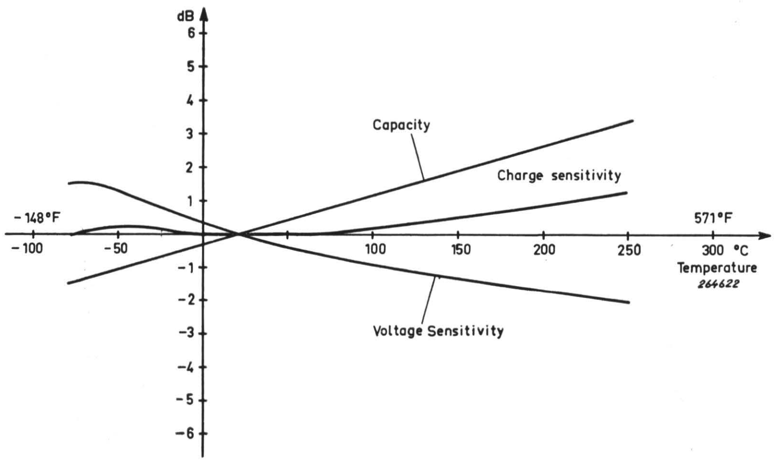


Fig. 1.3. Typical performance characteristics for the accelerometers in the temperature range −100 to +260°C.

The triaxial accelerometer Type 4340 is designed to be used for temperatures up to 260°C (500°F) without cooling. The sensitivity will be slightly reduced at the higher temperatures, but the necessary heat cycling process has been carried out, so that no permanent change will take place.

It should be noted that great care has been taken to use materials which will withstand high temperatures. The thermal coefficient of expansion of insulating material and metal parts are carefully matched in order to maintain humidity sealing.
It is, however, very difficult to guarantee a perfect seal for immersion in water when the accelerometers have been exposed to the high temperature limit. Therefore accelerometers which are to be used in liquids should not be exposed to more than 150°C for long periods of time.
The accelerometers are brought up to 250°C and left to cool down to about 50°C several times during production and calibration until performance is stable.
Tests have also been conducted in order to find the influence of low temperatures on accelerometer performance. The voltage sensitivity increases steadily down to some −100°C and then levels out, while the capacity undergoes a gradual decrease with decreasing temperature. The charge sensitivity is practically constant.
Typical performance characteristics are given in Fig. 1.3 for the temperature range −100 to +260°C (−150 to +500°F).

Cooling.
The Triaxial Accelerometer has provision for water cooling, so that it may be used for measurements on surfaces with temperatures up to 1000°C (1800°F) without seriously affecting performance.
Threaded connection tubes are supplied with the accelerometer for easy connection to a water supply. See Fig. 1.4.

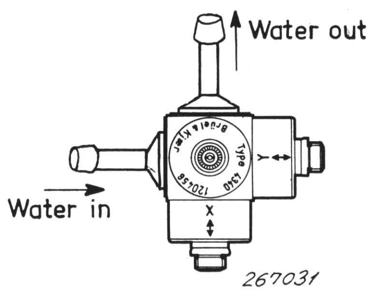


Fig. 1.4. Arrangement for water cooling of the accelerometer.

The water should preferably be supplied via silicon rubber tubes, such as the B & K Type AF 502, 3.8 mm (0.15") internal diameter. The amount of water necessary may be in the order of 1 to 20 litres per hour (1/4 to 5 gallons per hour).

It is also possible to reduce the temperature of the accelerometer base by inserting a cooling plate between the base and the measuring surface.
When a mica washer surch as the one included in the Accelerometer Set 4320 is used between the mounting surface and the cooling plate, experience has shown that temperatures up to 350–400°C may be measured on the mounting surface with less than 250°C in the accelerometer base.
A stream of air passing over the cooling plate considerably aids the cooling process.
For high temperature measurements one should always employ Teflon cable, B & K part No. AO 0038. The cable delivered with the accelerometer, B & K No. AO 0037 is based on Polyethylene and PVC which will not withstand more than 100°C. Also for low temperature measurements, from −40°C downwards, the Teflon cable should be employed.

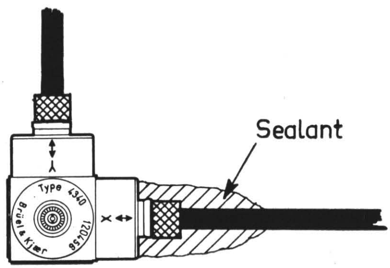


Fig. 1.5. Sealing of cable entry.

Vacuum Test.
The accelerometer is sealed and tested under water in a evacuated jar for leaks. This eliminates the risk of inferior performance in moist atmospheres or environmental test chambers where heavy condensation may take place.
When the accelerometers are used for measurements in liquids or in very moist environments it is necessary to seal the cable entry, as shown in Fig. 1.5.
A good sealant for the cable entry is for example Dow Corning Silastic RTV 731 (room temperature vulcanizing silicon rubber) or General Electric equivalent. These sealants show excellent performance for a wide temperature range, (−100 to +500°F).

Acoustical Sensitivity.
Effects due to acoustical excitation are unavoidable with piezoelectric accelerometers, but may be reduced by careful design. The B & K accelerometers are of a rigid, mechanically isolated construction and pressure variations in the air will have little effect on the force exerted on the piezo-

electric element. One may generally assume that the vibrations induced in the vibrating specimen will give rise to a much higher acceleration signal than the direct acoustical excitation of the accelerometer itself. In cases where very low accelerations are to be measured in an intense acoustic field however, care must be exercised in order to obtain correct results. Typical acoustic sensitivity for the accelerometers has been measured and found to be less than 0.2 μV/μbar, i.e. less than 0.2 μV for 74 dB sound pressure level. At 140 dB sound pressure level the output is less than 400 μV.

Magnetic Sensitivity.
The magnetic sensitivity has been found to be less than 2 μV/Gauss for the least favorable orientation of the accelerometer in the magnetic field.

Polarity.
The polarity of the accelerometer is such that an acceleration directed from the mounting surface into the body of the accelerometer results in a positive e.m.f. on the centre conductor of the output terminals.

Shock Performance.
In general the accelerometer will withstand shocks higher than 500 g and the output will be linear for shocks of this magnitude both in the positive and in the negative directions.

Effect of Mounting Torque.
The effect of mounting torque is less than 1 % change in sensitivity up to 5000 Hz for 6–60 kgcm (5 to 50 lb-in) mounting torque.

Long Term Stability.
A prime goal during design and manufacture has been to achieve maximum stability under severe environmental conditions. However, when an accelerometer is used for measurement under severe conditions of shock and heat, one should not rely on this as a primary standard. It would be advisable to recalibrate such an accelerometer at relatively short intervals of time.
A calibration vs. time history is closely followed for a number of representative units taken from production lots and they show less than 2 % change per year.

Piezoelectric Materials.
The quality of piezoelectric accelerometers depends largely upon the performance of the material used for the sensing elements. Monocrystalline materials such as quartz and Rochelle salt, have been used in the past, but are now superseded by polycrystalline, artificially polarized ceramics like barium titanate, lead zirconium titanate, lead metaniobate or similar materials.

Large variations in electrical and mechanical properties are obtained by small changes in composition, and most manufacturers are continuously investigating and improving their compositions in order to make them more suitable for their particular purposes.

The most important factors for general purpose accelerometers are Curie point, sensitivity, temperature stability, capacity, resistance and time stability. Unfortunately some of these are conflicting, high sensitivity for example, has often to be sacrified for good time or temperature stability.

In the table below are given some properties of commonly used ceramics as given by their manufacturers. The Curie point is the temperature at which the ceramic changes its crystal structure and looses its polarization, the piezoelectric constant indicates the sensitivity, and the dielectric constant indicates the capacity for a given shape and size. Trade names are used as the true composition of the ceramic is usually not disclosed by the manufacturer.

Manufacturer and Trade Name	Curie point °C	Piezoelectric Constant 10^{-12} Coul./Newt.	Dielectric Constant (Rel. Perm.)
Clevite Ceramic "B"	115	149	1300
Clevite PZT 4	325	285	1475
Quartz & Silice P 1-60	351	400	1500
Plessey Casonic Grade 3	120	83	1000
Quartz	300	2	4
B & K (1966)	350	300	1500

Natural Resonance Frequencies.

The natural resonance frequency of an accelerometer is not fixed. It depends not only upon the mass and stiffness of the accelerometer but also upon the mass (and stiffness) of the object on which it is mounted.

Some confusion persists as to what is the natural frequency and different definitions are seen.

The situation is best illustrated with a drawing. Fig. 1.6a shows a schematic drawing of an accelerometer which consists of several masses and springs connected in series. These springs are representations of the contact stiffness between the various parts of the accelerometer.

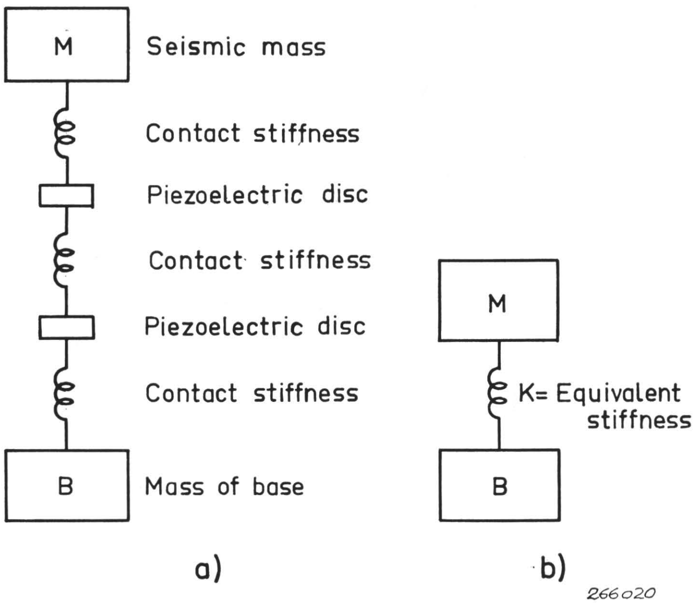


Fig. 1.6.
a. Schematic of accelerometer as a dynamic system.
b. Simplified system.

This mechanical system can be further simplified into that of Fig. 1.6b. Here M is the seismic mass resting on the piezoelectric element, B is the mass of the accelerometer base and housing. K is the equivalent stiffness of the system between M and B. The natural frequency of such a system is equal to

$$f_0 = f_M \sqrt{1 + \frac{M}{B}}$$

where f_M is the natural resonance frequency of the mass M upon the spring of stiffness K.

Now two resonance frequencies are easily thought of:

1. The *free hanging resonance frequency,* i.e. the resonance frequency obtained with the system freely suspended in air.
   This resonance frequency is entirely dependent upon the ratio of M and B, and it is seen that making the base B very light the resonance frequency may be very high. This resonance frequency is therefore of little practical value, in fact the higher it is compared with the mounted resonance frequency defined below the poorer is the mechanical construction of the transducer. (A thin base may cause bending of the piezoelectric due to strain from the mechanical part on which the vibration is measured).

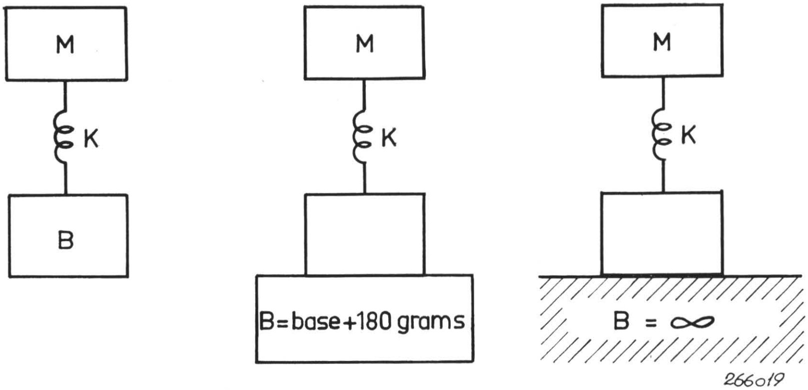


Fig. 1.7. Possible configurations for definition of natural resonance frequency.

