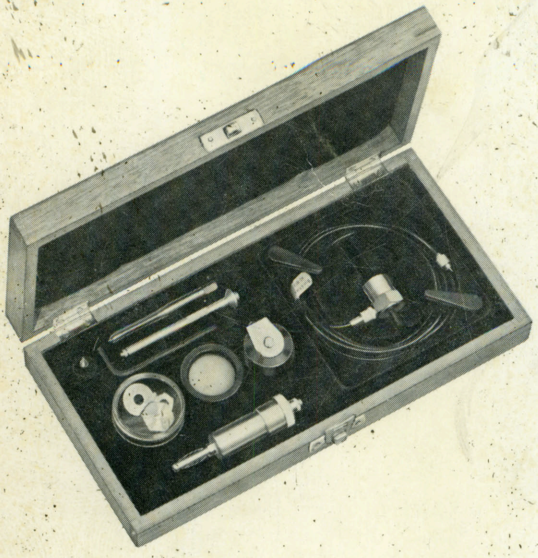
4319/23

INSTRUCTIONS AND APPLICATIONS

Accelerometer Sets Type 4319/4323
Accelerometer Packages Type 4359/4363



The Brüel & Kjær accelerometers have been designed for maximum dependability and versatility in use. A rugged waterproof construction together with low sensitivity to environmental changes make these accelerometers suitable for most vibration measurements both in the laboratory and under field conditions.

BRÜEL & KJÆR

NÆRUM, DENMARK. Teleph.: 80 05 00. Cable: BRUKJA. Telex: 5316. COPENHAGEN

BB 4319/23 - 0300069

Accelerometer Sets

Type 4319/4323

Accelerometer Packages

Type 4359/4363

OCTOBER 1968

Contents

1. Description

Construction

The Brüel & Kjær Accelerometers Type 4339 and 4343 are of the piezoelectric compression type with a construction indicated schematically in Fig. 1.1. They are made to have exactly 10 mV/g and 10 pC/g sensitivity respectively to be used with voltage and charge preamplifiers with fixed gain.. The single-ended compression build-up make them insensitive to acoustic noise, and by means of a specially constructed cable connection the influence of cable whip is reduced to a minimum.

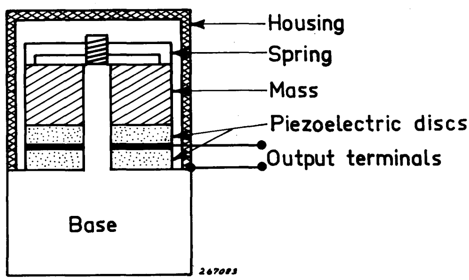


Fig. 1.1. Schematic drawing of a piezoelectric accelerometer.

The 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.

*) Lead Zirconium Titanate.

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 Brüel & Kjær accelerometers are 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, these accelerometers have 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.

The accelerometers are designed for measurements on parts subjected to mechanical vibrations, such as machinery, vehicles, ships, aircraft, buildings etc., and are also used as controlling elements for vibration test purposes. Combined with the B & K preamplifiers and frequency analyzers the frequency spectra of the vibrations can be readily analysed.

For absolute measurements it is necessary to know the sensitivity of the vibration transducer employed. Each B & K accelerometer is supplied with individual calibration data and a frequency response curve, 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 accelerometers.

The accelerometers have type numbers 4339 - 4343 during the production and calibration stages. When they are sold they are accompained by certain accessories, such as cables, mounting screws etc. and have the following ordering specifications.

Accelerometer Sets Type 4319 - 4323.
Accelerometer Packages Type 4359 - 4363.

See chapter 10, Specifications.

It has been the aim with these accelerometers to make a versatile transducer which can successfully meet the requirements of the majority of research scientists and vibration engineers. High precision and stability have been coupled with a universal applicability which makes the accelerometers suitable for all but the most specialized applications.
The accelerometer housing is of an all welded stainless steel construction which makes it absolutely waterproof. The special ceramic input socket ensures complete sealing even after several times of temperature cycling up to 250°C.

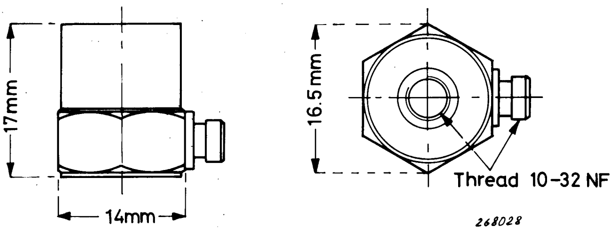


Fig. 1.2. Physical dimensions of the Accelerometers Types 4339 and 4334.

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 of high sensitivity, low strain sensitivity and good high frequency response are in conflict with requirements for small physical dimensions and weight, so that for general purpose accelerometers some useful compromise must be found.

The B & K Accelerometers Types 4339 and 4343 have a base made of stainless steel (AISI 303) and a total weight of 16 grammes (0.57 oz.). The physical dimensions are given in Fig. 1.2.

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 accelerometers 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.

The Brüel & Kjær accelerometers Type 4339-4343 are 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.

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).

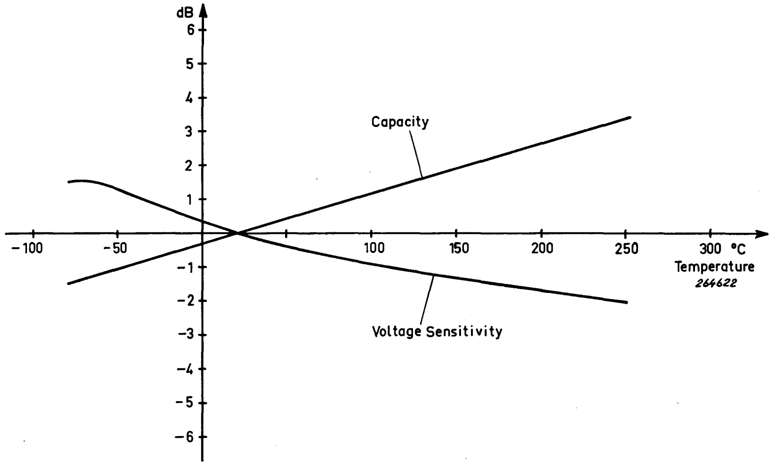


Fig. 1.3. Typical performance characteristics for the accelerometers in the temperature range −100 to + 260° C.

Cooling

When the accelerometers are fixed on surfaces with temperatures exceeding 250° C it is 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 such as the one included in the Accelerometer Kits 4319/4323 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. The set-up shown in Fig. 1.4 has been tested in the laboratory.

In this set-up the mounting surface was heated to 450° C while less than 200° C were measured in the accelerometer base.

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.

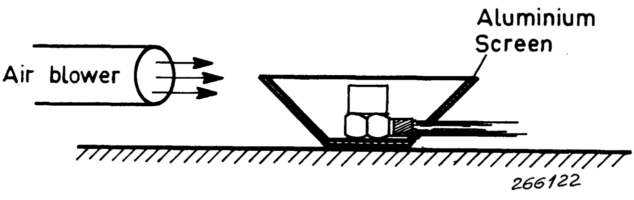


Fig. 1.4. Forced air cooling of an accelerometer.

Vacuum Test

The B & K accelerometers Type 4339-4343 are sealed and tested under water in an evacuated jar for leaks. This eliminates the risk of inferior performance in moist atmospheres or environmental test chambers where heavy condensation may take place.

A photograph of the test set-up is shown in Fig. 1.5. The smallest leaks show up immediately as bubbles rising to the surface.

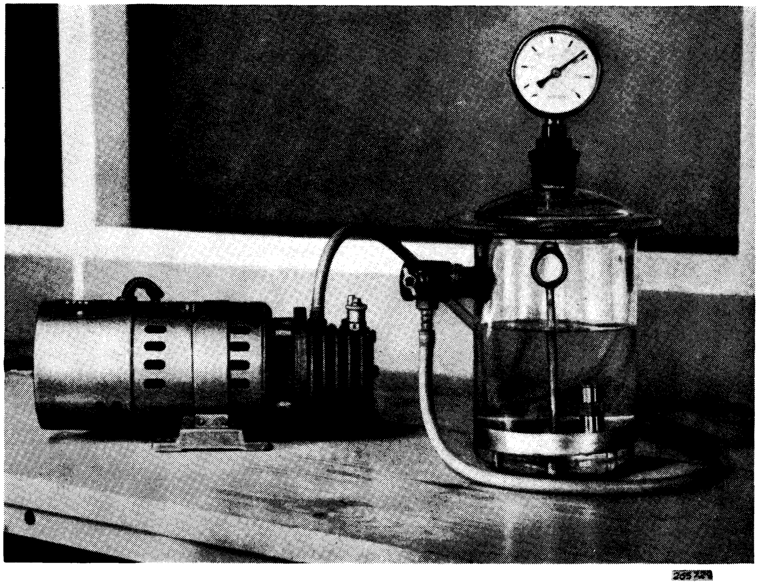


Fig. 1.5. Vacuum test set-up.

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. 1.6.

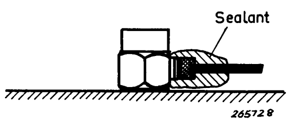


Fig. 1.6. Sealing of cable entry.

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 piezoelectric 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 0.1 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 100 μV.

Magnetic Sensitivity
The magnetic sensitivity has been found to be less than 0.5 μV/Gauss for the least favorable orientation of the accelerometer in the magnetic field.

Polarity
The polarity of the accelerometers 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.

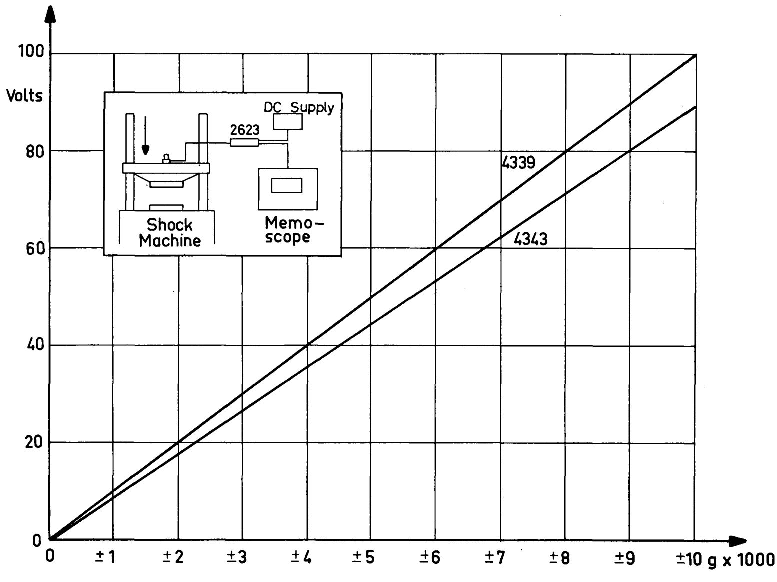


Fig. 1.7. Part of shock test machine and typical output versus shock amplitude plot.

Shock Performance

Accelerometers will often withstand higher shock in one direction than the other while not exceeding the maximum limit of the accelerometer. The mass is pressed against the ceramic with a certain force and this force determines the upper limit to which the accelerometer output will increase linearly with increased shock amplitude in the negative direction. In the case of 4339/4343, however, the mass-spring system is designed very carefully to avoid this affect. The curves given in Fig. 1.7 apply to shocks in both positive and 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.
However, 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	Curiepoint °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. 1.8a 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.
This mechanical system can be further simplified into that of Fig. 1.8b. 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 no practical

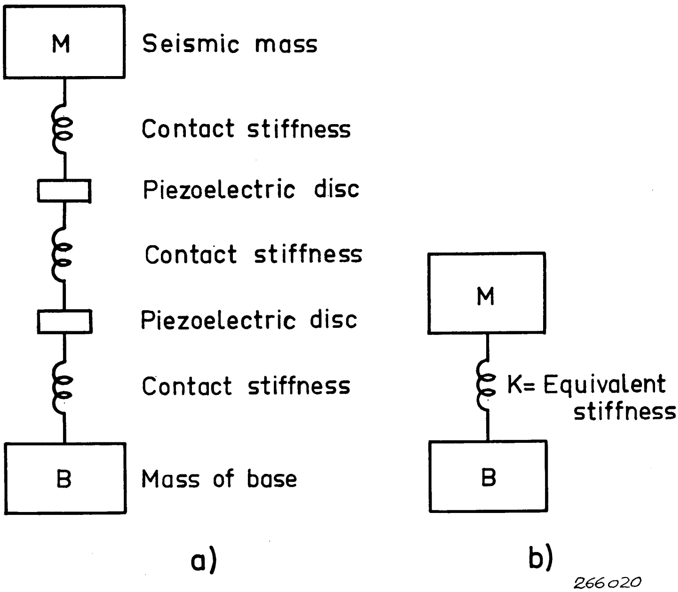


Fig. 1.8 a. Schematic drawing of accelerometer as a dynamic system.
b. Simplified system.

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).

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.

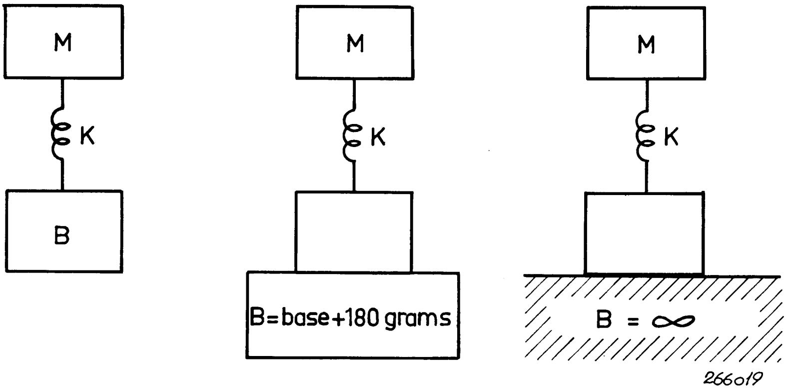


Fig. 1.9. Possible configurations for definitions of natural resonance frequency.