2. The *mounted resonance frequency* with the accelerometer firmly fixed to a structure of infinite stiffness and mass.
   This results in a value for B of infinity and the resonance frequency is equal to f_M which is the natural resonance frequency of the mass M on the spring of stiffness K.
   This resonance frequency is of great practical value as it is approximately the one obtained when the accelerometer is mounted on a structure which is heavy compared with the accelerometer mass.

Unfortunately it is difficult to measure the mounted resonance frequency as defined above, since an infinitely heavy mass is hard to bring into motion. A compromise has therefore to be made and there are standards which define the mounted resonance as that obtained with the accelerometer mounted on a one inch cube of steel (Brüel & Kjær use a steel block of weight 180 gram). Such a block is easily set into controlled motion at frequencies up to some 50 kHz.
This mounted resonance may be used directly as a basis for vibration measurements as long as the accelerometer seismic mass is much smaller than the mass of the calibration mounting blocck. The natural frequency obtained is practically identical with the mounted resonance frequency on an infinite mass.
However when the accelerometer mass is large the natural frequency obtained will be too high, thus if B = 5 M we obtain

$$f_0 = f_M \sqrt{1 + 0.2} = 1.1\ f_M$$

i.e. a value which is 10 % high.
For the Brüel & Kjær acccelerometers the ratio of weights of the seismic mass to the weight of the base is about 1 : 1 and therefore the free hanging

resonance will be about 1.5 times the mounted resonance and the resonance obtained on the 180 grams block of steel is 2–4 % higher than that which would be obtained on an infinite mass.

A small difference in resonance frequency is obtained by considering the damping present in the accelerometer. Thus *undamped natural frequency* is defined as the frequency at which the difference between the motion of the mass and base lags the motion of the base by a phase of 90°, whereas *damped natural frequency* is the frequency of decaying oscillations after an initial excitation. The difference is negligible for high Q piezoelectric accelerometers such as the ones manufactured by Brüel & Kjær.

The *undamped natural frequency* given on the B & K accelerometer calibration charts is the free hanging undamped natural frequency.

2. Factory Calibration

Each individual accelerometer has before leaving the factory undergone a very thorough ageing, testing and calibration procedure to ensure the user of a high quality product. It is supplied with three individual calibration charts giving a complete set of data for each measuring direction.
Typical calibration charts as supplied with the accelerometer is shown in Fig. 2.1.

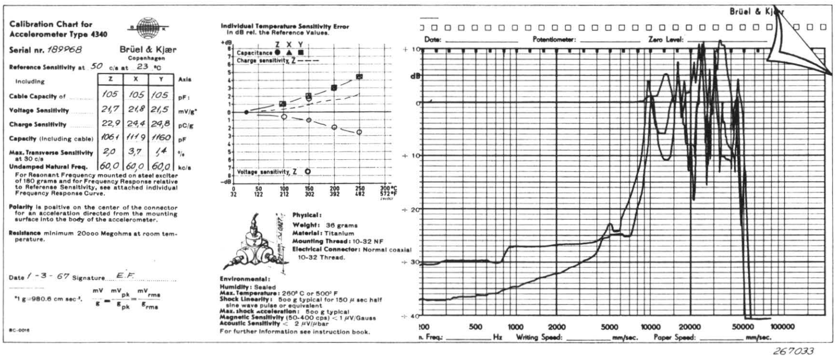


Fig. 2.1. Typical calibration charts.

Cable Capacity.

The capacitance of the accelerometers are given including the capacitance of the ordinary B & K connecting cable, so that when other cables are used, the change in cable capacitance must be taken into account, as this determines the effective sensitivity of the accelerometer. To find the capacitance of the accelerometer alone, deduct the cable capacitance given on the calibration chart. The standard length of cable included is 1.2 m (4 ft).
The capacity of the 1.2 m cable is around 105 pF (micromicrofarad) but the individual value is given on the calibration chart.

Voltage Sensitivity.

The voltage sensitivity of the accelerometers with connecting cable is determined at a frequency of 50 Hz and at room temperature (appr. 20° C).
Fig. 2.2 shows the instrumentation employed.

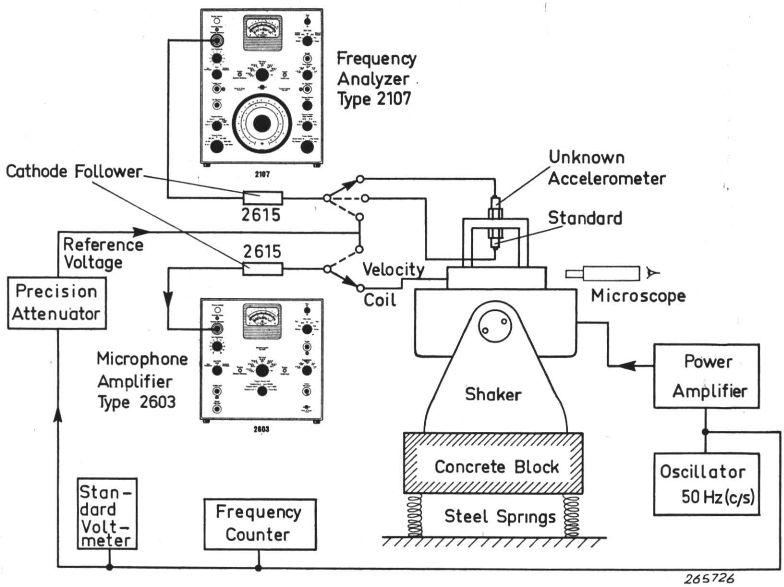


Fig. 2.2. Set-up used for calibration of absolute sensitivity of the accelerometers.

The accelerometers are calibrated at 50 Hz, the frequency being monitored by a crystal controlled electronic counter, and the periodic time of the vibration is kept within 200,000 ± 100 μsec. Thus the frequency accuracy is ± 0.05 %. The shaker providing the mechanical excitation is mounted on a large concrete block which is supported by steel springs, giving the whole assembly a natural resonance frequency of about 1 Hz. This ensures isolation from background vibration.

The calibration of all units is achieved by comparison between a standard accelerometer and the unknown in a back to back mounting as shown in Fig. 2.2. The standard is frequently checked with a microscope observing the displacement directly, with an accuracy of ± 1 %.

The distortion in actual vibration units is kept below 2 % and max. influence on peak to peak amplitude below 0.5 %.

The output from the accelerometer is measured with a B & K Frequency Aanalyzer set to 50 Hz and calibrated with a reference voltage of exactly the same frequency as the signal to the shaker, giving a total voltage measuring accuracy of ± 0.15 %.

The total accuracy on the sensitivity calibration of the accelerometers is thus better than ± 2 %.

The calibration vs. time history is closely followed for a number of representative units taken from production and they show less than 2 % change per year.
Note that the calibration is valid for the accelerometer with its individual connecting cables, and remember to take any change of cable capacitance into account when different cables are employed.
Also the input capacity of the preamplifier must be taken into account. The influence of this capacity in the calibration set-up is eliminated with a substitution measurement. In practice the capacity will be less than 10 pF using a normal B & K amplifier and plug such as B & K Cathode Follower Type 2615, Source Follower 2616 or 4 pF in the case of preamplifier 2623.
Note also the units employed in the calibration. The sensitivity is given in $mV/g = mV_{RMS}/g_{RMS} = mV_{peak}/g_{peak}$. If, for example, the sensitivity is required in mV_{RMS}/g_{peak} the sensitivity given should be multiplied by 0.707.

Charge Sensitivity.
This sensitivity is calculated from the voltage sensitivity and the equivalent capacitance of the accelerometer with normal connecting cable.
Charge sensitivity is expressed in pico-coulomb/g and is independent upon the capacitive loading on the accelerometer. It is determined by multiplying the voltage sensitivity with the total capacity used in the calibration, i.e. capacity of transducer and cable.

$$S_{charge} = S_{voltage} (C_a + C_c)$$

where C_a = accelerometer capacity and C_c = Cable capacity.
Since the voltage sensitivity is given as mV/g the charge sensitivity will be in pico-Coulomb/g or pico-$Coulomb_{peak}/g_{peak}$.

Capacity.
The capacity of the accelerometer is given for each direction including the cable capacity as specified on the calibration sheet. Accelerometer capacity comes into the question when the low frequency cut-off of the measuring system is computed, as it determines the effect of loading on the accelerometer.
The capacity is measured at 1000 Hz in a capacitance bridge, comparing with a standard capacity equal to the nominal capacity of the accelerometers. Accuracy ± 0.5 %.

Transverse Sensitivity.
Transverse sensitivity is the maximum sensitivity to a transverse acceleration expressed in percent of the reference sensitivity in the intended measuring direction.

The transverse sensitivity of the accelerometers is primarily due to irregularities in the ceramics, and limitations in the mechanical coupling between ceramic and metal parts. Careful mechanical machining helps to minimize transverse sensitivity.
Transverse sensitivity can be regarded as a result of the particular axis of the accelerometer making a small angle with the direction of the maximum sensitivity as shown in Fig. 2.3.

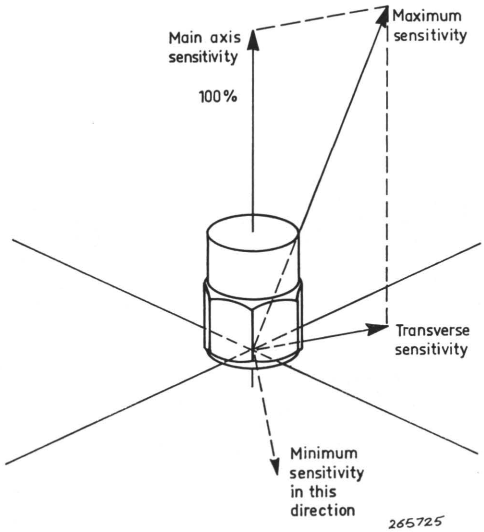


Fig. 2.3. Graphical illustration of transverse sensitivity.

Imagining the accelerometer placed in a rectangular coordinate system, as shown, the vector representing the maximum sensitivity can be resolved into two components: the main axis sensitivity which is the one called voltage or charge sensitivity on the calibration chart, and the transverse sensitivity given on the calibration chart as a percentage of the main axis sensitivity.
The voltage obtained from an accelerometer is a product of the acceleration vector and the component of the sensitivity in the same direction, so that in a certain transverse direction, at right angles to both the main axis and the max. transverse sensitivity axis the accelerometer output will be minimum.
In order to maintain a low transverse sensitivity the user should always mount the accelerometer on a flat, clean surface and keep the accelerometer mounting surface free from burrs and scratches. Also he should avoid very large shocks, such as might be caused by dropping the accelerometer on the floor, and large temperature shocks.

If the accelerometer is properly handled and mounted, the transverse sensitivity will normally be below 4 % up to 5000 Hz. Above 5000 Hz it is very difficult to establish useful test facilities for transverse measurements. The type of mounting of the accelerometer will, however, undoubtedly set a limit to the good performance of the accelerometer in the transverse direction at a frequency somewhat lower than that for operation in the main direction.

The transverse sensitivity for each axis of the accelerometer is specified as being less than 4 % of the sensitivity. However, the individual maximum transverse sensitivity is given on the calibration chart.

In the factory calibration the transverse sensitivity is measured at approximately 30 Hz on a rotating table whose motion sideways is more than 100 times larger than the motion in the vertical direction. See Fig. 2.4.

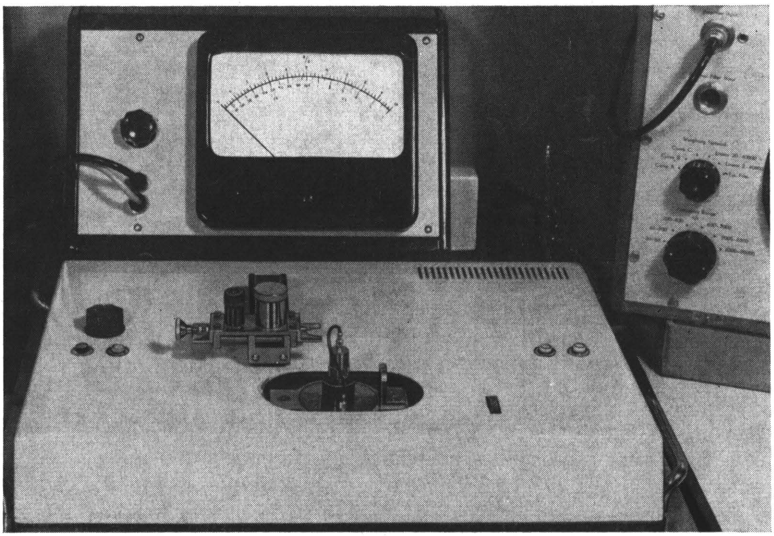


Fig. 2.4. Part of the arrangement for obtaining transverse sensitivity.

The accelerometer is first mounted with its main axis parallel to the direction of motion of the table and the deflection on the meter is adjusted to a reference mark (100 %). Then the accelerometer is mounted with its main axis at right angles to the motion and the table is rotated slowly. The meter is set to indicate full scale deflection for 10 % transverse sensitivity and the maximum value is noted.

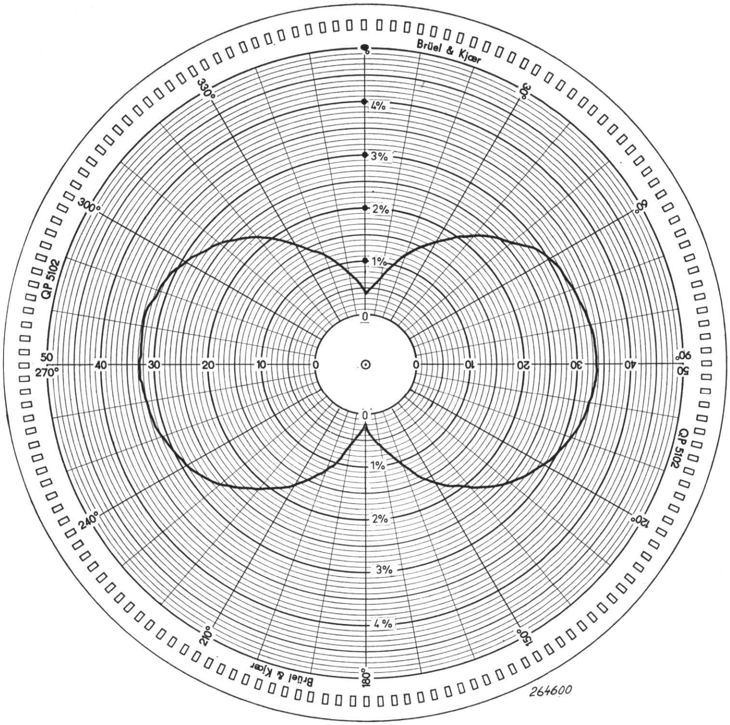


Fig. 2.5. Typical transverse sensitivity curve for the accelerometers.

The factory calibration of transverse sensitivity is carried out after 24 hours of storage at room temperature.

Fig. 2.5 gives a typical sensitivity pattern as recorded with a B & K Level Recorder Type 2305.

Undamped Natural Frequency.

The undamped natural frequency is the frequency at which the motion of the seismic mass element lags 90° behind the motion of the accelerometer housing.

The damping ratio, which is the ratio between the actual damping of the accelerometer and the damping for which the system would be critically damped, is very low: in the order of 0.02. Therefore the damped natural frequency, f_d, is nearly identical to the undamped natural frequency, f_u, since

$$f_d = f_u \sqrt{1 - 0.02^2}$$

The undamped natural frequency is measured electrically by finding the lowest frequency at which the 90° phase shift occurs when an electrical signal is applied to the terminals in series with a 1000 pF capacitor, and with the accelerometer freely suspended in air.

The mounted resonance frequency is the frequency at which the sensitivity of the pick-up is a maximum when mounted on a stainless steel block of approximately 180 grammes. In practice one may consider the mounted resonance as given on the calibration chart as being more useful than the undamped natural frequency. The mounted resonance will depend upon the mass of the structure on which the accelerometer is mounted, and upon the compliance of the contact between the accelerometer and the structure. As the mounted resonance given is obtained under actual operating conditions with the best possible contact between the accelerometer and the vibrating steel block this resonance can be taken as a practical upper limit. In practice the mounting will generally be less effective and a lower resonance frequency is obtained. See chapter on mounting techniques.

Frequency Response Curve.

Individual frequency response curves are supplied with each accelerometer. These are taken with the transducer mounted on a steel block of weight 180 grammes and with a plane mounting surface.

The instrumentation employed is similar to the set-up described in chapter "Calibration" and is based upon the B & K Calibration Exciter Type 4290.

In actual practice such a frequency response is to be expected from the accelerometer, provided the method of fixing to the vibrating specimen is satisfactory. It is generally accepted that the piezoelectric transducer may be used for frequencies up to about 1/3 of the resonance frequency shown by this curve for less than 1 dB error, or to 1/5 of the resonance frequency for less than 5 % error, but poor mounting methods will lower the resonance frequency and therefore also lower the upper frequency limit of the operating range.

The error at any frequency can be easily calculated from the formula for the relationship between the relative displacement of the mass spring system to the displacement of the base, viz.

$$\frac{\text{Relative Displacement of Mass-spring}}{\text{Displacement of base}} = \left| \frac{1}{1 - \left(\frac{\omega}{\omega_o}\right)^2} \right|$$

where

$\omega = 2\pi \times$ forcing frequency and

$\omega_o = 2\pi \times$ undamped natural frequency.

From this equation it may be seen that at 1/3 the resonance frequency the error will be 1 dB and at 1/5 the resonance frequency the error will be about 0.5 dB.

Temperature Sensitivity.

Changes in accelerometer capacitance, charge sensitivity and voltage sensitivity with temperature are given for the range 20–250°C (70–480°F) with reference to the values given at room temperature.

These are individual values obtained while heating the accelerometers to the appropriate temperatures, reaching a steady temperature before measurement is taken.

The information is given in curve form so that interpolation can be readily performed.

When an accelerometer is used as a voltage generator, the transducer output in mV/g will depend upon the temperature of the piezoelectric and on the external loading. The calibration curve given is valid for the accelerometer with 1.2 m cable and thus for a capacitive loading of about 105 pF. Any change in loading capacity will change the voltage sensitivity variation with temperature. It may therefore be possible to optimize the voltage sensitivity versus temperature characteristic.

The leakage resistance may also vary and alter the low frequency response. This effect is, however, negligible for the B & K accelerometers, since the leakage resistance is larger than 20,000 Mohm for all temperatures in the operating range.

Charge amplifiers eliminate any influence of parallel capacity on the charge sensitivity versus temperature curve. Only series capacity should be considered, if present.

Considering the accelerometer as a charge generator it is easily seen from Fig. 2.6 that the voltage sensitivity at any temperature with any amount of cable capacity is

$$E_t = \frac{Q_t}{C_t}$$

where

E_t = voltage sensitivity at temperature t

Q_t = charge sensitivity at temperature t

C_t = total capacity in the circuit at temperature t.

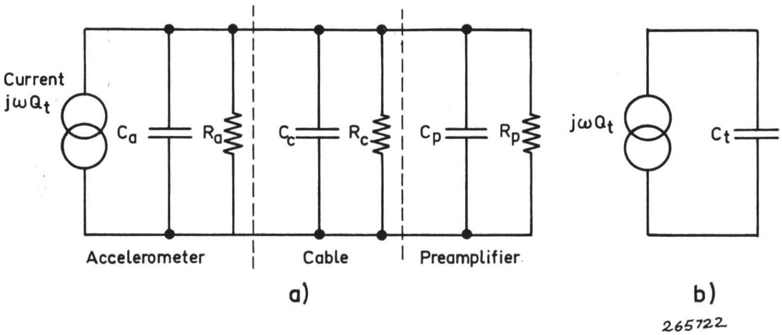


Fig. 2.6.
a) Equivalent circuit for accelerometer and preamplifier input.
b) The same circuit simplified for normal operating frequency range.

Now, the increase in charge sensitivity is given on the calibration chart in dB, so that knowing the charge sensitivity at room temperature the charge sensitivity at temperature t is easily found by using the conversion table for dB to ratio given in the appendix.

C_t is also easily found when the capacity external to the accelerometer is known. The increase in accelerometer capacity with temperature is given on the calibration chart, as well as the capacity at room temperature.

Therefore

$$Q_t = Q_o \times K_Q$$
$$C_t = C_a \times K_c + C_{ext} - C_c$$

where

Q_o = charge sensitivity at room temperature
K_Q = charge sensitivity factor
C_a = capacity of accelerometer plus associated cable (1.2 m) at room temperature
K_c = capacity factor
C_{ext} = total capacity external to the accelerometer (long cable plus preamplifier)
C_c = capacity of accelerometer cable used during factory calibration (1.2 m)

Then we have

$$E_t = \frac{Q_t}{C_t} = \frac{Q_o \times K_Q}{C_a \times K_c + C_{ext} - C_c}$$

Example:
What is the voltage sensitivity of the accelerometer with the curves shown in Fig. 2.7 at a temperature of 250°C and with a total external capacity (long cable plus preamplifier) of 1000 pF.

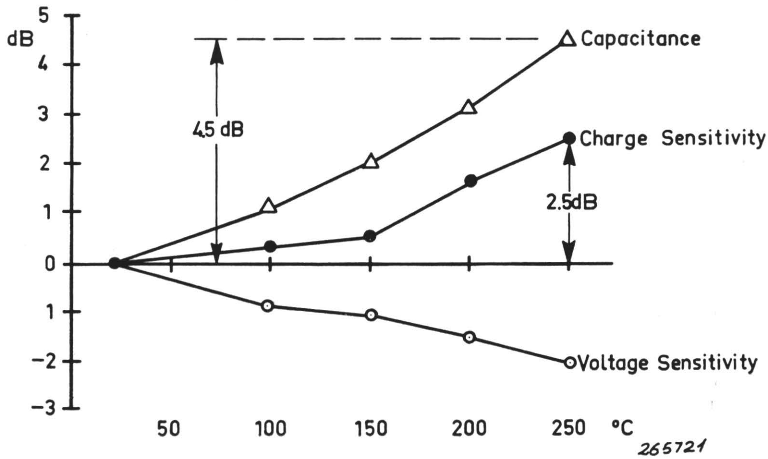


Fig. 2.7. Temperature sensitivity curves from a calibration chart.

Solution:

From the calibration chart we find

$$Q_o = 51.2 \text{ pCoulomb/g}$$
$$K_q = 2.5 \text{ dB} = 1.33$$
$$C_a = 1020 \text{ pF}$$
$$K_c = 4.5 \text{ dB} = 1.68$$
$$C_c = 106 \text{ pF}$$

Then the voltage sensitivity at 250° C

$$E_{250} = \frac{51.2 \times 1.33}{1020 \times 1.68 + 1000 - 106} = 0.026 \text{ V/g}$$
$$E_{250} = 26 \text{ mV/g}$$

Calibration Accuracy.

The accuracy of the above factory calibrations is better than ± 2 % for charge sensitivity, voltage sensitivity and capacity. The transverse sensitivity may change temporarily when the accelerometer is exposed to large shocks, especially sideways. Normally, however, it will return to the original value within the next 24 hours.

3. Mounting Methods

A proper mounting of the accelerometer to the specimen is of utmost importance especially when measurements are taken at higher frequencies. The frequency response curves given on the calibration chart is for the best possible mounting of the accelerometer. (Screwed tightly with a steel stud onto a polished metal surface). When other methods are used the resonance frequency will generally be lower. How much lower will be determined by the mass of the accelerometer and the stiffness of the mounting.

Mounting Thread.