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 block. 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

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

i.e. a value which is 10 % high.

For the Brüel & Kjær accelerometers 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 angle 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. A typical calibration chart as supplied with the accelerometers is shown in Fig. 2.1.

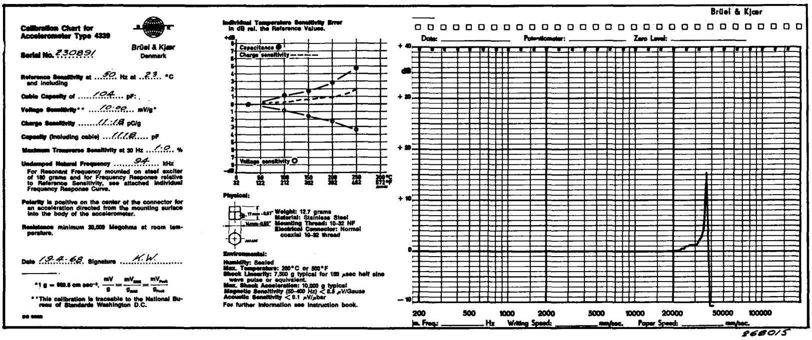


Fig. 2.1. A typical calibration chart.

Cable Capacitance

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 capacitance 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.
The accelerometers are calibrated at 50 Hz, the frequency being controlled by a crystal controlled 100 Hz frequency standard, which gives a frequency accuracy better than ± 0.01 %.

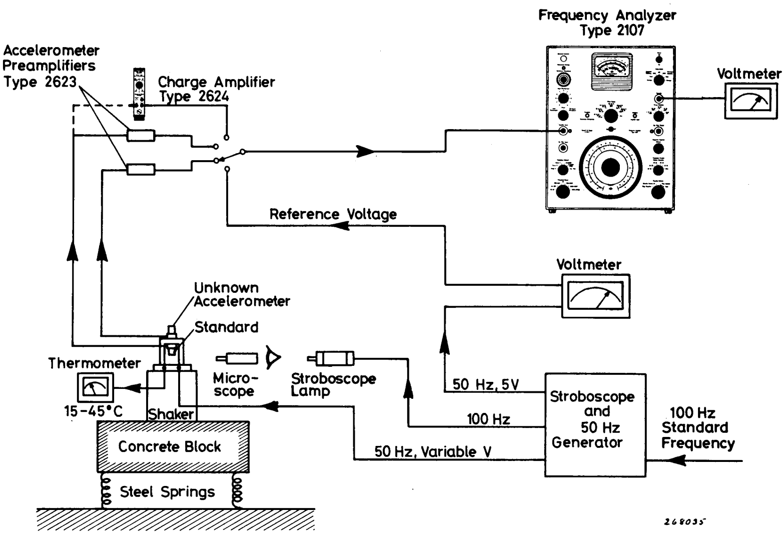


Fig. 2.2. Set-up used for calibration of absolute sensitivity of the accelerometers.

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 Analyzer 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 cable, 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

The calibration of the accelerometer charge sensitivity is achieved with the same set-up as described in the previous section. The voltage preamplifier (2623) is replaced by the charge amplifier (2624), see Fig. 2.2, and the accuracy of the calibration is the same as before. The charge sensitivity is expressed in pico-coulumb/g and is independent of the capacitive loading on the accelerometer.

Capacitance

The capacitance of the accelerometer is given including the cable capacitance as specified on the calibration sheet. Accelerometer capacitance 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 capacitance is calculated from the voltage sensitivity and the charge sensitivity. The relationship is given by:

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

$$C_a + C_c = \frac{S_{charge}}{S_{voltage}}$$

where C_a = accelerometer capacitance and C_c = cable capacitance.

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 axis of the accelerometer making a small angle with the direction of the maximum sensitivity as shown in Fig. 2.3.
Imagining the accelerometer placed in a rectangular coordinate system, as shown, the vector representing the maximum sensitivity can be resolved into

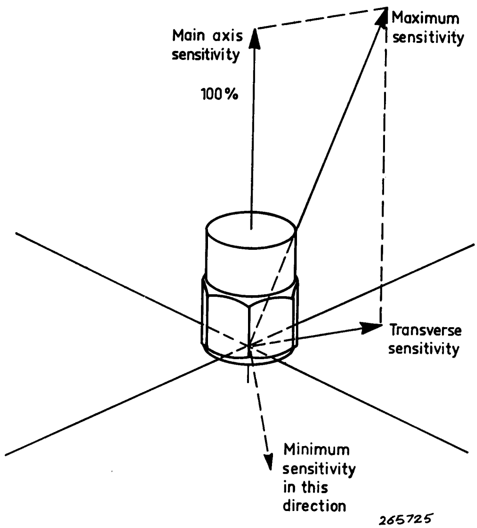


Fig. 2.3. Graphical illustration of transverse sensitivity.

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 in the transverse direction, 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 10 % 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 at a frequency somewhat lower than that for operation in the main direction. Fig. 2.4 is a typical frequency response for transverse sensitivity at frequencies up to 5000 Hz.

The transverse sensitivity of the accelerometers is specified as being less than 3 % of the main axis sensitivity. However, the individual maximum transverse sensitivity is given on the calibration chart, and in addition the direction of

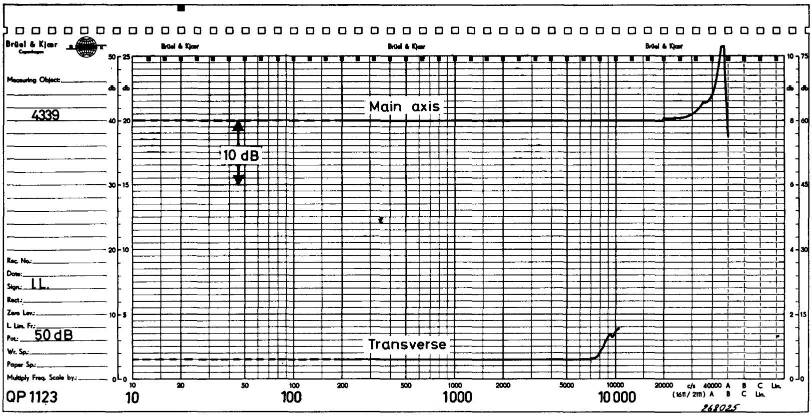


Fig. 2.4. Frequency response curve for transverse sensitivity of an accelerometer.

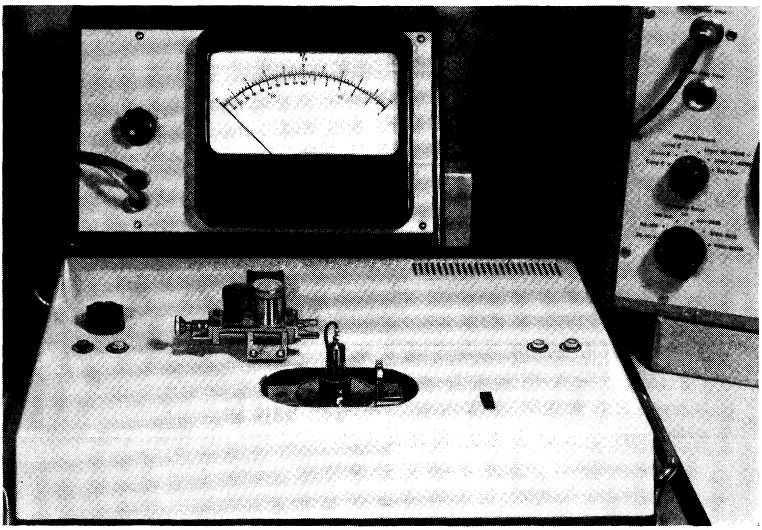


Fig. 2.5. Part of the arrangement for obtaining transverse sensitivity.

minimum transverse sensitivity is marked with a red dot on the side of the accelerometer.
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. 2.5.

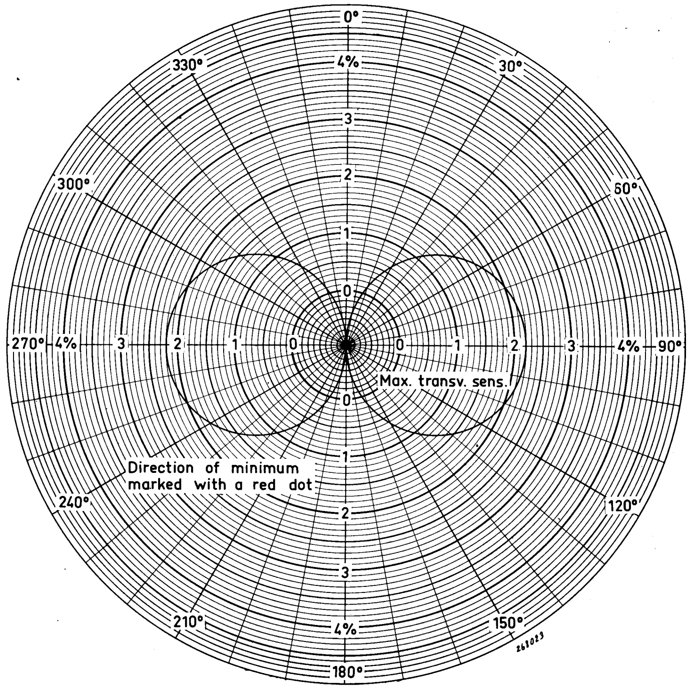


Fig. 2.6. Chart for finding transverse sensitivity in any direction, when maximum value is given.

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. The direction of the minimum (zero) sensitivity is marked with a red dot at the side of the accelerometer housing. This information is useful when measurement only in a certain direction is desired. Effects of cross motion can then be filtered out by mounting the accelerometer with its direction of minimum sensitivity coinciding with the direction of the cross motion.

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

If it is desired to find the transverse sensitivity in any particular direction use may be made of Fig. 2.6 as follows: Find the maximum transverse sensitivity from the calibration chart and use this value as the measure for the diameter of two circles as shown in the figure. (2.2 % is used as an example). The figure-eight curve obtained is the transverse sensitivity pattern for the accelerometer in question. Since the axis of minimum transverse sensitivity is marked on the accelerometer, its sensitivity in any direction is easily determined. Fig. 2.7 gives a typical sensitivity pattern as recorded with a B & K Level Recorder Type 2305.

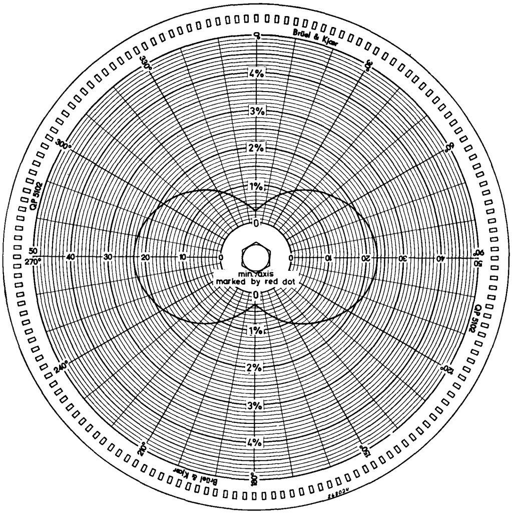


Fig. 2.7. Typical transverse sensitivity curve for the accelerometers.

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 signai 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 3 on mounting techniques.

Frequency Response Curve

An individual frequency response curve is supplied with each accelerometer. This is 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.

$$\frac{\text{Relative Displacement of Mass-spring}}{\text{Displacement of base}} = \left| \frac{1}{1 - (\omega/\omega_0)^2} \right|$$

where

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

$\omega_0 = 2\,\pi \times$ 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 0.5dB.

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 MΩ 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. 2.8 that the voltage sensitivity at any temperature with any amount of cable capacity is

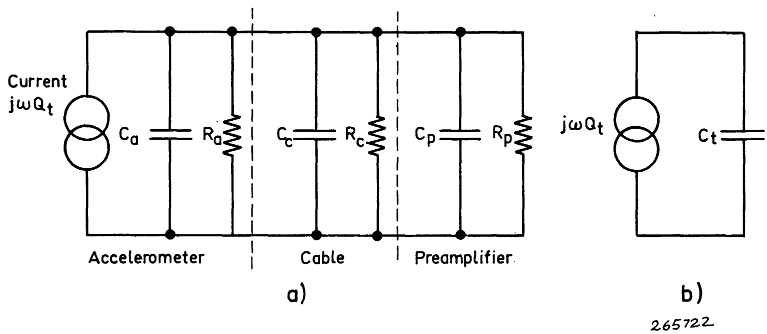


Fig. 2.8.
a) Equivalent circuit for accelerometer and preamplifier input.
b) The same circuit simplified for normal operating frequency range.

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

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.

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

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

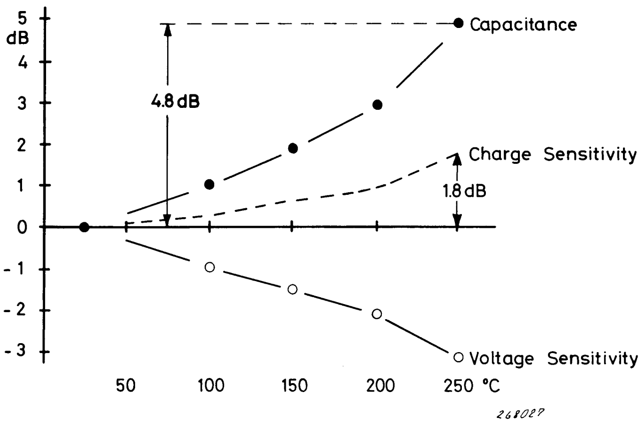


Fig. 2.9. Temperature sensitivity curves from the calibration chart on Fig. 2.1.

Example:
What is the voltage sensitivity of the accelerometer Type 4339, Serial No. 230891 (Fig. 2.1) at a temperature of 250° C and with a total external capacity (long cable plus preamplifier) of 1000 pF.

Solution:

From the calibration chart we find

$$Q_o = 11.18 \text{ pCoulomb/g}$$
$$K_Q = 1.8 \text{ dB} = 1.23$$
$$C_a = 1118 \text{ pF}$$
$$K_c = 4.8 \text{ dB} = 1.74$$
$$C_C = 104 \text{ pF}$$

Then the voltage sensitivity at 250° C

$$E_{250} = \frac{11.18 \times 1.23}{1118 \times 1.74 + 1000 - 104} = 0.00484 \text{ V/g}$$

$$E_{250} = 4.84 \text{ mV/g}$$

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 when measurements are taken, especially at higher frequencies. The frequency response curve 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 4339-4343 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 5000g shocks applied. No difference was noted between this type of mounting and the ordinary steel studs with matching thread. The shock was applied in the negative direction, i.e. lifting the accelerometer from the specimen.

There are several methods available for fixing the B & K 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 4319–4323:

10-32 NF threaded stud and nut
10-32 NF electrically isolated stud
Electrically isolated permanent magnet
Cementing stud
Wax
Probe with interchangeable sharp and rounded tips

Mica washers for electrical isolation of transducer
10-32 NF screw tap
Cable clip.

Mounting of Accelerometer

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

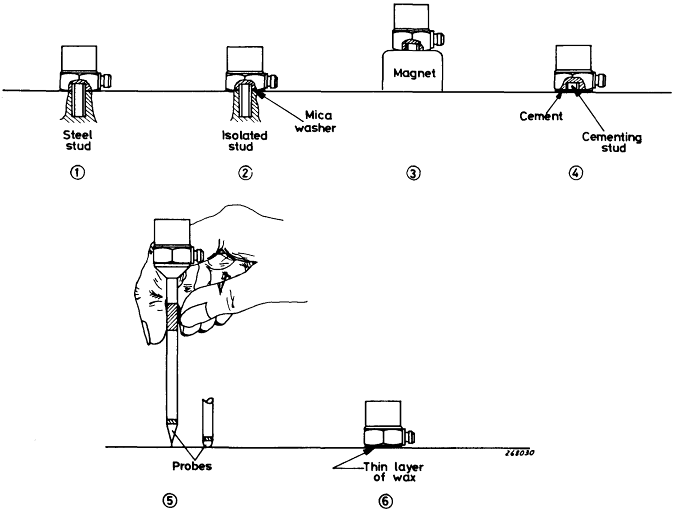


Fig. 3.1. Different ways of mounting the accelerometers.
1. *With steel stud.*
2. *With isolated stud and mica washer.*
3. *With permanent magnet.*
4. *With cementing stud.*
5. *Handheld with probe.*
6. *Accelerometer stuck on with wax.*

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.

It is essential whenever using a mounting screw, not to screw fully in as it may introduce base bending affecting the sensitivity of the accelerometer.

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 employs the permanent magnet which also gives electrical isolation from the vibrating specimen. A closed magnetic path has been used and there is virtually no magnetic field at the accelerometer position. This mounting method should not be used for acceleration amplitudes higher than about 200 g. Max. temp. 150° C, short time.
The holding force of the magnet has been investigated for various steel plate thickness and for various thickness of brass (non-magnetic) between the magnet and the steel. See Fig. 3.2.

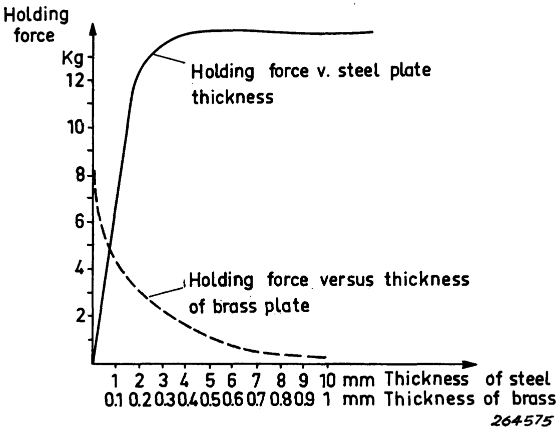


Fig. 3.2. Holding force of the mounting magnet versus thickness of steel plate and versus thickness of intermediate brass plate.

Type 4 mounting is convenient when a cementing technique is appropriate, with the possibility of removing the accelerometer from time to time.
Type 5 mounting employs the probe with interchangeable round and pointed tips. The method may be convenient for certain applications, but should not be used for frequencies much higher than 1000 Hz, since the natural resonance frequency in this case is very low.
Type 6 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. 3.3. 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.
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. 3.3 shows some frequency response curves obtained for various types of mounting. The importance of the mounting method used should be obvious.

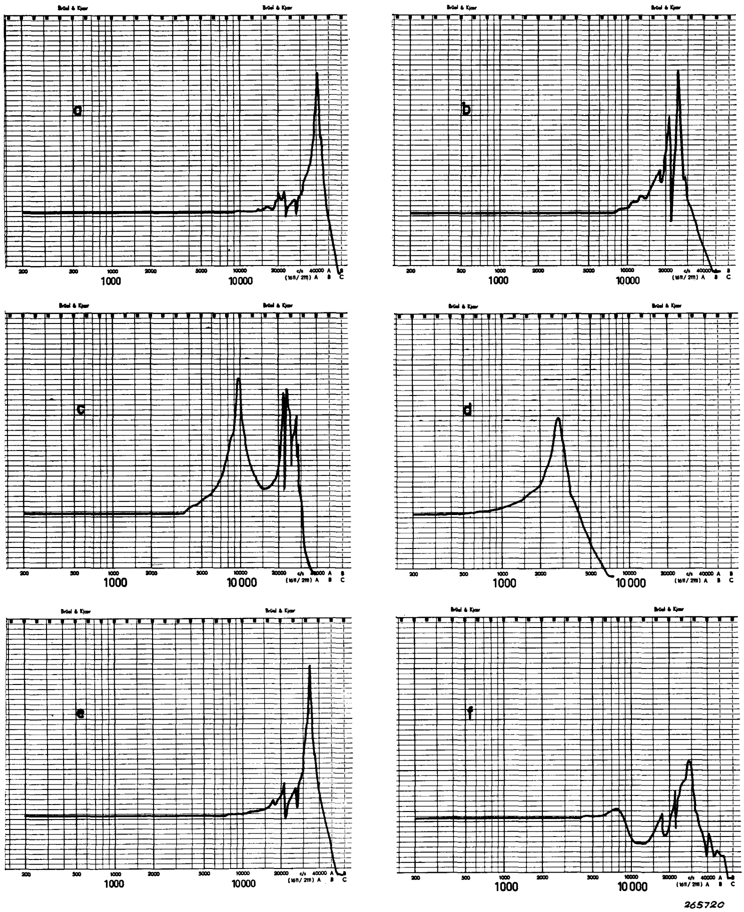


Fig. 3.3. Frequency response of an accelerometer for various types of mounting.

a) Steel stud. *b) Isolated stud.*
c) Magnet. *d) Probe.*
e) Wax. *f) Soft glue (not recommended).*

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.

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.

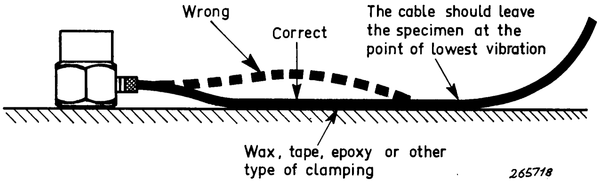


Fig. 3.4. Clamping of the cable to the vibrating specimen.

Mounting of Cable

The connecting cable should always be given particular attention. Especially at lower frequencies it may give rise to noise voltages, due to bending or cable whip. The B & K accelerometer cable is designed and treated for noiseless operation, however, it is always good policy to clamp the cables as firmly as possible in order to avoid retalive movement. See Fig. 3.3.

4. 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 voltage 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 circuit of an accelerometer with external loading is drawn in Fig. 4.1.

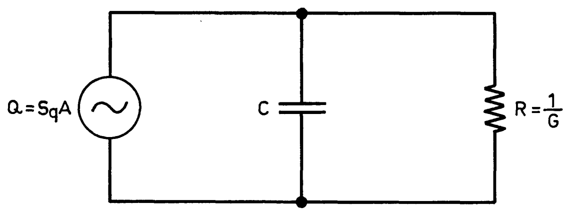


Fig. 4.1. Equivalent circuit of accelerometer and preamplifier.

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.

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

$$I = j\omega Q$$

and the voltage output

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

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:

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

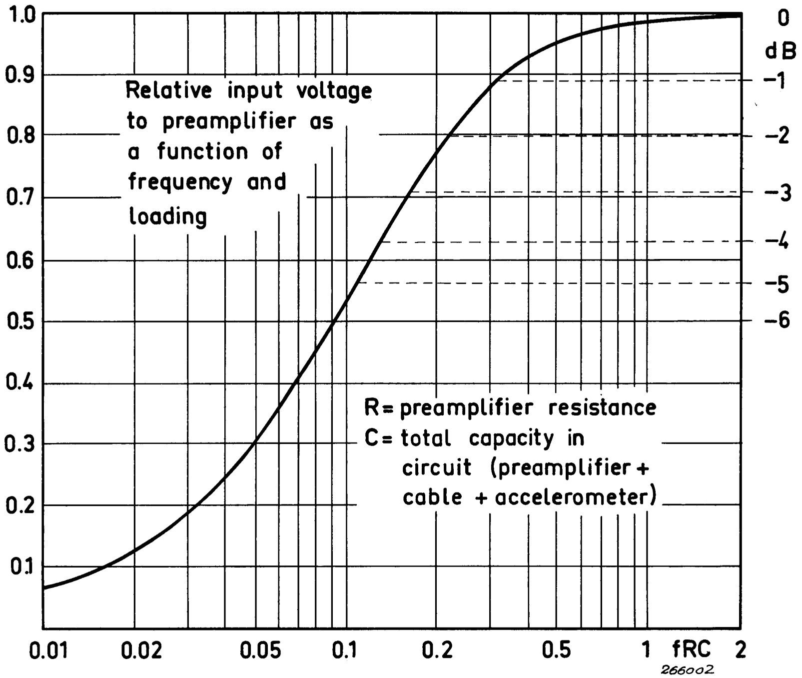


Fig. 4.2. Chart for finding required input impedance when accelerometer capacity and low frequency cut-off is given.

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 $/G/ = /j\omega C/$

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

where f_c is called the "cut-off frequency".

The internal resistance of the accelerometers is extremely high, always exceeding 20,000 MΩ at room temperature (~ 20° C). The resistance of the piezoelectric material is lower at high temperatures but usually still higher than 20,000 MΩ 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. Fig. 4.2 gives a chart for finding the required input resistance for a given lower limiting frequency and a given accelerometer capacity.

Example:

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

Solution:

A 1 dB cut-off is seen to give a value of about 0.3 for *fRC,* i.e.

$$fRC = 0.3$$

$$R = \frac{0.3}{fC} = \frac{0.3}{1 \times 1000 \times 10^{-12}}$$

$$R = 300 \text{ M}\Omega$$

The minimum acceptable input resistance of the preamplifier is 300 MΩ.

Cable Capacitance Sensitivity Correction

The capacity of the cable connecting the accelerometer to the preamplifier will reduce the voltage sensitivity of the accelerometer. When the charge sensitivity of the accelerometer is given, as is the case with all B & K accelerometers, the easiest way to obtain the voltage sensitivity for any particular system is to divide the charge sensitivity by the total shunt capacity in the input circuit, i.e. accelerometer capacity, cable capacity and preamplifier input capacity. The capacity of the B & K accelerometer cable is about 90 pF/m (27 pF/ft).

Example:

An accelerometer has a charge sensitivity of 11.18 pCoulomb/g and a capacity without cable of 1014 pF. What is its voltage sensitivity with a connection cable of 4 m length? Preamplifier input capacity negligible.

Solution:

Cable capacity $4 \times 90 = 360$ pF

Total capacity $360 + 1014 = 1374$ pF

Voltage sensitivity $\frac{11.18}{1374} = 0.00816$ V/g $= 8.16$ mV/g

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

$$E_o = \frac{Q}{(C_a + C_c + C_i) / A - C_f (1 - 1/A)}$$

$$= \frac{QA}{C_a + C_c + C_i - C_f (A - 1)}$$

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

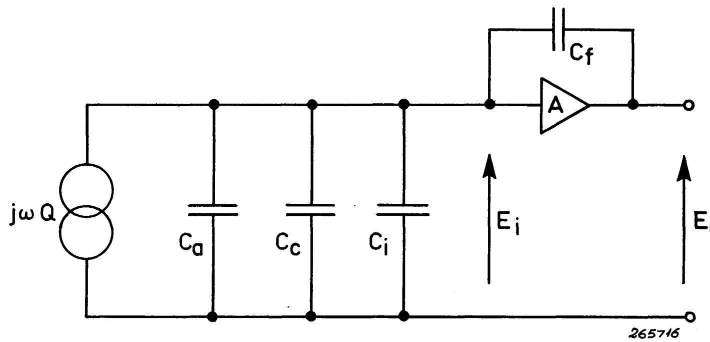


Fig. 4.3. Equivalent circuit diagram for accelerometer, cable and charge amplifier.