The mounting thread used for the accelerometers Type 4340 and accessories is NF 10-32, both for fixing the accelerometer to the specimen and for the cable connection. Relevant data for the thread:

32 threads per inch.
Outside diameter 4.826 mm (0.19")
Drill size for tapping 4.1 mm

If a metric thread is preferred the 10-32 NF thread in the accelerometer may easily be changed to 5 mm by using an M5 × 0.8 standard hand tap with flat tip. The M5 × 0.8 thread is very close to the NF 10-32 thread in dimensions, the diameter being 5 mm (0.197") compared with 4.826 mm (0.190") and the pitch being 0.8 or 31.8 threads per inch compared with 0.794 or 32 threads per inch. Thus all the normal accessories may be used even when the thread has been modified to M5 × 0.8.

Tests have been carried out using NF 10-32 brass screws in M5 thread fixing 30 gramme accelerometers with up to 5000 g shocks applied. No difference was noted between this type of mounting and the ordinary steel studs with matching thread. The shocks were applied in the negative direction, i.e. lifting the accelerometer from the specimen.

There are several methods available for fixing the accelerometer to the specimen on which the vibration is to be measured. The following accessories for fixing purposes are included in the Accelerometer Sets Type 4320:

10-32 NF threaded stud and nut
10-32 NF electrically isolated stud
Cementing stud
Wax
Mica washers for electric isolation of transducer
10-32 NF screw tap

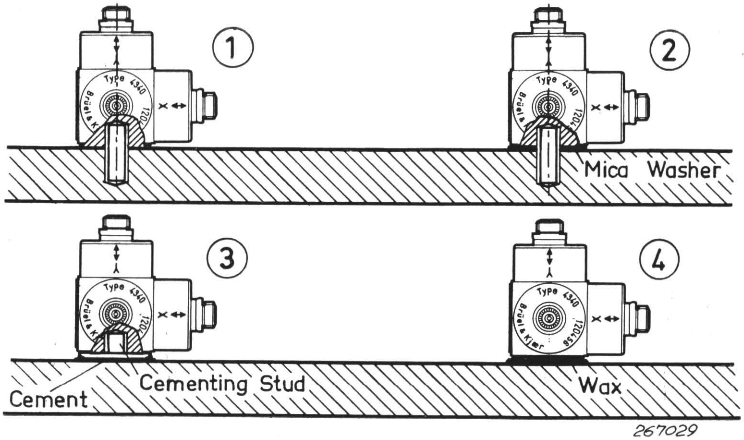


Fig. 3.1. Different ways of mounting the accelerometers.
1. *With steel stud.*
2. *With isolated stud and mica washer.*
3. *With cementing stud.*
4. *Accelerometer stuck on with wax.*

The possible ways of applying the accelerometer to the vibrating specimen are depicted in Fig. 3.1.

Type 1 mounting is the best solution frequency response wise, approaching a condition corresponding to the actual calibration curve supplied with the accelerometer. If the mounting surface is not quite smooth it is a good idea to apply a thin layer of silicon grease to the surface before screwing down the accelerometer. This increases the mounting stiffness.

Type 2 mounting is convenient when electrical isolation between accelerometer and vibrating body is necessary. It employs the isolated stud and a thin mica washer. Frequency response is good due to the hardness of the mica. Make sure that the washer is as thin as possible. (It can easily be split up into thinner layers). The maximum torque used for mounting the accelerometer should not exceed 18 kgcm (15 lb-in).

Type 3 mounting is used when a cementing technique is desirable, while at the same time the accelerometer may be removed and replaced at any time. If an electrically isolating cement is used, the accelerometer is effectively isolated from the specimen.

Type 4 mounting employs a thin layer of wax for sticking the accelerometer onto the vibrating surface. The wax is delivered with the Accelerometer Sets. A frequency response curve is given in Fig. 3.2. It is seen that this method of mounting gives a very good frequency response due to the stiffness of the wax. At higher temperatures this will decrease.

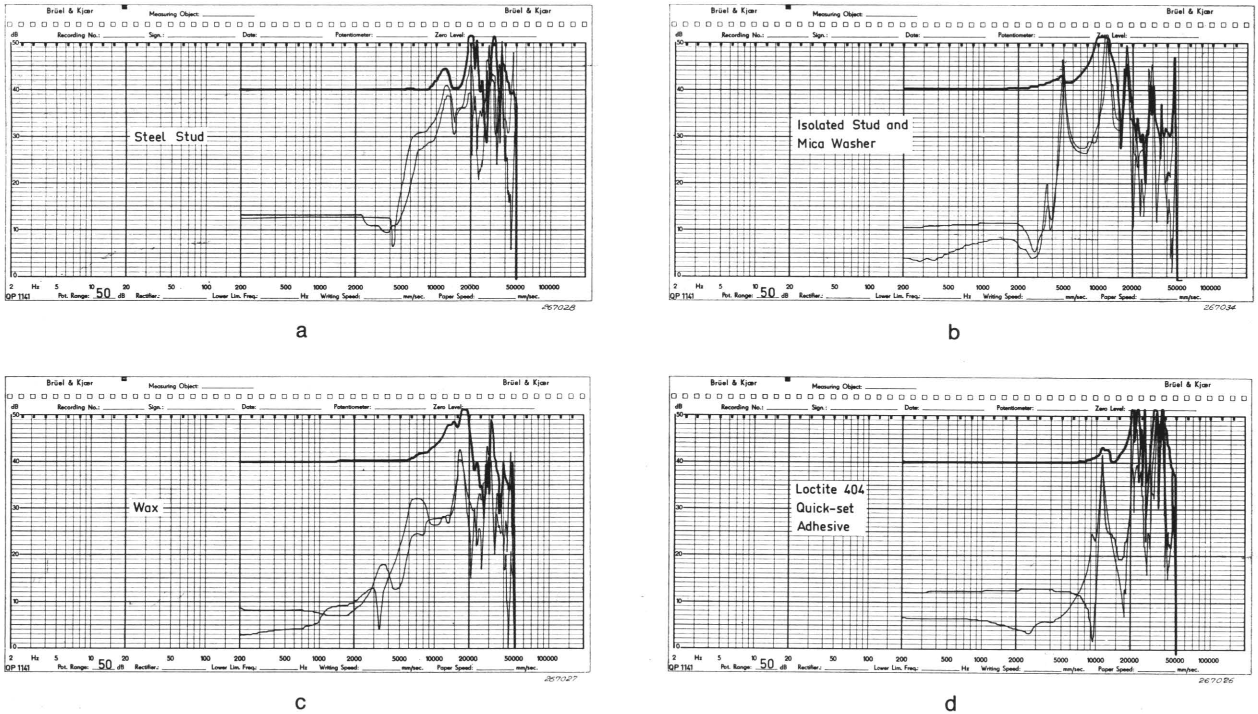


Fig. 3.2. Frequency response of an accelerometer for various types of mounting.

a) Steel stud. *b) Isolated stud.*
c) Wax. *d) Quick-set adhesive.*

Soft setting glues or gum should be avoided because of decoupling and bad frequency response.
For minimum weight and optimum performance of the mounting one may also recommend the Eastman 910 cement, marketed by the Armstrong Industry, or Tixo K-1 manufactured by Tiox-Tinten und Klebstoffwerk G.m.b.H., Vienna. Dental cement and epoxy resins are also very useful, especially in connection with the cementing stud which is intended for use in applications where mounting by cementing techniques is preferred, while retaining the possibility of removing the accelerometer itself.
Fig. 3.2 shows some frequency response curves obtained for various types of mounting. The importance of the mounting method used should be obvious.
The mounting torque for threaded screws should be around 18 kgcm or 15 lb-in. The accelerometers are not harmed by a larger torque, but the isolated stud may not stand more than 30 lb-in. A mounting torque of the correct value is applied with a 10 cm (4") spanner with normal pressure on the handle. A 6" or larger spanner should be used with care. If a smaller spanner is used one cannot do any harm to the thread, but the accelerometer may not be sufficiently well secured.

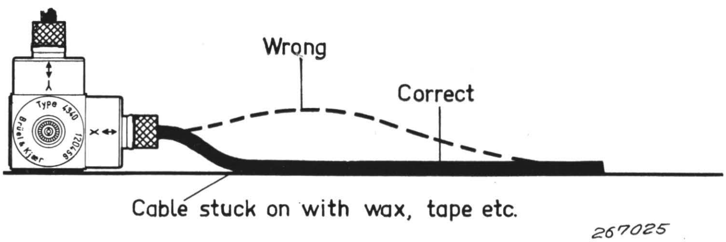


Fig. 3.3. Clamping of the cable to the vibrating specimen.

Always fix the accelerometer to the specimen in the best possible way, and make sure that no resonances of the mounting will influence the measurement being taken. At low frequencies this presents no problem but for frequencies above 2–3000 Hz it may be difficult to obtain a satisfactory mounting.
It is also important to make sure that there is a minimum of noise from the connecting cable due to bending or cable whip. The B & K accelerometer cables are specially designed and treated for minimum noise output, but it is always good policy to clamp the cables as firmly as possible to the specimen as shown in Fig. 3.3.

4. Measuring Systems

Basic System.

An accelerometer always works in connection with amplifiers and indicating instruments in order that the signal on the output terminals can be of some use to the operator. The measuring system consists of the following parts:

Accelerometer
Preamplifier
Integrating networks
Amplifier
Filter network
Indicating device.

Preamplifiers.

Preamplifiers are used for conversion of the rather weak transducer signal into a stronger signal which can be handled by the succeeding storage or read-out equipment. The signal from the piezo-electric accelerometer appears as a charge across a capacitive impedance. The charge generated is proportional to the acceleration.

We have the choice of making the total capacity in the circuit as small as possible and thus obtain the highest possible voltage into the preamplifier, or to load the accelerometer so heavily with a shunt capacity that we have a system independent of small changes in cable capacity due to different lengths of cable. The first solution is called a voltage amplifier and the second a charge amplifier.

Voltage Preamplifiers.

When used as a voltage source the accelerometer must be loaded by an extremely high impedance in order to retain its sensitivity versus frequency characteristic. Capacitive loading reduces the sensitivity over the whole frequency range, while conductive loading reduces the sensitivity at low frequencies. This can be seen from the following:

The equivalent circut of an accelerometer with external loading is drawn in Fig. 4.1.

Q = charge induced across the accelerometer capacitive element
S_q = charge sensitivity of the accelerometer (Coulomb/g)
A = acceleration to which the accelerometer is subjected (g)
C = total capacity in the circuit, including accelerometer, cable and preamplifier
R = $1/G$ where G is the total conductance in the circuit, including accelerometer, cable and preamplifier.

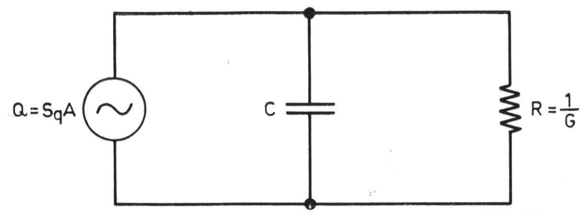


Fig. 4.1. Equivalent circuit of accelerometer with external loading.

Assuming a sinusoidal acceleration of angular frequency ω we have the current flowing in the circuit

$$I = j\omega Q$$

and the voltage output

$$E = \frac{I}{G + j\omega C} = \frac{j\omega Q}{G + j\omega C} \qquad (1)$$

This shows that when $G \ll j\omega C$, i.e. when the shunt resistance in the circuit is very high or at high frequencies the output voltage depends only upon the capacitive loading:

$$E = \frac{j\omega Q}{j\omega C} = \frac{Q}{C}$$

It is also seen that the output is directly proportional to 1/C. This must be taken into account when long accelerometer cables are employed.
From equation (1) it can also be seen that when $G \gg j\omega C$, i.e. for low frequencies or for low shunt resistance the output is frequency dependent:

$$E = \frac{j\omega Q}{G} = j\omega RQ$$

This means that the output falls off at the same rate as the frequency at the low frequency end. The corner frequency, where the output is 3 dB down, is where $/ G / = / j\omega C /$

$$\text{i.e.} \qquad f_c = \frac{1}{2\,\pi\,RC}$$

where f_c is called the "cut-off frequency". A graph giving the relative output as a function of frequency, capacity and resistance is given in Fig. 4.2.

Example:

Find the required input impedance for a 1 dB cut-off at 1 Hz using an accelerometer with capacity 1000 pF.

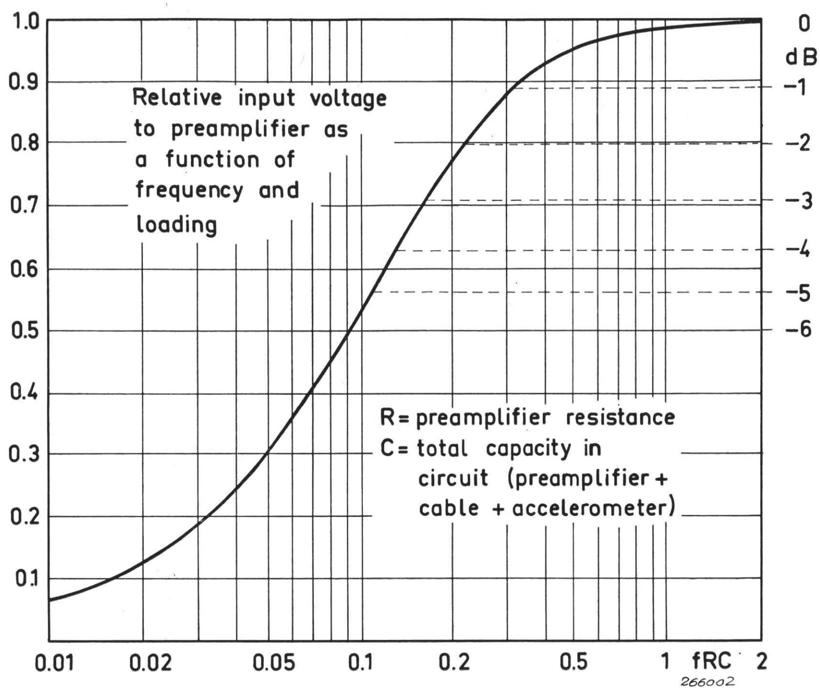


Fig. 4.2. Low frequency cut-off of an input circuit as a function of frequency, capacity and resistance.

Solution:

A 1 dB cut-off gives from the graph an fRC product of about 0.32, i.e.

$$fRC = 0.32$$

$$R = \frac{0.32}{1 \times 1000 \times 10^{-12}} = 320 \text{ Mohm}$$

The required input impedance is 320 Mohm.

The internal resistance of the accelerometer is extremely high, always exceeding 20.000 Mohm at room temperature (~20°C). The resistance of the piezoelectric material is lower at high temperatures but usually still higher than 20.000 Mohm at 250°C. This large resistance gives a low frequency cut-off value of 0.008 Hz for the accelerometer alone and thus makes measurement possible down to practically DC with specially designed amplifiers.

Cable Capacitance Sensitivity Correction.

The capacity of the cable connecting the accelerometer to the preamplifier will reduce the voltage sensitivity of the accelerometer. Looking at the expression above, it is seen that E is proportional to Q/C. Therefore, when the

cable capatitance becomes significant, due to for example long connection cables, a sensitivity correction is necessary.
When, as in the case of the B & K accelerometers, the charge sensitivity is given, the voltage sensitivity of any combination of accelerometer, cable capacity and preamplifier impedance is found simply by dividing the charge sensitivity by the total shunt capacity in the circuit, i.e. accelerometer, cable and preamplifier capacities all added in parallel.

Example:

Figures from the accelerometer calibration chart:
Charge Sensitivity: 20 p Coulomb/g
Capacity (incl. cable): 1100 pF
Cable Capacity: 100 pF
Find the voltage sensitivity with a new cable of capacity 400 pF. Preamplifier capacity negligible.

Solution:

Accelerometer Capacity = 1100 − 100 = 1000 pF
Total capacity = 1000 + 400 = 1400 pF

$$\text{Voltage sensitivity} = \frac{20}{1400} = 0.0143 \text{ V/g} = 14.3 \text{ mV/g}$$

The capacity of the ordinary B & K accelerometer cable is approximately 90 pF/m (27 pF/ft), so that knowing the cable length, the voltage sensitivity can be calculated with a good degree of accuracy.
Note: When charge amplifiers are employed no correction for cable capacitance is normally necessary.

Charge Amplifiers.
The charge amplifier is gaining widespread acceptance mainly because of its simplicity of operation. It eliminates the effect of shunt capacity in the input circuit, so that the operator can work without attention to variable accelerometer cable lengths. The only information required is the charge sensitivity of the accelerometer.
An equivalent circuit diagram for accelerometer, cable and charge preamplifier is given in Fig. 4.3. By some calculation it is found that the output voltage is

$$E_o = \frac{Q}{\frac{C_a + C_c}{A} - C_f\left(1 - \frac{1}{A}\right)} = \frac{QA}{C_a + C_c - C_f(A-1)}$$

which means that as long as $C_f\ (A - 1) \gg C_a + C_c$ the output voltage is $-QA/C_f\ (A - 1)$ independent upon cable capacity.

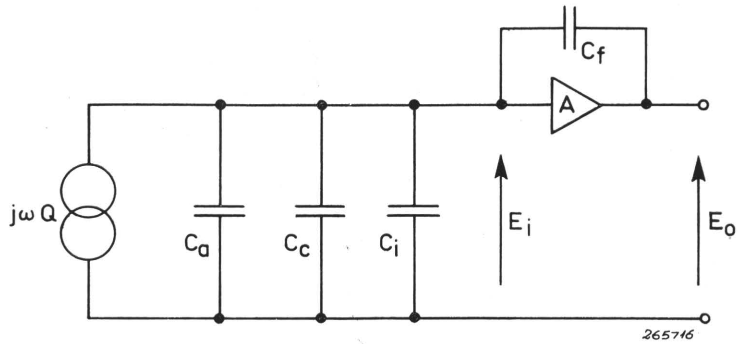


Fig. 4.3. Equivalent circuit of accelerometer, cable and charge preamplifier.

A representative amplification factor may be A = 1000 and C_a for the Triaxial Accelerometer is about 1000 pF. This means that as long as the cable capacity is small compared with 999,000 pF, the output voltage is not affected. 1000 pF is roughly equivalent to 10 m (30 ft) of accelerometer cable, so that 100 m cable will only result in about 1 % change in sensitivity. With a voltage amplifier such a cable capacity would have reduced the sensitivity by about 90 %.
Note that the charge sensitivity of piezoelectric accelerometers does in general change with temperature. An individual charge sensitivity versus temperature curve is therefore supplied with each B & K accelerometer, covering the range 20–250°C (70–480°F).

Brüel & Kjær Measuring Systems.
In the Brüel & Kjær systems the amplifier, filter network and indicating device are often contained in one instrument. A block diagram of possible instrument combinations from the B & K program is given in Fig. 4.4.
Preamplifier. Brüel & Kjær produce several types of preamplifier for use with the accelerometer in vibration measuring set-ups. These include:

1. Cathode followers (several types)
2. Preamplifier Type 1606
3. Preamplifier Type 2622
4. Battery Driven Preamplifier Type 2623.
5. Battery Driven Preamplifier Type 2616

1. The microphone cathode followers fitted with input adaptors are excellent preamplifiers for the accelerometers when the measurement is one of acceleration only. Type 2615 is recommended. It has an input impedance of 700 Mohm in parallel with 3 pF which gives a low-frequency cut-off of approximately 0.2 Hz. The low-frequency cut-off

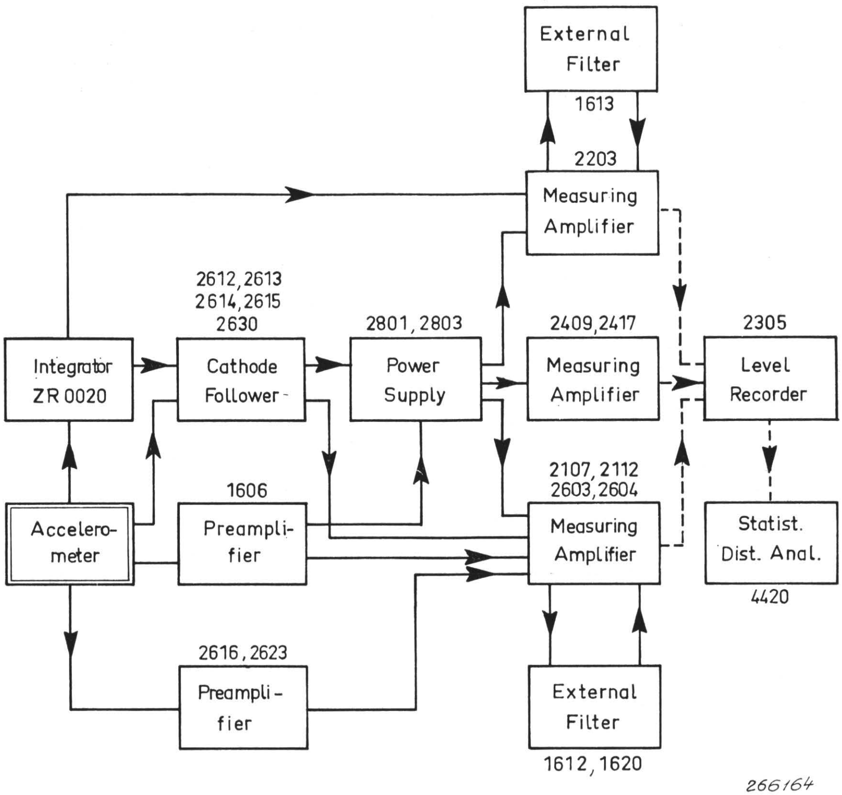


Fig. 4.4. Possible instrument combinations for vibration measurement and analysis. Each path, following the arrows from the accelerometer, gives a feasible system.

of the system will therefore usually be determined by the following instruments. The cathode follower attenuation is approximately 0.9 dB. The Integrator ZR 0020 may be screwed directly onto the 1" cathode followers, so that measurement of velocity and displacement may be carried out in addition to acceleration. See description below.

2. The Preamplifier Type 1606 is especially designed for vibration measurements. It contains integrating networks for measurement of velocity or displacement as well as acceleration. The gain is variable from 0 to about 38 dB and the input impedance is 200 Mohm in parallel with some 50 pF. The low-frequency limit is lower than 2 Hz for zero gain of the amplifier. A small shaker table on the preamplifier may be used to calibrate the whole vibration measuring set-up at a vibration

level of 1 g peak (= 980.6 cm/sec² peak). The preamplifier is powered from the microphone input socket of one of the B & K microphone amplifiers or analyzers.

3. The Preamplifier Type 2622 is designed especially for use in vibration test set-ups in connection with other B & K vibration generators and control equipment, but may equally well be used on its own as an ordinary accelerometer preamplifier. It is a two-channel instrument which can be used either as a voltage or as a charge amplifier. Each channel has a three-decade attenuator which is set to the voltage or charge sensitivity of the accelerometer in use, within the range 10–100 mV/g or 10–100 pCoulomb/g. The output signal is then scaled to 10 mV/g.
   The lower limiting frequency can be chosen as 2–5–10 or 50 Hz. Apart from the two outputs there is a third output which can be automatically switched between the two channels, used for example for changing between two control accelerometers on a shaker table.
4. The Preamplifier Type 2623 is an impedance conversion device of an extremely small and rugged construction. See Fig. 4.5.
   An extremely high input impedance has been achieved through the use of a "field effect" transistor in the input circuit. The preamplifier is designed to withstand severe environmental conditions and its sensitivity to vibration is extremely small.