The charge sensitivity is given on the calibration chart for the B & K accelerometers, but when this is not given it can easily be calculated by multiplying the voltage sensitivity with the total capacity (accelerometer plus cable) used in the calibration.

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).

Although the charge amplifier has advantages for certain applications, the following points should be considered:

The large amplification necessary for proper operation of the charge amplifier requires more components than what is necessary for a voltage amplifier. In practice this means higher costs and less reliable operation in severe environments.

More serious is the inferior rise time and recovery time obtained for most charge amplifiers. This is especially important for shock-measurements.

One of the arguments in favour of the charge amplifier is the possibility of using long cables between transducer and amplifier. This is, however, just as possible with voltage amplifier, if the gain is high enough to offset the loss in sensitivity, and in addition to this the voltage amplifier may have a superior signal to noise ratio. Charge amplifiers are therefore not recommended when low signals are to be measured.

One may conclude that voltage preamplifiers are to be preferred for the majority of applications. For special installations where long cables are used in different lengths, for example on vibration test sites or for measurements on large structures, the charge amplifier would be a natural choice.

Brüel & Kjær Preamplifiers

Brüel & Kjær produce several types of preamplifiers for use with the accelerometers in vibration measuring set-ups.

1. F.E.T. Preamplifier Type 2623.
2. F.E.T. Preamplifier Type 2616.
3. F.E.T. Vibration Pick-up Preamplifier Type 2625.
4. F.E.T. Charge Amplifier Type 2624.
5. Preamplifier Type 1606.
6. Two-Channel Preamplifier Type 2622.
7. F.E.T. 1/2" Microphone Preamplifier Type 2619.
8. Cathode Followers (several types).

A brief description of these follows.

1. Preamplifier Type 2623

The Preamplifier Type 2623 is an impedance conversion device of an extremely small and rugged construction. See Fig. 4.4. It is designed to withstand severe environmental conditions and its sensitivity to vibration is negligible. Attempts have been made to measure its output signal due to direct vibration but no progress was made, as the output from the connecting lownoise cables was greater than the preamplifier signal.

The Preamplifier is a two-stage transistorized amplifier with a field effect transistor in the input stage, coupled to the input via a 1000 pF capacitor. The equivalent circuit diagram is shown in Fig. 4.5. The input impedance together with the accelerometer capacitance, determine the lower cut-off frequency of the system, e.g. with a 1000 pF accelerometer the limit is about 0.12 Hz. (The 1000 pF capacitor in the input must be added in series with the accelerometer capacity).

Fig. 4.4. Preamplifier Type 2623.

The input resistance is about 2700 MΩ at room temperature and lower, but decreases at higher temperatures. A curve of this effect is shown in Fig. 4.6. At 100° C the resistance is about 300 MΩ and the lower limiting frequency increases to about 1.2 Hz.

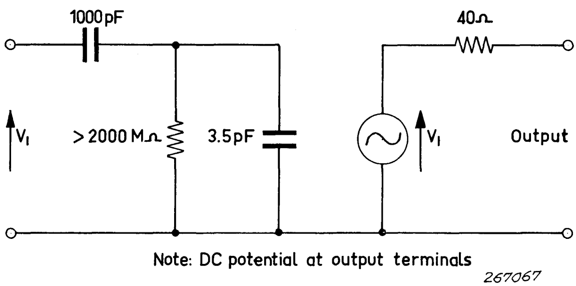


Fig. 4.5. Equivalent circuit for the preamplifier.

The input transistor is DC coupled to the following stage. This stage produces a negative feedback, which is adjusted so that the total voltage gain is 0 dB. There is a DC potential at the output of about 11 V and therefore the resistive load on the output should not be less than 50 kΩ. The capacitive load depends

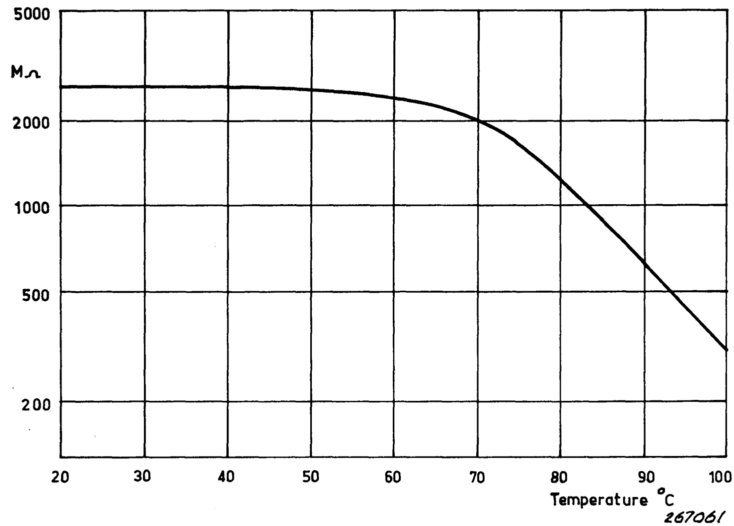


Fig. 4.6. The effect of temperature on the input resistance of the preamplifier.

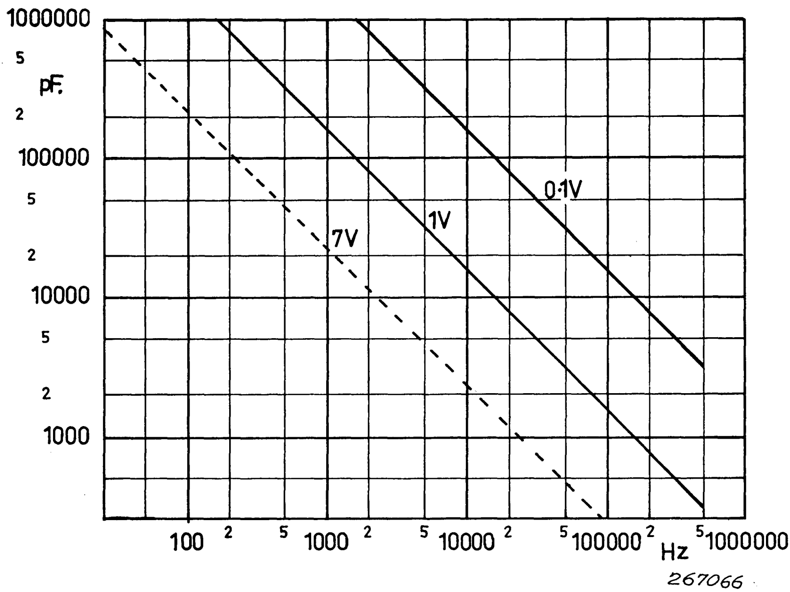


Fig. 4.7. High frequency limit of the preamplifier as determined by capacitive loading and signal level.

upon the upper limiting frequency desired and on the signal level. (Max. output current 1 mA for about 1 % distortion). A load of 10,000 pF (100 m of cable) at 1 V RMS will give an upper limiting frequency of 15 kHz. See Fig. 4.7.

The rise time of this preamplifier is extremely short, making it eminently suited for shock work. Fig. 4.8 shows rise time for positive and negative step voltages as obtained on an oscilloscope.

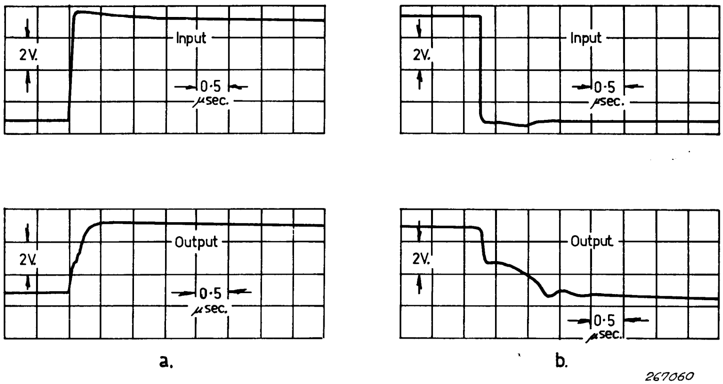


Fig. 4.8.
a) Response of the preamplifier to a positive step input.
b) Response to negative step input.

The preamplifier may be mounted close to the accelerometer. The mounting method is shown in Fig. 4.9.

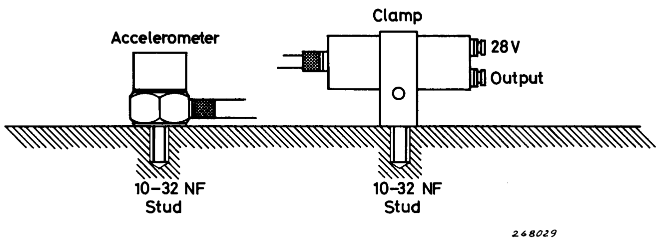


Fig. 4.9. The Preamplifier Type 2623 clamped near to the accelerometer.

The power for the Preamplifier is taken from an external 28 V DC supply, a battery or the Power Supply ZR 0024 which is plugged into the condenser microphone socket of the B & K amplifiers. The current consumption is about 2 mA.

SPECIFICATIONS 2623

Input Resistance:	Min. 2000 MΩ at 25° C Min. 200 MΩ at 100° C
Input Capacitance:	3.5 pF parallel 1000 pF series
Output Resistance:	40 Ω (typical)
Max. Output Current:	1 mA
Voltage Gain:	0 dB ± 0.05 dB
Frequency Range:	0.12 Hz – 500 kHz with 1000 pF across input
Noise:	15 μV, 2–40,000 Hz 3.5 μV, curve C 300 pF across input
Dynamic Range:	30 μV – 7 V RMS with 28 V DC supply
Power Supply:	External, 28 V DC
Diameter:	14 mm (0.55 in)
Length:	45 mm (1.77 in) 52 mm (2.05 in) with accelerometer adaptor
Weight:	20.6 g (0.73 oz)
Accessories Included:	1 Adaptor for accelerometer 1 Clamp 2 Cables AO 0037 Screws (NF 10-32)

Fig. 4.10. Preamplifier Type 2616.

2. Preamplifier Type 2616

The Preamplifier Type 2616 is a battery driven transistorized unit with a field effect transistor in the input stage. Due to the small dimensions of the Preamplifier it can usually be placed very close to the accelerometer and its low output impedance ensures that noise and loss in the cable do not interfere with the measurements even when a very long cable connection is used between the preamplifier and the indicating instrument.

From the input terminals the signal is fed via a 2000 pF capacitor and a capacitive attenuator to the input stage which is DC coupled to the second stage. This stage acts as a feedback amplifier. An equivalent diagram is shown in Fig. 4.11. Note that the 2000 pF series capacitor does not show up in the input impedance. Thus the lower limiting frequency is calculated on the basis of the accelerometer capacity (in parallel with any cable capacity) and the input resistance of the preamplifier. A 1000 pF accelerometer then gives a lower limiting frequency of about 0.13 Hz.

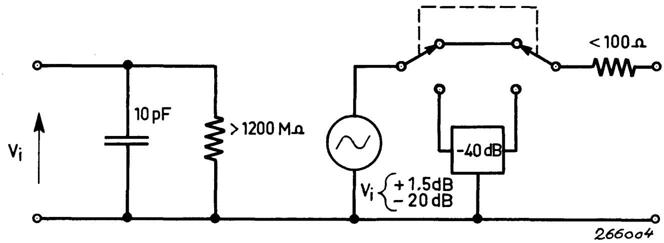


Fig. 4.11. Equivalent circuit for the preamplifier.

A peak indicating overload indicator reacts on signals with crest factor up to 10 and for frequencies higher than 20 Hz.

The signal is fed to the output stage via a potentiometer. This makes it possible to adjust the voltage gain from + 1.5 to – 20 dB.

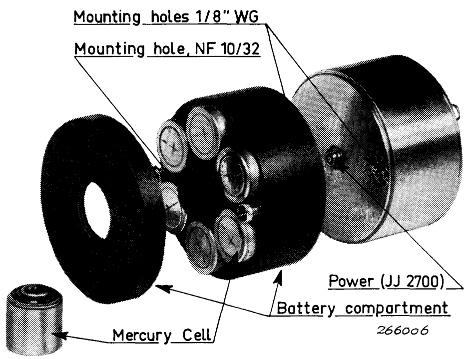


Fig. 4.12. Exploded view of the preamplifier with battery compartment.

The output current should not exceed 1 mA giving the same high frequency limits as for Type 2623 (see Fig. 4.7). However, Type 2616 has a built-in 40 dB attenuator which may be used to attenuate the input signal and thereby increase the useful dynamic range of the preamplifier.
Power is taken from six mercury cells (1.35 V each) contained in a battery compartment attached to the preamplifier. See Fig. 4.12. This compartment is removable and the preamplifier may be connected to an external power supply of any voltage from 6–35 V DC. A built-in network stabilizes the voltage and reduces ripple from an external power supply by about 40 dB.

SPECIFICATIONS 2616

Input Resistance:	$>$ 1200 MΩ
Input Capacitance:	10 pF (typical)
Output Resistance:	$<$ 100 Ω
Max. Output Current:	1 mA
Frequency Range:	0.13 Hz – 500 kHz with 1000 pF across input
Noise:	Max. 20 μV, 2 Hz – 40 kHz with 1000 pF across input
Dynamic Range:	30 μV – 1 V RMS with attenuator on 0 dB. 40 mV – 100 V RMS with attenuator on – 40 dB
Rise Time:	1 μsec
Signal Adjustment:	+ 1.5 to – 20 dB with attenuator on 0 dB
Power:	Internal battery. Six mercury cells of 1.35 V. External supply 6–35 V DC
Current Consumption:	4–10 mA
Dimensions:	Diameter 52 mm (2 in). Total height including battery compartment 66 mm (2.6 in)
Weight:	290 g (10.3 oz) 162 g (5.7 oz) excl. battery compartment.

3. Vibration Pick-up Preamplifier Type 2625

The Vibration Pick-up Preamplifier Type 2625 is provided with integration networks for measurement of velocity and displacement in addition to acceleration.
A block diagram of the preamplifier is shown in Fig. 4.14. There are three input sockets connected to a selector switch with individual sensitivity adjustment of each input. The two inputs not in use are connected to ground. The function selector controls four different gain ranges for the three inputs:

1) variable from – 40 dB to – 20 dB
2) variable from 0 dB to + 20 dB
3) fixed at 0 dB
4) fixed at – 40 dB

The integration networks are passive RC networks with three different lower frequency limits, 1, 10 and 100 Hz for velocity measurements, and six limits, 1, 3, 10, 30, 100 and 300 Hz for displacement measurements. These different

Fig. 4.13. Vibration Pick-up Preamplifier Type 2625.

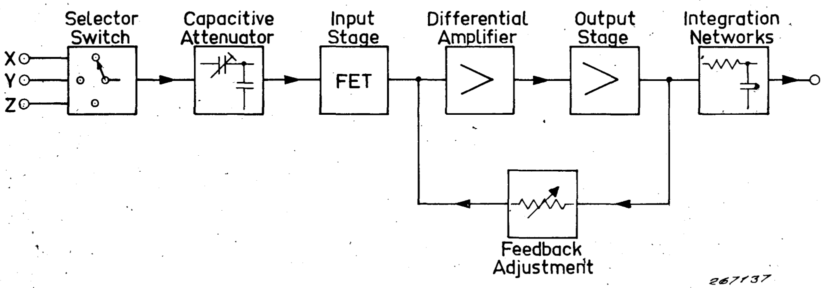


Fig. 4.14. Block diagram of Type 2625.

networks are used in order to obtain the best possible signal to noise ratio, and the low frequency limit should be set as high as possible. The frequency response curves for the various modes of operation are given in Figs. 4.15 and 4.16.

The output signal can be taken from a standard microsocket 10-32 NF or a B & K coaxial socket at the front panel. Additionally there is a microsocket output at the back of the preamplifier.

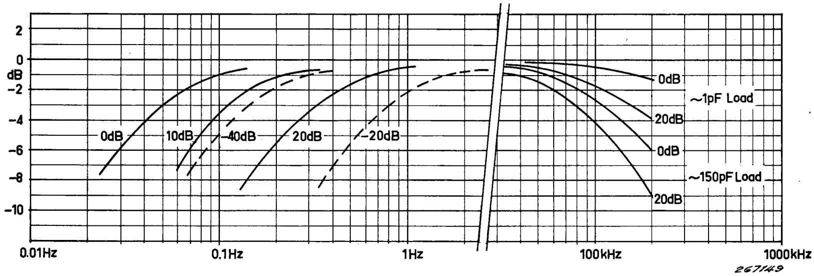


Fig. 4.15. Frequency response of Type 2625 in the acceleration mode.

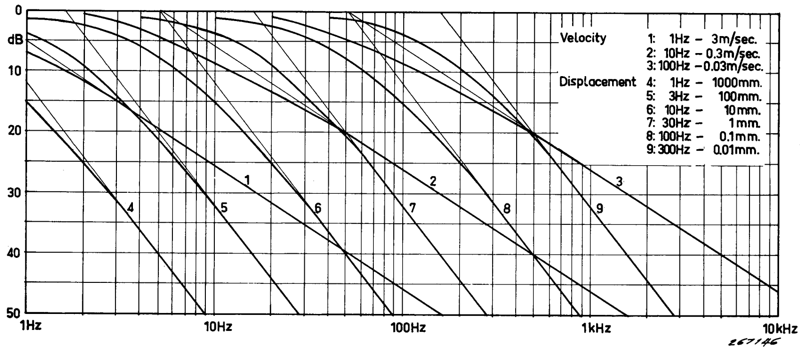


Fig. 4.16. Frequency characteristics of integration networks.

A field effect transistor stage in the input circuit gives extremely high input impedance. It varies, however, with the gain adjustment, being at maximum at zero gain as shown in Fig. 4.17. For very low frequency or shock measurements it may therefore be an advantage to set the gain to 0 dB as the low frequency limit is influenced by the input impedance.

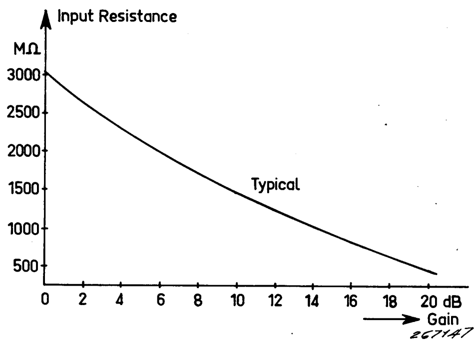


Fig. 4.17. Typical input impedance as a function of the gain.

The maximum output voltage is ± 7 volts with a maximum current of ± **1 mA** peak. Distortion originating in Type 2625 is shown in Fig. 4.18 for 0 dB **and** 20 dB gain setting.
The preamplifier has built-in battery compartment for battery operation or may be powered by external source, 28 V DC.

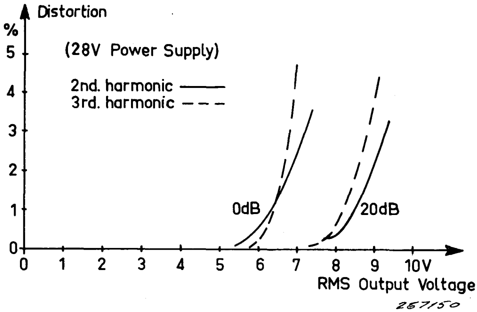


Fig. 4.18. Distortion as a function of output voltage.

SPECIFICATIONS 2625

Input Resistance: Varies from 3 GΩ at 0 dB gain to 450 MΩ at 20 dB gain

Input Capacitance: 14 pF

Frequency Range:

Acc.			1 Hz –	35 kHz
Vel.	3.16	m/sec	1 Hz –	4 kHz
Vel.	0.316	m/sec	10 Hz –	10 kHz
Vel.	0.0316	m/sec	100 Hz –	30 kHz
Displ.	1000	mm	1 Hz –	30 Hz
Displ.	100	mm	3 Hz –	100 Hz
Displ.	10	mm	10 Hz –	300 Hz
Displ.	1	mm	30 Hz –	1,000 Hz
Displ.	0.1	mm	100 Hz –	3,000 Hz
Displ.	0.01	mm	300 Hz –	10,000 Hz

Max. Input Signal:
± 0.7 V at 20 dB gain
± 7 V at 0 dB gain
± 70 V at – 20 dB gain
± 700 V at – 40 dB gain

Gain: Fixed 0 dB and – 40 dB. Variable 0 dB to 20 dB and – 40 dB to – 20 dB

Inherent Noise: Max. 20 μV from 2 Hz to 40 kHz with 1 nF across input (referred to input)

Load Impedance: Min. 1 MΩ//max. 100 pF.

Harmonic Distortion: Less than 1 % with 5 V RMS output

Power Supply: External 28 V DC source (for example ZR 0024) or internal 3 × 9 V batteries (not included)

Batteries: 3 × 9 V. IEC Recommendation 6 F 22, size 25.5 × 17.5 × 48.5 mm

Examples:

Manufacturer	Type
Union Carbide	Ever Ready No. 216
Hellesen	Type H 10
Varta Pertrix	No. 438
Tudor	No. 9 T 4
National	U-006 P

Current Consumption: Approximately 2 mA.

Dimensions (excluding knobs and feet):

Height: 132.6 mm (5.22 in)
Width: 61 mm (2.40 in)
Depth: 200 mm (7.87 in)

Weight: 820 g (1.8 lb.)

Accessories Included: Two cables AO 0037, 1.2 m (4 ft.) long. One coaxial plug JP 0018

4. Charge Amplifier Type 2624

The combination of a charge amplifier and a piezoelectric accelerometer gives a sensitivity which is independent upon cable length within very wide limits. This makes a charge amplifier especially attractive in vibration systems where different cables are used. The Charge Amplifier Type 2624 may be used with cable lengths up to several thousand metres. A charge amplifier also gives possibility of very low frequency measurements and in the case of Type 2624, the limit is 0.003 Hz in the least sensitive mode. This makes the preamplifier ideal for measurements of shocks and long duration transients.

The preamplifier is provided with an overload indicator which lights up when the dynamic range is exceeded and when the amplifier is blocked due to saturation. A reset button is used for recovery of normal working conditions after overload. CAUTION: This preamplifier must not be used in servo control loops because of the blocking of the amplifier when overloaded. The output impedance is extremely low and if necessary long output cables may be used without causing distortion. There is a permanent voltage of 12.5 V DC at the output.

The output may be scaled to 0.1, 1 or 10 mV/pC with different low frequency limits. See specifications. The low frequency limit should be set as high as possible to reduce recovery time without making use of the reset facility. Input and output sockets are microsockets 10-32 NF.

Fig. 4.19. The Charge Amplifier Type 2624.

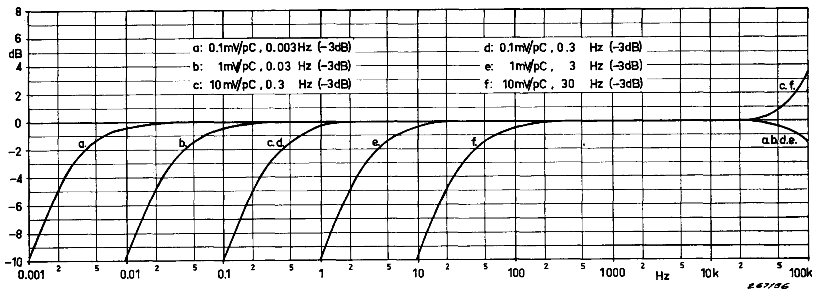


Fig. 4.20. Typical frequency curves of the charge amplifier.

The preamplifier is completely protected against overload and short circuits. It is also protected against interchanging the supply and signal cables and there is a possibility of separating electrical and mechanical ground by removing only one connection in the instrument.

A mounting system has been designed which allows the mounting of several preamplifiers, power supply etc. into a common housing, which again may be fitted into standard 19" racks.

SPECIFICATIONS 2624

Sensitivity: 0.1 – 1 – 10 mV/pC, tolerance at 100 Hz: ± 1 %.

Input Load: Maximum permissible capacitive load for the three ranges is 1 μF, 0.1 μF and 10 nF respectively (10 km, 1 km and 0.1 km with cable 100 pF/m). This load will cause less than 1 % reduction of sensitivity.

Frequency Range: Lower 3 dB limits (half-power points): 0.003, 0.03 and 0.3 Hz or alternatively 0.3, 3 and 30 Hz. Lower limiting frequency tolerance: ± 20 %.

With negligible capacitive load at the input the frequency ranges in the six positions are:

	Sensitivity mV/pC	– 3 dB point Hz	Frequency range Hz
a	0.1	0.003	0.3–30,000 ± 1 %
b	1	0.03	0.03–30,000 ± 1 %
c	10	0.3	5–10,000 ± 5 %
d	0.1	0.3	3–30,000 ± 1 %
e	1	3	30–30,000 ± 1 %
f	10	30	150–10,000 ± 5 %

Capacitive input load causes a high frequency boost with a maximum peak at frequencies higher than 20 kHz. Under full capacitive load conditions (see "Input Load"), i.e. about 10 km, 1 km and 100 m cable, the increase of sensitivity at 20 kHz is less than 10 %.

Input DC Shunt Resistance: Greater than 10 GΩ. While resetting 25 kΩ ± 10 %.

Output Voltage and Current: Max. 20 V peak-to-peak (DC voltage typically 12.5 V), ± 10 mA. The output is short circuit protected.

Output Impedance: Less than 1 Ω when input load is less than 1/4 full load. 3–5 Ω at full input load.

Harmonic Distortion: Less than 0.5 % at full output and no capacitive load, frequency lower than 20 kHz. Less than 5 % at full output and full cable capacity, frequency lower than 20 kHz.

Noise Level: Referred to the output terminal the maximum self-generated noise in the three ranges is:

0.1 mV/pC: 10 μV + max. 0.05 μV per 100 pF source capacity.

1 mV/pC: 10 μV + max. 0.5 μV per 100 pF source capacity.

	10 mV/pC: 20 μV + max. 5 μV per 100 pF source capacity.
	(Source capacity = cable capacity + transducer capacity).
	Noise bandwidth 2 Hz – 40 kHz.
	Typically 8 μV in the 0.1 mV/pC range at short cable lengths.
Pulse Response:	Measured without cable capacity, rise time is proportional to pulse height featuring a slope of typically 1.8 V/μsec. Decay-time is constant and typically 2 μsec.
Overload Recovery Time:	The input is overload protected. Overload recovery time constant is equal to $1/2\pi f_n$ in pos. d, e and f (see "Frequency Range") i.e. min. 5 msec. The amplifier has been provided with overload indicator and manual reset facilities.
Power Supply:	External 28 V DC ± 10 %. Current consumption: Normal working conditions 17 mA (typical). With overload indicator lit max. 40 mA. With output terminals shorted max. 150 mA.
Dimensions: (excl. knobs and feet)	Height: 132.6 mm (5.22 in) Width: 30.3 mm (1.19 in) Depth: 200 mm (7.87 in)
Weight:	585 g (1.29 lb).
Accessories Included:	Two cables AO 0037, 1.2 m (4 ft.) long.

5. Preamplifier Type 1606

The Preamplifier Type 1606 is designed for measurements of acceleration, velocity and displacement, when used with an accelerometer type of pick-up. In addition it provides facilities for absolute calibration of the vibration measuring set-up.