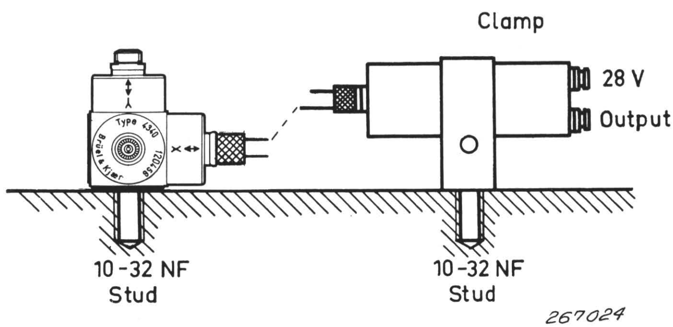


Fig. 4.5. The Preamplifier Type 2623 clamped near to the accelerometer.

Special features:

Input impedance:	Min. 2000 Mohm at 25°C
	Min. 200 Mohm at 100°C
	3.5 pF, typical
Output resistance:	40 ohm
Voltage gain:	0 ± 0.05 dB
Frequency range:	0.5–500.000 Hz
Noise:	Max. 15 μV, 2–40000 Hz for 1000 pF across input

Output voltage:	Max. 20 V peak-peak
Rise time:	$< 10\ \mu$sec.
Recovery time:	$< 50\ \mu$sec.
Dimensions:	45 mm × 14 mm dia. (1.77″ × 0.55″ dia.)
Weight:	20.6 grammes

5. The Preamplifier Type 2616 is a battery driven three-stage transistorized impedance conversion device, suitable for use with high impedance transducers. Due to its small size it can be placed close to the accelerometer, thus minimizing sensitivity loss and noise from the connecting cable. See Fig. 4.6.

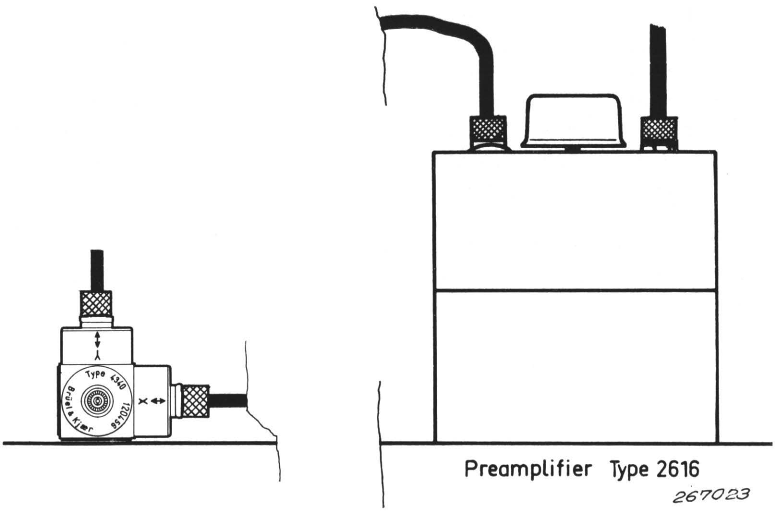


Fig. 4.6. The battery driven Preamplifier Type 2616.

The preamplifier is battery driven from six built-in mercury cells or supplied from an external DC source, 6–35 volts.

Special features:

Input impedance:	1200 Mohm, 10 pF
Output Resistance:	< 100 ohm
Frequency range:	0.5–500,000 Hz
Dynamic range:	96.5 dB
Attenuation:	0 or 40 dB (fixed)
Amplification:	+ 2 to – 20 dB (continuously variable)
Output voltage:	Max. 2.8 V peak-peak
Rise time:	$< 10\ \mu$sec.
Recovery time:	$< 50\ \mu$sec.

Integrating Networks.

Apart from the integrating networks contained in the Preamplifier Type 1606, Brüel & Kjær produce a separate unit called the Integrator ZR 0020.

The Integrator, containing two stages of integration, is designed for screwing directly onto a B & K Precision Sound Level Meter Type 2203, effectively converting this into a handy, portable vibration meter, capable of indicating levels of acceleration, velocity and displacement when an acceleration pick-up is employed as a vibration transducer. A slide rule is delivered with the Integrator which may be set to the acceleration pick-up sensitivity and used for direct conversion of dB-readings to units of vibration (metric and British). Accelerometer sensitivities from 10 to 1000 mV/g are covered.

The components of the RC integrating networks have been chosen to give a low-frequency cut-off (−3 dB point) at about 5 Hz. This is sufficiently low, since the Precision Sound Level Meter itself has a low-frequency cut-off of about 5 Hz. The high-frequency limits are determined by the capacitive coupling between input and output and are about 15 kHz for velocity and 4 kHz for displacement measurements. These ranges are sufficiently large for the majority of applications.

It is also quite possible to use the Integrator with the B & K 1" Cathode Followers, whereby measurement and analysis of acceleration, velocity and displacement may be carried out with any of the B & K analysing/indicating instruments, i.e. 2107, 2112, 2603 or 2211.

Amplifiers and Indicating Instruments.

Brüel & Kjær produce a number of indicating amplifiers for use in vibration measuring set-ups. They include:

1. Microphone Amplifier Type 2603, 2604
2. Frequency Analyzer Type 2107
3. Audio-Frequency Spectrometer Type 2112
4. Sound Level Meter Type 2203
5. Vacuum Tube Voltmeter Type 2409
6. Vacuum Tube Voltmeter Type 2417
7. Vibration Meter Type 2502
8. Level Recorder Type 2305.

1. **Microphone Amplifiers.** These are convenient to use both with cathode followers and with the other preamplifiers: They measure overall vibration level, but are equipped with filter input and output sockets for operation with external filters in frequency analyzing set-ups. Frequency range 2603: Flat to within ± 0.5 dB from 2 to 40,000 Hz. 2604: Flat to within ± 0.5 dB from 10 to 200,000 Hz.

2. **Frequency Analyzer Type 2107.** This is a microphone amplifier similar to Type 2603 but with a frequency selective filter network built-in. In vibration measurements it is an excellent means for analyzing the frequency

contents of the vibration signal. The analyzer is of the constant percentage bandwidth type and the bandwidth is selectable from about 6 % to 29 % of the tuned-in frequency. Using the 6 % bandwidth gives a clear indication of each frequency component of the vibration. An important advantage is the possibility for driving the frequency tuning mechanism from the Level Recorder Type 2305, to give automatic frequency spectrum analysis curves on precalibrated paper, when the two instruments are synchronized. Frequency range 2–40000 Hz for overall measurements (frequency selective part switched out), 20–20000 Hz for frequency analysis.

3. **Audio Frequency Spectrometer Type 2112.** This is again a microphone amplifier but with 1/3 and full octave, contiguous fixed filters built-in. The frequency range covered is 22 to 4500 Hz when used selectively, 2 to 40000 Hz when used for overall measurements. When used with the Level Recorder Type 2305 the filters may be switched automatically from the recorder and frequency spectra are recorded on preprinted, calibrated paper as either third octave or octave analysis.

4. **The Precision Sound Level Meter** has its own cathode follower built-in and may therefore be used with the accelerometer connected directly to its input terminals. Using the Integrator ZR 0020 described above the Precision Sound Level Meter is effectively converted into a light, portable vibration meter, for measurement of acceleration, velocity and displacement. The Octave Filter Set Type 1613 may be attached to the Sound Level Meter for a rough frequency analysis of the vibration. Frequency range for overall measurements: 10 to 20000 Hz, and for octave analysis: 22.5 to 20000 Hz.

5. **Vacuum Tube Voltmeter Type 2409.** This voltmeter is an excellent instrument for overall vibration measurements, used with for example the Microphone Power Supply Type 2801 and a Cathode Follower Type 2615. The frequency characteristic of the voltmeter is flat to within ± 0.2 dB from 2 to 200,000 Hz with true rms, peak or arithmetic average indication of the vibration signal. Using the Preamplifier Type 1606 one can measure velocity and displacement as well as acceleration level.
   The Vacuum Tube Voltmeter may also be used with an input directly from the accelerometer, since the input impedance is as high as 10 Mohm in parallel with 20 pF. This means that vibration measurements may be carried out down to as low as 20 Hz employing the Voltmeter alone.

6. **Random Noise Voltmeter Type 2417.** This meter may be used as the above Type 2409, but the meter circuit employs selectable time-constants from 0.3 to 100 seconds, which is used to obtain a stable reading when the vibration is irregular or "random" at low frequencies. An output socket is provided for use with the Level Recorder Type 2305. The out-

put signal is DC, proportional to the rms level of the vibration, and the Level Recorder must be switched to DC operation. The frequency characteristic of the voltmeter is flat to within ± 0.2 dB from 2 to 20000 Hz.

7. **Vibration Meter Type 2502.** The Vibration Meter Type 2502 is a controlling-measuring amplifier, designed for use in vibration test systems with the B & K Automatic Vibration Control Type 1019 and the Sine-Random Generator Type 1040. It can also be used independently as a vibration meter.
Two inputs are provided, one for calibrated accelerometer preamplifiers providing an input voltage of 10 mV/g, and one for measuring acceleration density in connection with wideband vibration analyzing equipment calibrated for 1 volt per g^2/cps.
When used in vibration test systems the Vibration Meter is connected in the feedback circuit (compressor) from the control accelerometer to the signal generator and integrating networks are provided making possible the measurement and control of displacement, velocity and acceleration gradient as well as acceleration. Facilities are included for connection of external filters.
The meter circuit employs a quasi-RMS rectifier, giving the same reading for sinusoidal signals and white noise having the same RMS value. Selectable meter time constant from 0.3 to 30 sec. can be automatically controlled from the signal generator in synchronism with the changing of compressor speed. The DC voltage to the meter is connected to a socket so that the large time constants of the meter circuit may be used for other purposes, such as for example recording on the Level Recorder Type 2305.

8. **Level Recorder Type 2305.** All the amplifying-indicating instruments described above have an output terminal for feeding for example the B & K Level Recorder Type 2305. This provides a permanent written record of whatever is measured, as a function of time, or when the Recorder is coupled to a frequency analyzer, as a function of frequency. The Level Recorder is in itself a very versatile measuring instrument, capable of measuring rms, peak and average values of signals from 2 to 200,000 Hz or DC signals. Its dynamic range is variable from 10 dB to 75 dB, and the writing width is 50 or 100 mm.
The Statistical Distribution Analyzer Type 4420 may be coupled to the Level Recorder to give a level/time distribution of the measured signal.
The sampling frequency is variable from 0.1 to 10 seconds and the width of the amplitude window is one tenth of the writing width of the Level Recorder.
As the counters employed go up to 999,999, an analysis time of more than 24 hours is possible even with the highest sampling frequency.

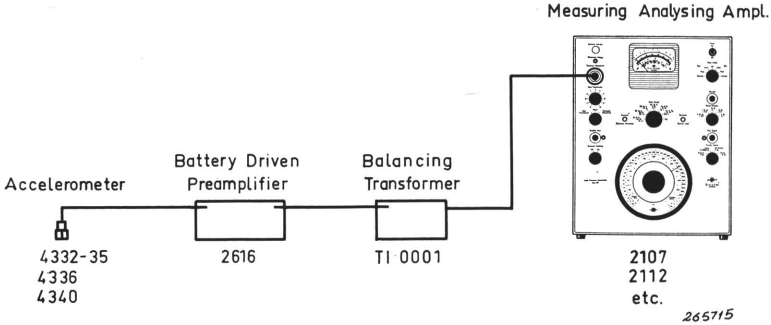


Fig. 4.7. Use of Balancing Transformer to eliminate ground loops.

Ground Loops.
In set-ups where ground loops are disturbing or where ground currents may be carried in the shield of the transducer cable, thus superimposing a noise voltage on the signal, one should first of all consider the use of isolated mounting. One may use the isolated stud and mica washer, the magnet clamp, or the cementing stud with a glass woven layer in the cement between the stud and the measuring object. If one of these methods cannot be employed, a battery driven system may be the solution, or a battery driven preamplifier connected to AC driven equipment via a balancing transformer such as the B & K Type TI 0001. See Fig. 4.7.

5. Calibration

When absolute vibration level is measured it is necessary to know the absolute sensitivity versus frequency characteristic of the measuring instrumentation. As a rule piezoelectric accelerometers of careful design and manufacture are extremely stable, but after exposure to high temperature or shock environments it may be wise to recalibrate.

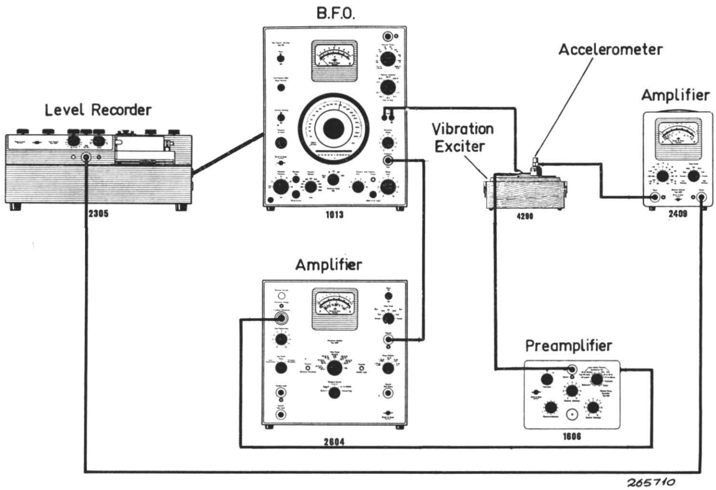


Fig. 5.1. Set-up suitable for the calibration of accelerometers. There are many possible alternatives to the various instruments shown.

Equipment for relatively quick and simple calibration of vibration pick-ups is available from Brüel & Kjær. This consists of a small electrodynamic shaker Type 4290 with an accurately calibrated control accelerometer built in. Using the control accelerometer in a feedback loop with a B & K feedback controlled sweep oscillator the vibration of the shaker table is held constant in the frequency range 100 to 30000 Hz, and when an accelerometer is fixed onto the shaker table its frequency response is easily measured, e.g. with a Level Recorder Type 2305, or point by point. A suitable set-up is shown in Fig. 5.1.

The Level Recorder is used for obtaining a permanent record of the frequency characteristic of the accelerometer. The absolute sensitivity of the accelerometer is found by comparing the output with the output from the

built-in calibrated control accelerometer. Since the shaker table itself is part of the control accelerometer, the vibration is exactly the same for the two accelerometers.
The comparison method gives an accuracy on the absolute calibration of better than ± 1 dB.
When higher accuracy is needed, or when it appears necessary to check the sensitivity of the control accelerometer, the same shaker may be used for reciprocity calibration. The procedure is described fully in the instruction manual for the Calibration Exciter Type 4290. The accuracy of this method is better than ± 0.5 dB with careful procedure.
An alternative method is to keep a "secondary standard" for reference calibration only. For this purpose any one of the accelerometers 4332–33 –34–35 may be used. If this is kept for reference only and is not exposed to extreme mechanical shocks or temperatures, it will serve as a stable reference over a long period of time. Comparison between the reference and an unknown may easily be carried out on for example the 4290 shaker table. 2 % absolute accuracy is obtainable this way.

6. Applications

The Triaxial Accelerometer is well suited for all general vibration measurements, but because of its construction it is especially useful for certain applications. These include shock and vibration testing, balancing of machinery and measurements on all kinds of complex structures where the direction of vibration is not known. A few examples will be given here, mainly in order to show how to connect up the vibration measuring system.

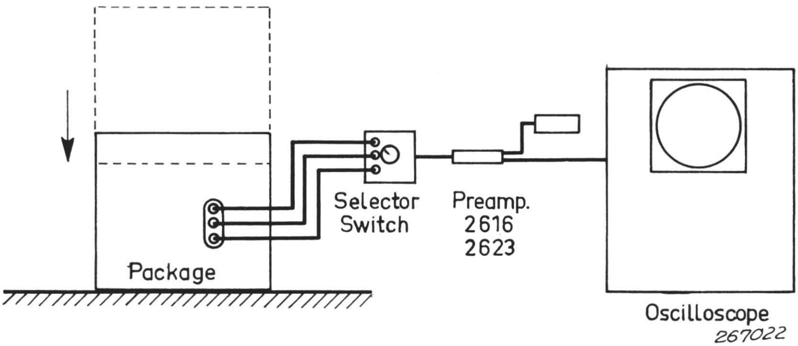


Fig. 6.1. System used for drop testing of packaged electronic instruments.

Shock Tests.

A simple system for drop testing is shown in Fig. 6.1. The test item is a packaged electronic instrument which is dropped from a certain height onto a solid foundation. A Triaxial Accelerometer is fixed to the instrument inside the package and the three output leads are connected to a selector switch. Any one output (x, y or z-direction) may be selected for display on an oscilloscope.

Only one preamplifier (Type 2623) is required in this set-up. If a dual beam oscilloscope is available, two directions may be measured simultaneously using two preamplifiers.

Note that no amplifier has been inserted between the preamplifier and the oscilloscope, in order to obtain the correct shock waveform on the oscilloscope screen.

The measurement of shock waveforms presents much more stringent requirements to the instrumentation than is generally realized. Thus in order to measure a half sine pulse with less than 5 % error the low frequency time constant of the measuring system should be at least 10 T, where T is the pulse duration in seconds,

$$\text{i.e.} \qquad RC = 10\,T$$

so that any amplifier which is inserted in the circuit should have a flat frequency response down to at least

$$f_L = \frac{1}{2\,\pi\,RC} = \frac{1}{2\,\pi\,10\,T} \doteq \frac{16}{1000\,T}$$

Also the input circuit time constant RC of the preamplifier must of course be at least 10 T. Thus without any amplifier in the circuit the Preamplifier Type 2623 and Triaxial Accelerometer Type 4340 may be used for pulse lengths up to

$$T = \frac{RC}{10} = \frac{2000 \times 10^6 \times 1000 \times 10^{-12}}{10} = 0.2 \text{ seconds}$$

with 5 % accuracy.
If for example an amplifier with cut-off frequency 2 Hz is used this length is reduced to

$$T = \frac{1}{2\,\pi \times 10 \times 2} = 0.008 \text{ sec}$$

Furthermore if amplifiers are used in the circuit their phase shift should be

$$\varphi\,(f) = k\,f$$

where $\varphi\,(f)$ is the phase shift at a certain frequency f, and k is a constant (which may be zero).
This relationship should hold over the significant part of the frequency range, i.e. down to the frequency calculated by the above relationships.
The high frequency requirements are usually easy to comply with. A cut-off frequency.

$$f_H > \frac{10}{T}$$

is adequate for most cases.

Motor Balance.
The Triaxial Accelerometer is used with advantage for motor balance investigations. Maximum information is obtained when the vibration is measured in three directions. A suitable set-up is shown in Fig. 6.2.
Only one preamplifier is required in this set-up. A selector switch is used for selecting the required measuring direction and the Spectrometer is used for analysing the vibration in 1/3 or 1/1 octaves. The Level Recorder Type 2305 is used for recording the spectrograms on frequency and amplitude calibrated paper. By running the paper back the spectrograms for all three directions may be recorded on the same paper chart.

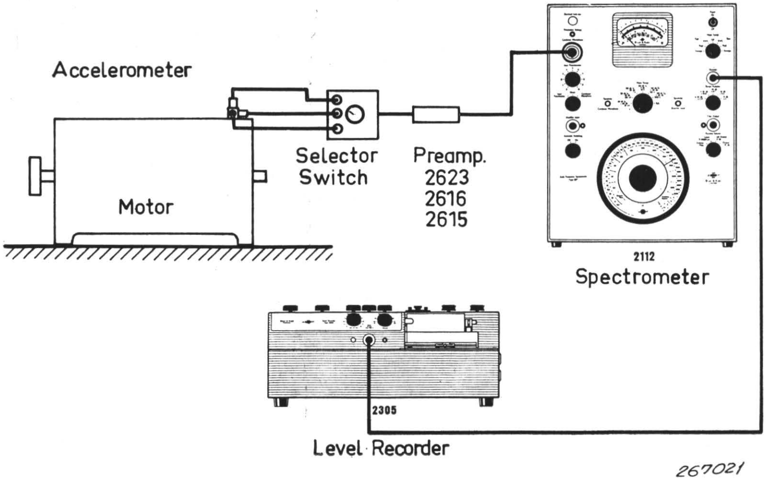


Fig. 6.2. Set-up used for finding motor unbalance.

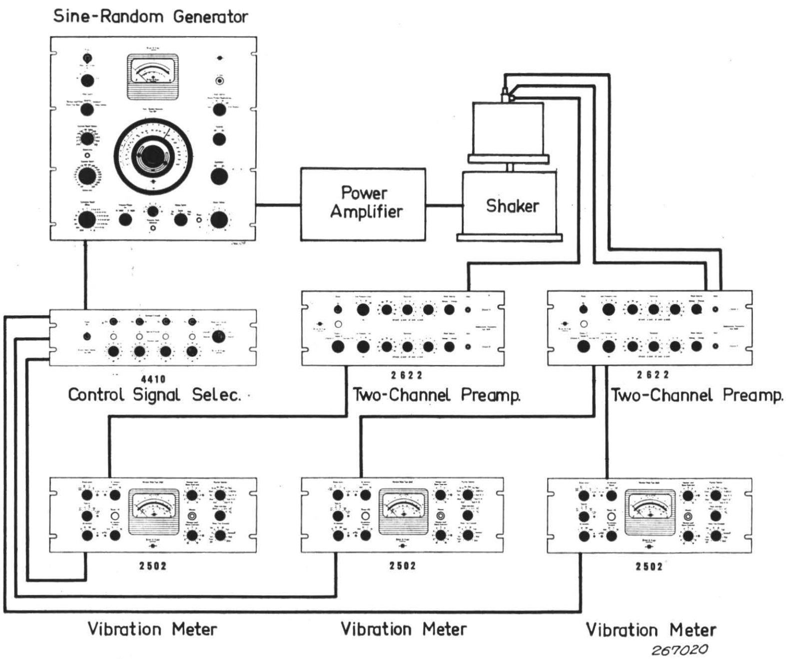


Fig. 6.3. Vibration testing using triaxial accelerometer to control motion in three directions.

Vibration Testing.

When carrying out vibration tests one can not always be sure that the maximum vibration of the tested structure occurs in the direction of vibration of the shaker, especially when the test item is a complex structure. The Triaxial Accelerometer may then be used for controlling the vibration, for example in connection with the Control Signal Selector Type 4410. A possible set-up is shown in Fig. 6.3.

The Control Signal Selector selects the highest or the lowest of up to four vibration signals from Vibration Meters Type 2502, and transmits this signal to the compressor circuit of the Sine-Random Generator Type 1040.

Thus by setting the Selector to the function "Highest" the vibration of the test specimen will not exceed the preset level in any of the three directions and the vibration will stay at this level throughout the selected frequency range in at least one of the three directions.

7. Accessories

The following accessories are available for mounting of the accelerometers and the transistorized preamplifiers.

UA 0125 Set of studs containing 10 isolated studs YS 0420, 10 steel studs YQ 2960, 10 nuts YM 0414, 10 mica washers YO 0534, 1 die and 1 tap NF 10–32.

UA 0142 1 set of clamping magnet containing 5 permanent magnets UA 0070 with isolated mounting.

UA 0129 Set of 20 miniature plugs JP 0012 with tools and instruction for mounting of the plugs on cable.

UA 0130 Set of 25 miniature plugs JP 0012.

AO 0037 1.2 m (4 ft.) of mininoise cable for operation to 100° C (212° F) fitted with miniature plugs. Individually calibrated.

AC 0010 Mininoise cable up to 600 ft. in one length.
90 pF/m or 30 pF/ft., for operation to 100° C (212° F).

AC 0005 Mininoise cable up to 600 ft. in one length.
90 pF/m or 30 pF/ft., for operation to 260° C (500° F).