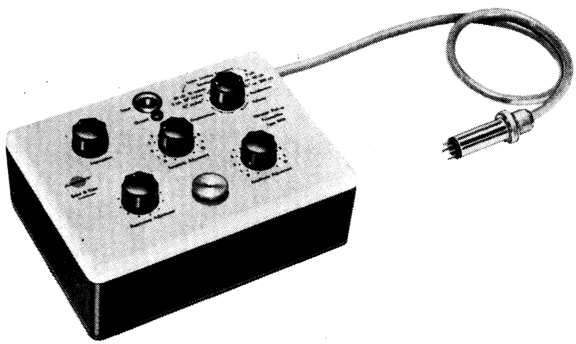


Fig. 4.21. Preamplifier Type 1606.

A block diagram of the Preamplifier is shown in Fig. 4.22. It consists of a capacitive attenuator, an amplifier with variable feedback and integrating networks for signal processing. A mains operated shaker table with adjustable amplitude is included for accelerometer calibration. The output is taken to any B & K amplifier with a condenser microphone input socket.

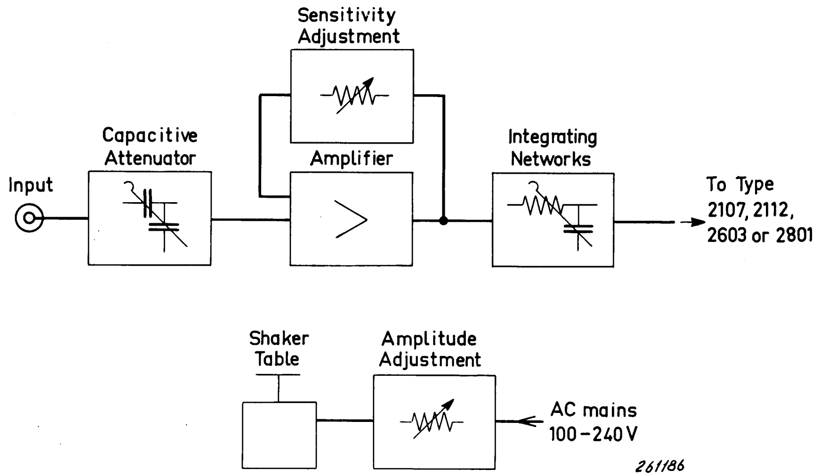


Fig. 4.22. Block diagram of the preamplifier.

The amplifier is a two-stage RC coupled amplifier with a large amount of negative feedback. The input attenuator is variable in two 40 dB steps. A sensitivity adjustment potentiometer varies the feedback of the amplifier whereby the preamplifier gain is varied from 0 to 38 dB. The high input impedance makes measurement possible down to lower than 2 Hz. See Fig. 4.23.

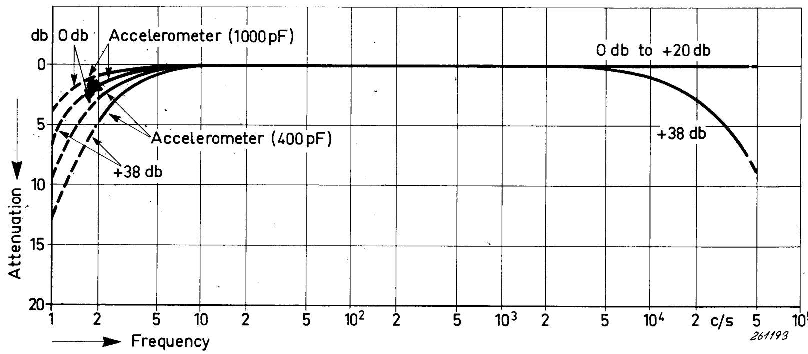


Fig. 4.23. Frequency response of the preamplifier adjusted to 0, 20 and 38 dB gain.

The integrating networks succeeding the amplifier are designed as simple RC networks. One integrating network is used for velocity measurements and two cascaded networks for displacement. To provide sufficient dynamic range two different velocity networks with cut-off frequencies 3 and 30 Hz respectively, and three displacement networks with cut-off frequencies 3, 30 and 300 Hz are included.

SPECIFICATIONS 1606

Input Impedance:	200 MΩ in parallel with approx. 50 pF
Amplification:	0–38 dB
Input Attenuator:	Two steps of 40 dB
Max. Output Voltage:	20 V peak in acceleration
Noise:	Approx. 12 μV referred to input at max. amplification
Vibrating Table:	Mains driven at 50 or 60 Hz. Can be adjusted to 1 g by the rattling ball method. Power supply 100–240 V
Dimensions:	Height: 10.5 cm (4 in) Width: 25 cm (10 in) Depth: 18 cm (7 in)
Weight:	3.9 kg (9 lbs)
Accessories Included:	1 power lead, 3 screws W 1/8" 1 screened plug JP 0018, 1 Allen key 1 adaptor W 1/8" to NF 10-32

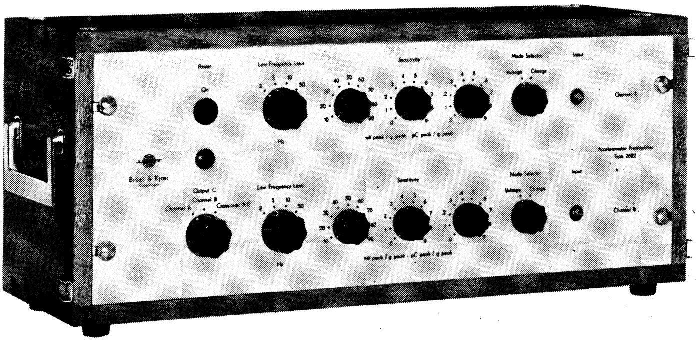


Fig. 4.24. Preamplifier Type 2622.

6. Accelerometer Preamplifier Type 2622

This is a two-channel accelerometer preamplifier which can be used both as a voltage amplifier and as a charge amplifier, the conversion from one to the other being effected with a front panel switch. Each channel has a three-decade attenuator which is set directly to the voltage or charge sensitivity of the accelerometers employed, in the range 10–100 mV/g or 10–100 pCoulomb/g. The output voltage is then scaled to 10 mV/g.

The Preamplifier is designed with a definite view to being employed with other B & K instruments in vibration test systems, but may equally well be used as an ordinary voltage or charge amplifier in vibration measuring systems. Efforts have been taken to make the two channels identical, with identical phase characteristics, so that the Preamplifier may be employed in correlation measurements, mechanical impedance measurements or otherwise where phase relations are investigated. A block diagram of the Preamplifier is shown in Fig. 4.25. Only one channel is drawn since the two channels are identical.

The main features of this preamplifier is its ability to switch between voltage amplification and charge amplification, together with its sensitivity scaling and cut-off filters for convenient operation in the compressor loops of the B & K generators in vibration test systems.

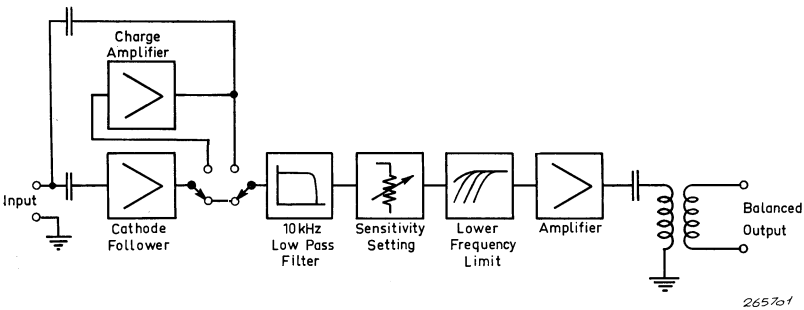


Fig. 4.25. Block diagram of the preamplifier.

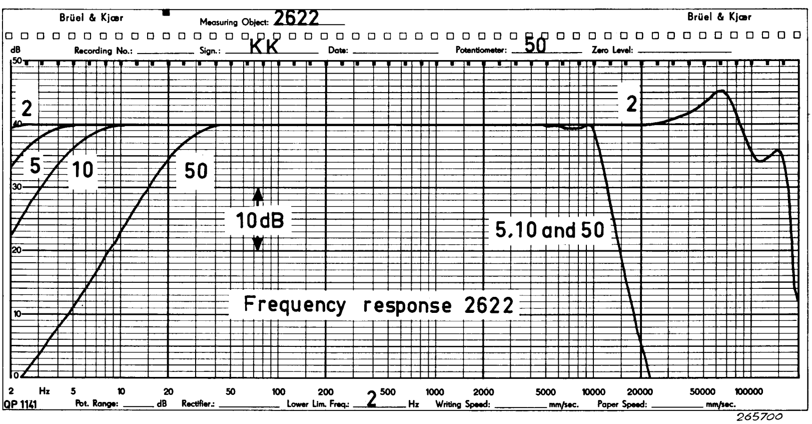


Fig. 4.26. Frequency response of the preamplifier for the different settings of LOW FREQUENCY LIMIT.

Low frequency noise which is especially disturbing in velocity or displacement measurements using integrating circuits is eliminated with a variable high-pass filter with cut-off frequencies of 2, 5, 10 and 50 Hz.
A low-pass filter is included in the circuit in order to cut off high frequency signals, due for example to extraneous noise and accelerometer resonance. The cut-off frequency of the low-pass filter is 10 kHz. When the high-pass filter is set to cut off at 2 Hz the low-pass filter is not in circuit. See Fig. 4.26.
The outputs from the two channels are taken to the output sockets via balancing transformers so that the accelerometer and preamplifier may be isolated from the rest of the system to reduce effects of ground loops. Apart from the two outputs there is a third output socket which may be switched to any one of the two channels, either with a switch on the instrument itself or by remote control.

SPECIFICATIONS 2622

Two identical channels which may be switched individually to voltage or charge amplification.

Input Impedance: Voltage Amplifier: Greater than 600 MΩ in parallel with 16 pF.
Charge Amplifier: Approx. 0.75 μF input capacity at 1000 Hz. Less than 2 % change in gain from 0 to 10,000 pF source capacity.

Output Impedance: Smaller than 200 Ω.

Scaling: Output scaled to 10 mV/g ± 1 % for correct setting of accelerometer sensitivity.

Accelerometer Sensitivity: Between 10 and 100 mV/g or 10 and 100 pCoulomb/g for correct scaling.

Input Voltage Level: Max. 40 mV peak at 2 Hz, max. 1.5 V peak at 5 Hz, max. 20 V peak at frequencies between 40 Hz and 10,000 Hz for distortion less than 1 %.

Frequency Limits: (High-pass filter setting 2, 5, 10 or 50 Hz).
2 Hz: Low frequency limit 2 Hz (0.5 dB), high frequency limit 10,000 Hz (0.5 dB), filters not switched in.
5 Hz: Low frequency limit 5 Hz (0.25 dB point), 6 dB down at 2 Hz, high frequency limit 10,000 Hz (0.5 dB point), 30 dB down at 20,000 Hz.
10 Hz: Low frequency limit 10 Hz (0.25 dB point), 15 dB down at 2 Hz, high frequency limit 10,000 Hz (0.5 dB point), 30 dB down at 20,000 Hz.
50 Hz: Low frequency limit 50 Hz (0.25 dB point), 40 dB down at 2 Hz, high frequency limit 10,000 Hz (0.5 dB point), 30 dB down at 20,000 Hz.

Frequency Response:	Flat within ± 0.2 dB from low frequency limit to 5000 Hz, 0.5 dB ± 0.5 dB down at 10,000 Hz.
Noise and Hum Level:	Voltage Amplifier: Less than 80 μV noise. Less than 10 μV hum. Charge Amplifier: Less than 80 μV noise plus 5 μV per 1000 pF of source capacitance. Less than 10 μV hum plus 5 μV per 1000 pF of source capacitance. (Worst case). With 300 pF on input, 10 Hz lower limiting frequency, and the preamplifier followed by two integrators with 5 Hz corner frequencies, the displacement signal noise level is better than 30 μV, i.e. equivalent to about 0.033 in or 77 μmetre.
Cross-Talk:	More than 60 dB attenuation from one channel to the other.
Third Output:	May be switched to any one of the channel outputs. Manual or remote control.
Phase Relations between channels:	Less than 5° difference in the range 2 Hz to 10 kHz. LOW FREQUENCY LIMIT set to 2 Hz.
Mains Supply:	100 – 115 – 127 – 150 – 220 or 240 V ± 10 %, 50–400 Hz.
Accessories Supplied:	1 power cable, 2 input plugs, 3 output plugs, 1 remote control plug, spare panel lamp and fuses.

Dimensions and Weight:

	Height	Width	Depth	Weight
Type 2622 B (Mahogany cabinet)	20.6 cm 8″	51 cm 20″	20.6 cm 8″	9.5 kg
Type 2622 C (For stand. 19″ rack)	17.7 cm 7″	48 cm 19″	16.6 cm 6.5″	6.5 kg

7. 1/2″ Microphone Preamplifier Type 2619

This microphone preamplifier is also an excellent preamplifier for piezoelectric accelerometers due to its extremely high input impedance and very wide frequency and dynamic ranges. Among other accessories an Adaptor JJ 2615 is included for the connection of miniature accelerometer cables. This adaptor contains a 50 pF capacitor for blocking the polarization voltage. With its wide frequency range and short rise and fall times, the preamplifier is ideal for measurements of transient signals and shocks. The preamplifier can be plugged into any B & K instrument with a microphone input socket.

Fig. 4.27. 1/2" Microphone Preamplifier Type 2619 and accessories.

SPECIFICATIONS 2619

Supply Voltage, DC	120 V	28 V
Frequency Range ± 1 dB	2 Hz – 200 kHz[1]) 2 Hz – 20 kHz[2])	2 Hz – 200 kHz[3]) 2 Hz – 20 kHz[4])
Dynamic Range, 20 Hz – 200 kHz (5 dB above noise to 4 % dist.)	115 dB	98 dB
Input Resistance at 20°C at 80°C	> 4000 MΩ > 2500 MΩ	> 2900 MΩ > 1500 MΩ
Input Capacity	< 0.5 pF	< 0.6 pF
Output Impedance	Approx. 25 Ω	Approx. 70 Ω
Gain	– 0.01 dB	– 0.04 dB
Max. Inp. Volt., Sine Wave (4 % dist.)	40 V RMS	5 V RMS
Max. Output Current	1.5 mA Peak	0.5 mA Peak
Power Consumption	2 mA	1 mA

[1]) 4 V RMS [2]) 15 V RMS [3]) 0.1 V RMS [4]) 2.5 V RMS

Noise, 20 Hz – 200 kHz: (JJ 2615 at input)	$< 18\ \mu V$ $< 17\ \mu V$ with heating element disconnected
Pulse Rise Time:	0.2 μsec
Decay Time:	0.6 μsec
Temperature Range:	– 20 to + 100°C (+ 60°C only for the socket unit)
Dimension:	1/2" dia
Connection Type:	7-pin, B & K
Cable Length:	2 m (6.6 feet)
Accessories Included:	Adaptor for 1" microphone (DB 0375), Coaxial input plug adaptor for miniature cables (JJ 2615), Goose-neck UA 0196).

Fig. 4.28. B & K Cathode followers.

8. Cathode Followers

The B & K cathode followers are excellent preamplifiers for piezoelectric accelerometers due to their high input impedance and very wide frequency and dynamic ranges. Small size and a rugged construction make them suitable for operation in most laboratory and field measuring set-ups. Type 2615 is recommended for shock work.

The cathode followers are plugged into any B & K instrument with a microphone input socket.

SPECIFICATIONS

Cathode Follower Type	*2612*	*2613*	*2614*	*2615*
Input Impedance	270 MΩ paralleled by 3 μμF		700 MΩ paralleled by 3 μμF	
Output Impedance	Approximately 750 Ω		Approximately 750 Ω	
Gain	− 0.8 dB ± 0.2 dB		− 0.9 dB ± 0.2 dB	
Self-generated Noise Level in wide band (20 Hz—200 kHz)	Less than 30 μV (input loaded by 60 μμF)		Less than 40 μV (input loaded by 20 μμF)	
Max. input voltage	20 V (4 % distortion limit when loaded by a resistance greater than 50 kΩ)			
Frequency range	Only limited by the capacity connected at the output (up to above 100 kHz with B & K equipment and without extension cables)			
Connection type	goose neck	2 m long cable	goose neck	2 m long cable
Diameter of the housing Length of the housing	0.936 inch (23.77 mm) 2 inches (50 mm)		½ inch (12.7 mm) 2¾ inches (70 mm)	

5. Measuring Systems

Brüel & Kjær Measuring Systems

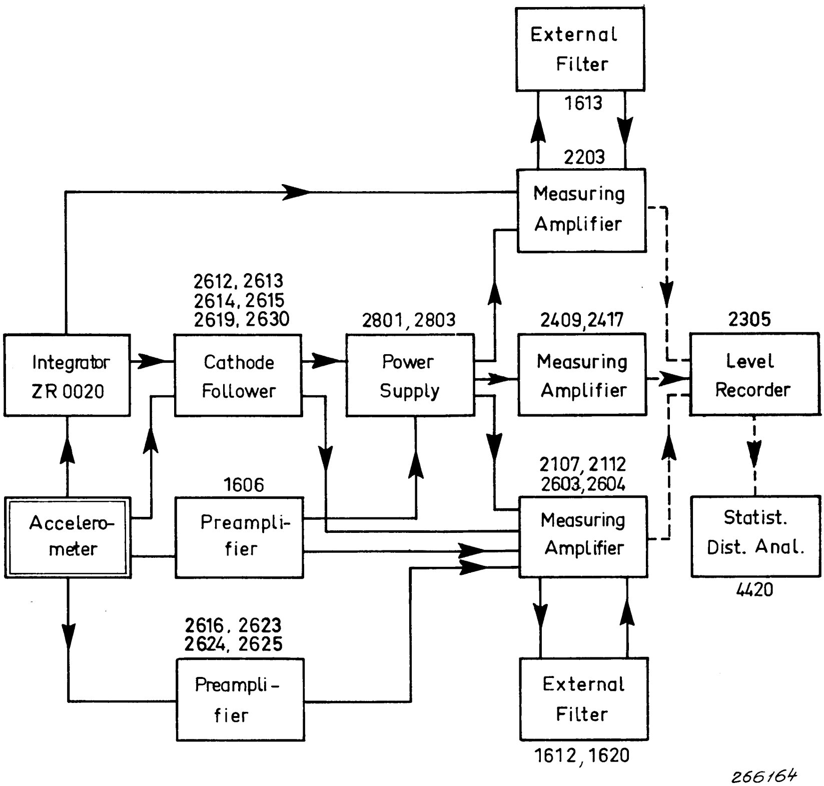


Fig. 5.1. Possible instrument combinations for vibration measurement and analysis. Any path from accelerometer to measuring amplifier gives a feasible measuring system.

A vibration measuring system usually consists of the following parts:

- Accelerometer
- Preamplifier
- Integrating networks
- Amplifier

Filter network
Indicating device.

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. 5.1.

Preamplifier. Brüel & Kjær produce several types of preamplifier for use with the accelerometer in vibration measuring set-ups. These are described in Chapter 4.

Integrating Networks

Apart from the integrating networks contained in the Preamplifiers Type 1606 and Type 2625, 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 conversation 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 Preamplifier Type 1606. 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 2–40,000 Hz for overall measurements (frequency selective part switched out), 20–20,000 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 45,000 Hz when used selectively, 2 to 40,000 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 F.E.T. preamplifier 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 20,000 Hz, and for octave analysis: 22.5 to 20,000 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 MΩ 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 output 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 $\pm$ 0.2 dB from 2 to 20,000 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 1025 and the Sine-Random Generator Type 1042. 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.

Ground Loops.

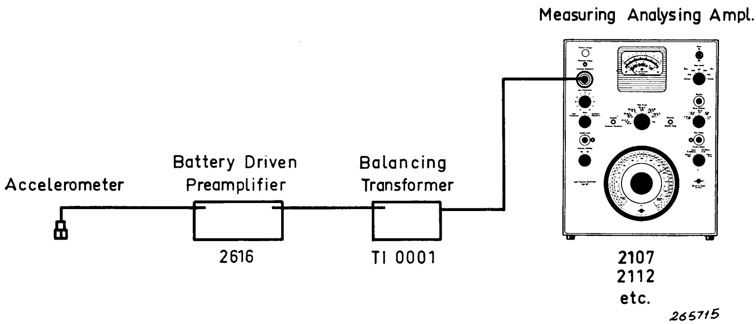


Fig. 5.2. Use of Balancing Transformer to eliminate ground loops.

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. 5.2.

6. Calibration

When absolute vibration level is measured is 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.

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 200 to 30,000 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. 6.1.

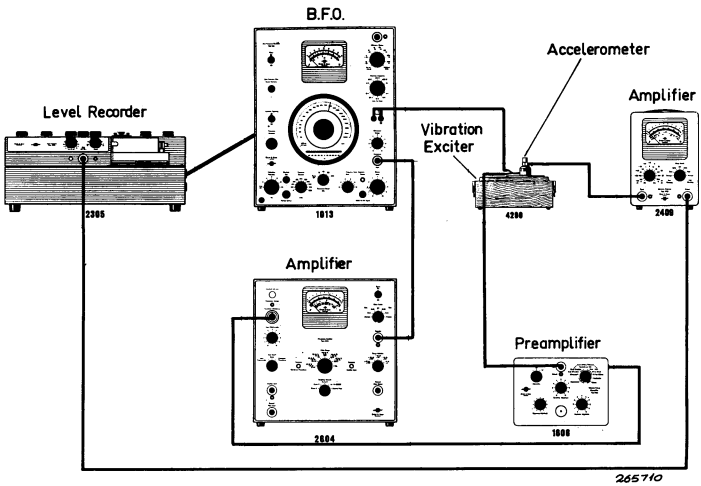


Fig. 6.1. Set-up suitable for the calibration of accelerometers. There are many possible alternatives to the various instruments shown.

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 – 39 – 43 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.

7. Applications

The following are a few suggestions for instrument combinations which may be used in some common accelerometer applications. It is in no way suggested that this list covers more than just a fraction of the possibilities one might meet in practice. Nor does it necessarily give the one and only solution to the given problem. The selection of instrument combinations should always be given careful attention with due regard to frequency response, dynamic range, operating environment, accuracy, read-out device etc. It is hoped that the foregoing chapters will be of some assistance to the person responsible for such a selection.

Further information about the various B & K instruments is found in their respective Instruction and Application books.

Portable Instrumentation

The Precision Sound Level Meter Type 2203 is an excellent indicating amplifier for vibration measurements when portable instrumentation is required. Used with the Integrator ZR 0020 it can measure velocity and displacement in addition to acceleration. An octave filter set Type 1613 can be joined to the Precision Sound Level Meter for frequency analysis of the measured vibration quantity. See Fig. 7.1.

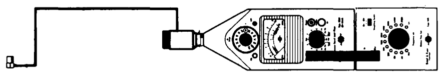


Fig. 7.1. Portable, battery driven instrumentation for measurement and analysis of vibration.

When long cables are required between the accelerometer and the indicating instrument a good solution may be to use the Preamplifier Type 2623 or 2616. These are small, compact, battery driven, transistorized units which may be used with very long cables. See Fig. 7.2.

Another possibility is to use the Charge Amplifier Type 2624 and in this case the long cable in inserted between the accelerometer and the preamplifier.

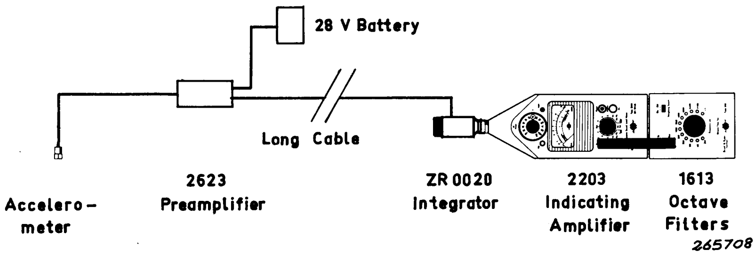


Fig. 7.2. Portable instrumentation suitable for use with long connection cable.

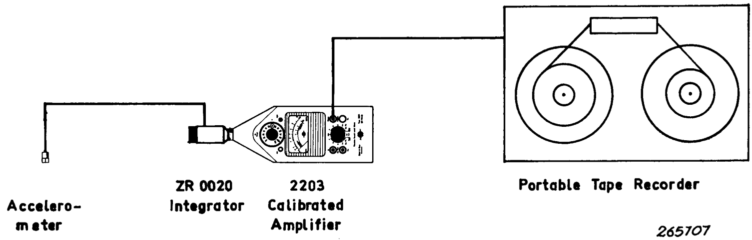


Fig. 7.3. Instrumentation for collecting vibration data in the field for later analysis.

Such instrumentation is also well suited for collecting vibration data in the field with the aid of a portable tape recorder. Any desired vibration signal may then be recorded on the tape and brought back to the laboratory for subsequent analysis with more powerful instrumentation systems.

Vibration Isolation

The effectiveness of vibration isolators may be conveniently measured using an accelerometer and one of the B & K indicating analysing amplifiers, e.g. the Audio-Frequency Spectrometer Type 2112, the Frequency Analyzer Type 2107, or the Precision Sound Level Meter Type 2203, fitted with the Octave Filter Set Type 1613.

An example of a set-up is shown in Fig. 7.4 where the Audio-Frequency Spectrometer is used for measuring the vibration isolation between a motor and its foundation. The Spectrometer is automatically driven from the Level Recorder and may be set to 1/3 or 1/1 octave analysis in the frequency range 22–45,000 Hz. Additional filters may be obtained extending the frequency range down to 11 Hz.

A Preamplifier Type 2625 is employed. With this arrangement it is possible to switch between the two measuring points and the curves drawn by the

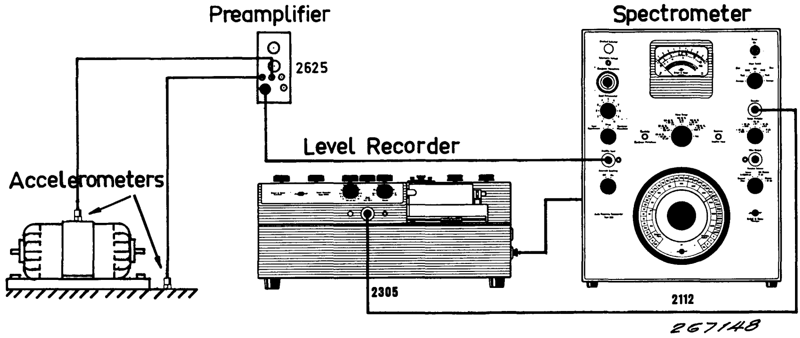


Fig. 7.4. Set-up for finding motor vibration and vibration isolation of motor foundation.