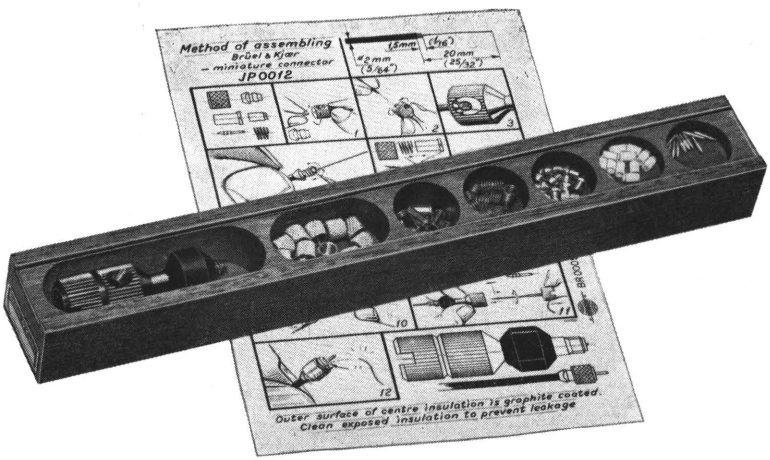


Fig. 7.1. Photograph of UA 0129 with instructions for assembly of JP 0012.

8. Conversion Charts, Tables etc.

The following table is given in order to facilitate the conversion from dB to a (voltage) ratio. It is used as follows:

Subtract a whole number of $n \times 20$ from the dB value to be converted which gives a positive remainder between 0 and 20. Look up the ratio in the table corresponding to the remainder. The value sought is then $10^n \times$ value from the table.

Example: Convert 65.3 dB re. 1 g into units of g.

$65.3 = (3) \times 20 + 5.3$

5.3 gives from table 1.841. The g-value is then $10^3 \times 1.841 = 1841$ g.

With negative values the procedure is the same, e.g.:

Convert – 31.8 dB re. 1 g units of g.

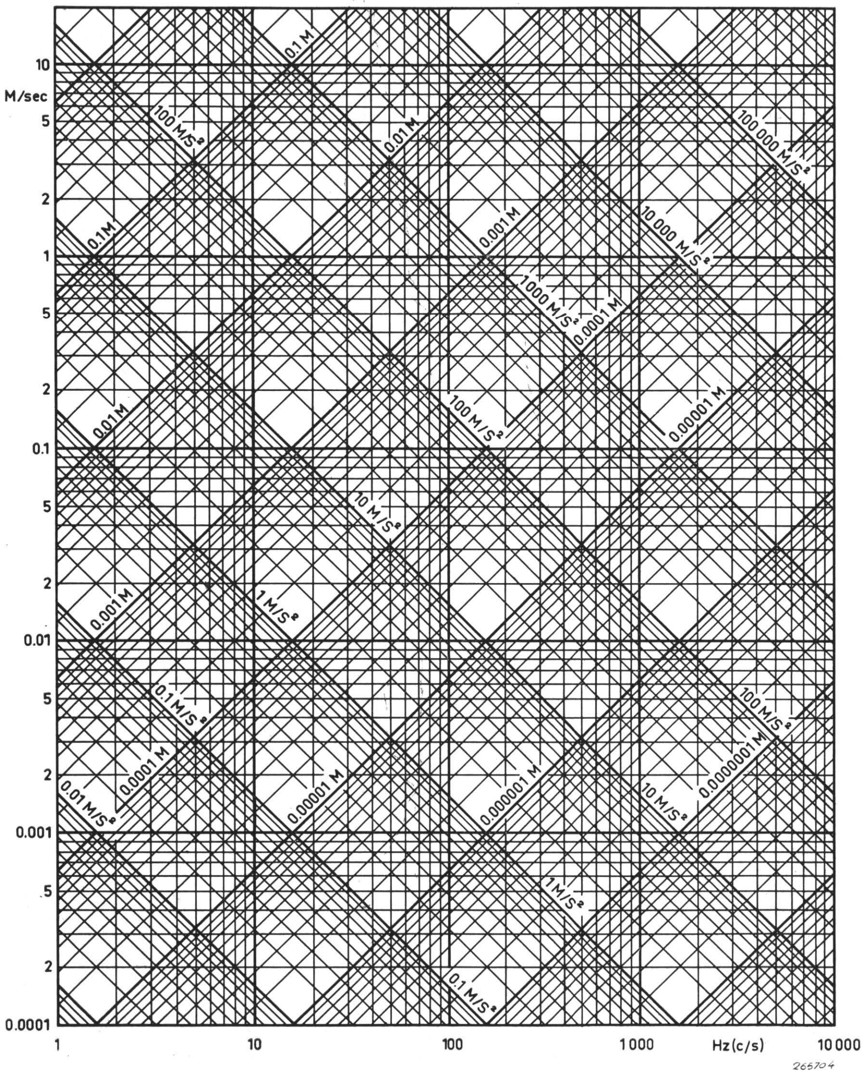
$-31.8 = (-2) \times 20 + 8.2.$

8.2 gives from table 2.570. The g-value is then $10^{-2} \times 2.570 = 0.02570$ g.

Table for Converting Decibels into (Voltage) Ratio.

dB	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
0	1.000	1.012	1.023	1.035	1.047	1.059	1.072	1.084	1.096	1.109
1	1.122	1.135	1.148	1.161	1.175	1.189	1.202	1.216	1.230	1.245
2	1.259	1.274	1.288	1.303	1.318	1.334	1.349	1.365	1.380	1.396
3	1.413	1.429	1.445	1.462	1.479	1.496	1.514	1.531	1.549	1.567
4	1.585	1.603	1.622	1.641	1.660	1.679	1.698	1.718	1.738	1.758
5	1.778	1.799	1.820	1.841	1.862	1.884	1.905	1.928	1.950	1.972
6	1.995	2.018	2.042	2.065	2.089	2.113	2.138	2.163	2.188	2.213
7	2.239	2.265	2.291	2.317	2.344	2.371	2.399	2.427	2.455	2.483
8	2.512	2.541	2.570	2.600	2.630	2.661	2.692	2.723	2.754	2.786
9	2.818	2.851	2.884	2.917	2.951	2.985	3.020	3.055	3.090	3.126
10	3.162	3.199	3.236	3.273	3.311	3.350	3.388	3.428	3.467	3.508
11	3.548	3.589	3.631	3.673	3.715	3.758	3.802	3.846	3.890	3.936
12	3.981	4.027	4.074	4.121	4.169	4.217	4.266	4.315	4.365	4.416
13	4.467	4.519	4.571	4.624	4.677	4.732	4.786	4.842	4.898	4.955
14	5.012	5.070	5.129	5.188	5.248	5.309	5.370	5.433	5.495	5.559
15	5.623	5.689	5.754	5.821	5.888	5.957	6.026	6.095	6.166	6.237
16	6.310	6.383	6.457	6.531	6.607	6.683	6.761	6.839	6.918	6.998
17	7.079	7.161	7.244	7.328	7.413	7.499	7.586	7.674	7.762	7.852
18	7.943	8.035	8.128	8.222	8.318	8.414	8.511	8.610	8.710	8.810
19	8.913	9.016	9.120	9.226	9.333	9.441	9.550	9.661	9.772	9.886

Frequency, Acceleration, Velocity, Displacement Nomograph. (RMS-values).



Conversion of Length.

m	cm	mm	ft	in
1	100	1000	3.281	39.37
0.01	1	10	0.0328	0.3937
0.001	0.1	1	0.00328	0.03937
0.3048	30.48	304.8	1	12
0.0254	2.54	25.4	0.0833	1

Conversion of Acceleration.

g	m/sec^2	cm/sec^2	ft/sec^2	in/sec^2
1	9.81	981	32.2	386
0.102	1	100	3.281	39.37
0.00102	0.01	1	0.0328	0.3937
0.03109	0.3048	30.48	1	12
0.00259	0.0254	2.54	0.0833	1

Conversion of Weight (Mass).

kg	gram	lbs.	oz.
1	1000	2.205	35.3
0.001	1	0.0022	0.0353
0.4536	453.6	1	16
0.02835	28.35	0.0625	1

Temperature:

$$F = \frac{9}{5} C + 32 \qquad C = \frac{5}{9} (F - 32)$$

Single Degree of Freedom System.

M $=$ mass (kg)

K $=$ stiffness (Newt/m)

$$\omega_o = \sqrt{\frac{M}{K}} = 2\pi \times \text{resonance frequency}$$

$$\omega_o = \sqrt{\frac{g}{\Delta_{st}}}$$ where Δ_{st} = static deflection of the mass.

For Single Frequency (Sinusoidal) Vibration.

Acceleration	Velocity	Displacement
$a \cos \omega t$	$\frac{1}{\omega} a \sin \omega t$	$-\frac{1}{\omega^2} a \cos \omega t$
$-\omega v \sin \omega t$	$v \cos \omega t$	$\frac{1}{\omega} v \sin \omega t$
$-\omega^2 d \cos \omega t$	$-\omega d \sin \omega t$	$d \cos \omega t$

RMS Values.

A	A/ω	A/ω^2
ωV	V	V/ω
$\omega^2 D$	ωD	D

9. Specifications

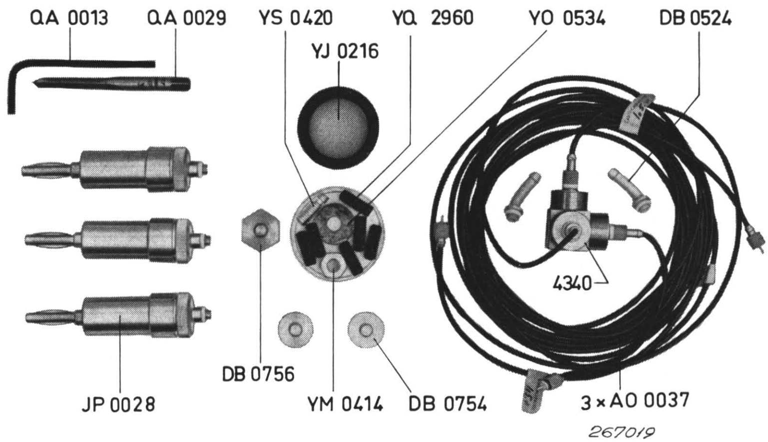


Fig. 9.1.

Fig. 9.1 shows the Triaxial Accelerometer Set Type 4320.
It consists of the following parts:

Triaxial Accelerometer Type 4340	
Low noise, low temperature cables	AO 0037
Microplug to B & K adaptors	JP 0028
10–32 NF steel stud	YQ 2960
10–32 NF nut	YM 0414
10–32 NF isolated stud	YS 0420
Mica washer	YO 0534
Cementing stud	DB 0756
Counterweights	DB 0754
Wax	YJ 0216
10–32 NF screw tap	QA 0029
Allen key for steel studs	QA 0013
Tubes for water cooling	DB 0524
Calibration Chart	

The technical specifications for the accelerometer are as follows:

Accelerometer Type	*4340*
Contained in Accelerometer Set	4320
*Sensitivity (mV/g)	14–24
*Charge Sensitivity (pC/g)	14–20
*Free Resonance (kHz (kc/s))	45
*Mounted Resonance (Solid Steel) (kHz)	23
*Capacity Includ. Cable (pF)**	1000
*Transverse Sensitivity (%)	∠4
Max. Ambient Temperature (°C)	260
*Temperature Stability (dB/°C)	0.02
Lowest Leak Resist. at 20°C (MΩ) Typical value at 250°C (MΩ)	20000 20000
Magnetic Sensitivity (μV/Gauss)	1
Acoustic Sensitivity (μV/μbar)	∠0.2
Torque Sensitivity, 6–60 kgcm (%)	∠1
Max. shock (g's)	500
*Frequency Range (Hz) 2 % 10 %	0.5–5000 0.5–7000
Type of Connection	Triaxial
Height (mm)	26
Weight (grams)	35
Material of Base	Titanium
Provision for Water Cooling	Yes
Mounting thread	10–32 NF

* Individual values given on the calibration chart.

** With standard low-noise cable, 1.2 m (3 feet) long. Special low-noise high temperature cable may be ordered. (Type No. AO 0038).

B K

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