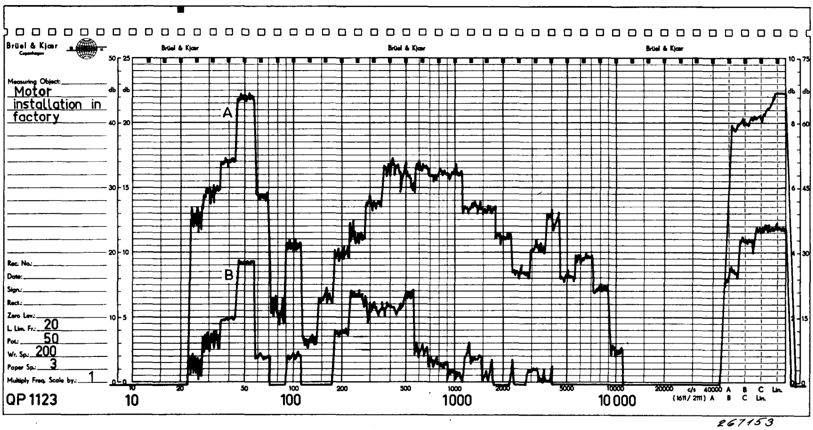


Fig. 7.5. Frequency analysis of the vibration signal as obtained with the set-up shown in Fig. 7.4.

Level Recorder Type 2305 gives the vibration of the motor and the isolation between the motor and its foundation. A typical set of curves is shown in Fig. 7.5. The vibration isolation at the various frequencies is the difference in dB between the two curves. Since the Preamplifier contains integration networks the measurements may represent either acceleration, velocity or displacement.

Vibration Tests. Fig. 7.6 shows a typical arrangement for vibration testing of mechanical components. The component under test is mounted on an electrodynamic vibration exciter (shaker) which is fed from the Sine-Random Generator via a power amplifier. To maintain constant vibration level on the shaker

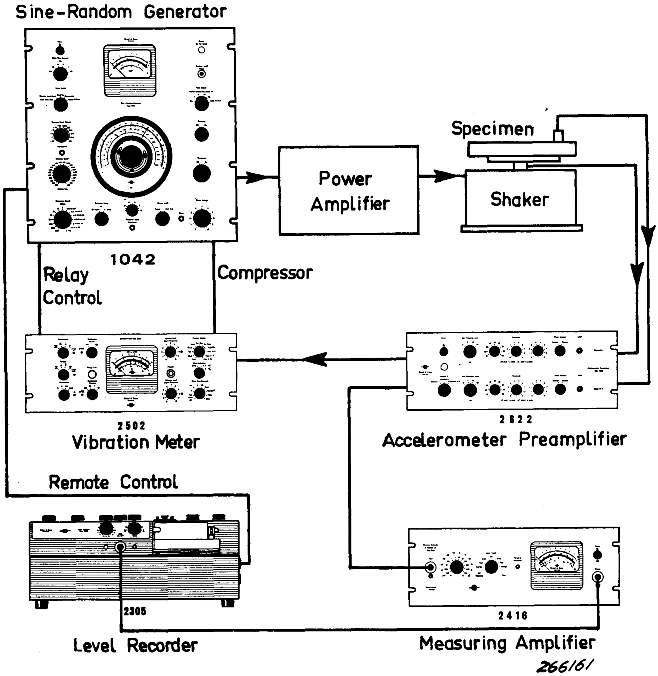


Fig. 7.6. Vibration test set-up.

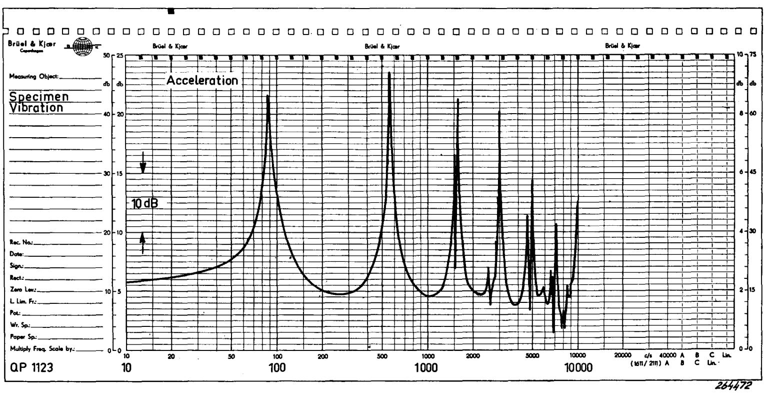


Fig. 7.7. Example of acceleration level at the top of a specimen shaken at constant acceleration.

table, independent of frequency, the output from the Sine Random Generator is regulated by the signal from an accelerometer mounted on the table. The Preamplifier Type 2622 is used in the feedback loop to match the impedance of the accelerometer to that of the Vibration Meter Type 2502. This meter can measure acceleration, velocity, displacement or acceleration gradient, and the same quantities may be held constant at the shaker table. The instrument combination can be used both for sweep sine and sweep random vibration tests.

Quality Control. In the last few years it has been realized that a vibration measuring system may be used for quality control of such items as electric

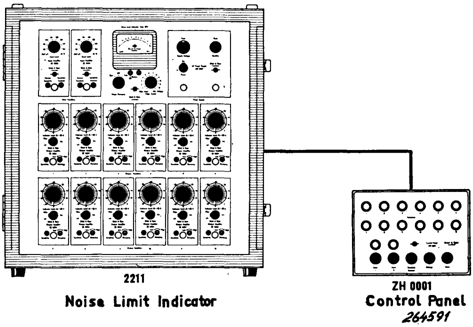


Fig. 7.8. The Noise Limit Indicator Type 2211.

motors, vacuum cleaners, refrigerator units etc. The Brüel & Kjær Noise Limit Indicator has been designed especially for production control of mass produced items with regard to their noise and vibration output. The instrument has two alternative inputs for B & K Cathode Followers or Preamplifiers Type 1606. 12 parallel output amplifiers may be fitted with plug-in filters, e.g. 1/3 or 1/1 octave filters, and a control panel with red lamps will indicate when the input signal level exceeds any preset value in each frequency band. On the basis of noise or vibration investigations on satisfactory production items, these limits may be set, and a quick production line control may be set up.

In case of a fault in the item being tested, the vibration may be high in one or two particular frequency ranges. By looking at the frequency range in which the preset level is exceeded, it is often possible to tell straight away what the fault is, and it may be corrected without loss of time.

This method of quality control is covered more fully in B & K Technical Review No. 2-1963, "Quality Control by Noise Analysis". The Technical Review is mailed free of charge upon request.

Shock Measurements

Shock measurements place rigid requirements upon the measuring system, especially with regard to frequency response, phase distortion and amplitude linearity. When measuring shock the information one tries to extract is the instantaneous value versus time of the measured quantity, e.g. acceleration. A calibrated oscilloscope is often used for displaying the shock waveform, since ordinary meters can not be used due to the short duration of the signal.

Frequency Response

Shock pulses in practice contain continuous frequency spectra from DC up to many thousand cycles per second, and it is very important that the measuring system covers essentially the whole frequency range in order that the shock waveform may be reproduced faithfully on the oscilloscope screen.

The frequency range of the instrumentation should preferably extend from

$$\frac{0.008}{T} \text{ Hz to } \frac{10}{T} \text{ Hz}$$

where T is the duration of the shock pulse in seconds. See B & K Technical Review No. 3-1966.

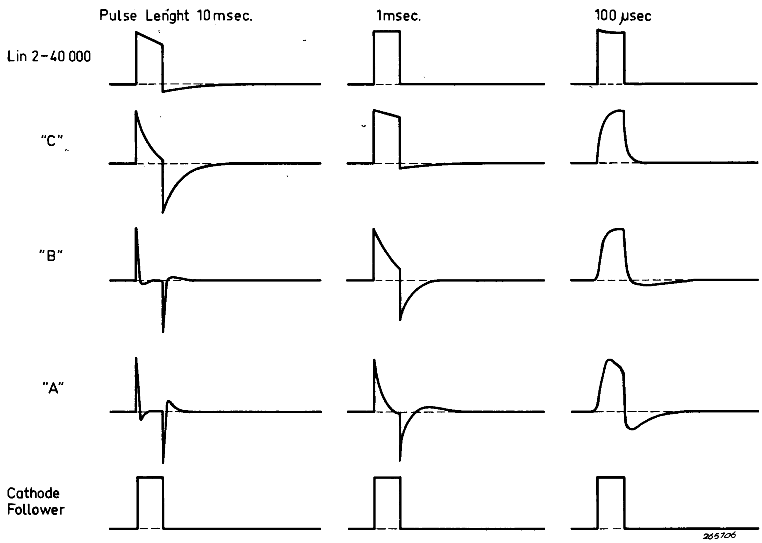


Fig. 7.9. Output waveshapes of amplifiers with various frequency characteristics for single square pulse input of variable duration. The corresponding frequency characteristics are shown below.

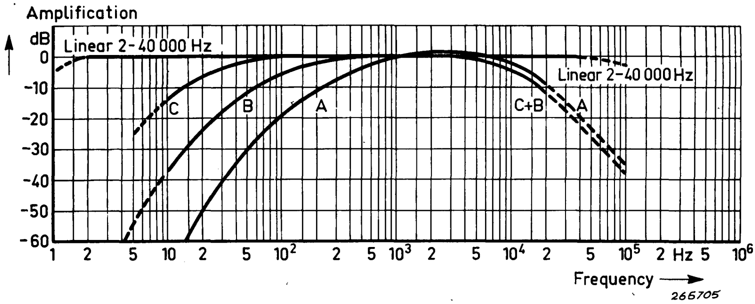


Fig. 7.10. Frequency response characteristics of the amplifiers used in the example above.

Fig. 7.9 shows the output signal from an amplifier with various frequency characteristics resulting from single rectangular pulse inputs of variable duration. The corresponding frequency characteristics are shown in Fig. 7.10. This example demonstrates the importance of the measuring system frequency response when employed for shock measurements.

Phase Distortion

In order to obtain an undistorted display it is also necessary that the various frequency components are phase delayed by an amount proportional to the frequency, i.e.

$$\varphi = k f$$

where φ is the phase distortion of the system at frequency f.

The system may be used for shock measurements when $k = 0$, i.e. no phase distortion, or when k is some positive or negative constant.

In shock measurements extremely high signal peaks may be encountered, and it is necessary to make absolutely certain that the dynamic capacity of the measuring system is sufficiently large.

High shock pulses, resulting in saturation of the amplifiers, may cause blocking of the amplifiers, and a certain "recovery time" will elapse before the next pulse can be measured correctly. This recovery time is to a certain

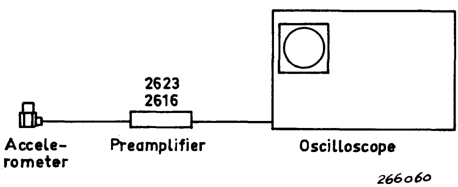


Fig. 7.11. Instrumentation suitable for shock measurements.

extent dependent upon the low frequency cut-off of the amplifiers, so that the lower one's low frequency cut-off is, the more careful one must be not to overdrive the amplifiers. For pulse train measurements this is especially important.

Fig. 7.11 gives a set-up suitable for the measurement of mechanical shock. This instrument combination gives a very large dynamic range and an excellent signal to noise ratio. The low-frequency cut-off is around 0.2 Hz. As no phase-shift is introduced by the preamplifier the shock waveform is reproduced faithfully on the oscilloscope screen.

8. Accessories

The following accessories are available for 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 magnets 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.

UA 0186 Set of 25 extension connectors JJ 0032.

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

AO 0038 1.2 m (4 ft.) of mininoise cable for operation to 260° C (500° 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).

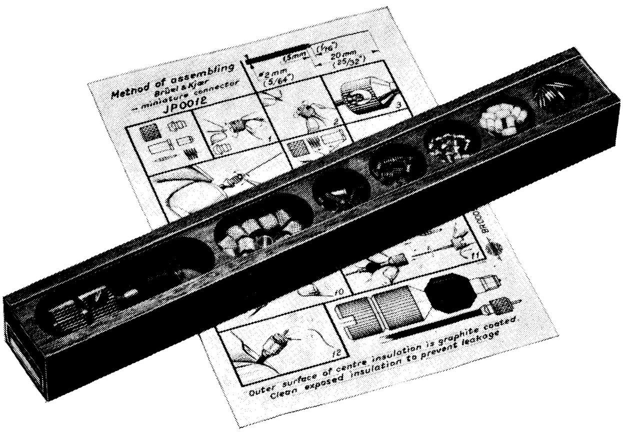


Fig. 8.1. Photograph of UA 0129 and instructions for mounting of the plug JP 0012.

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).

JP 0028 Adaptor plug, microplug to B & K coaxial.

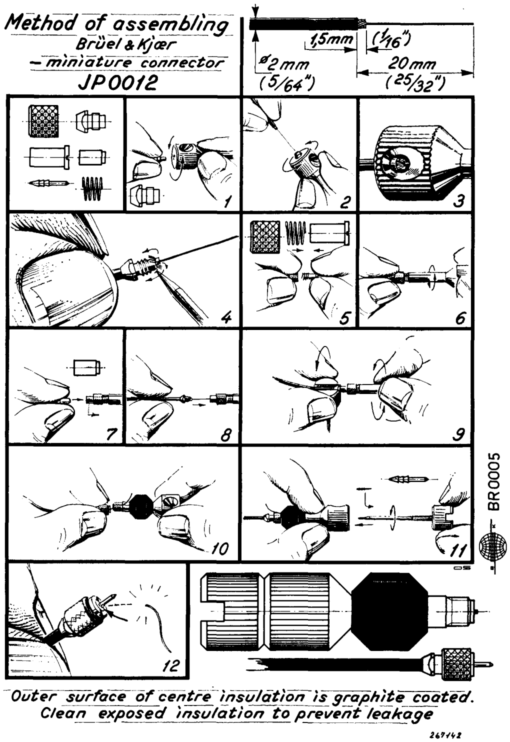


Fig. 8.2. Instructions for using UA 0129.

9. Conversion Charts, Tables etc.

The following table is given in order to facilitate the concervion 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 into units of g.

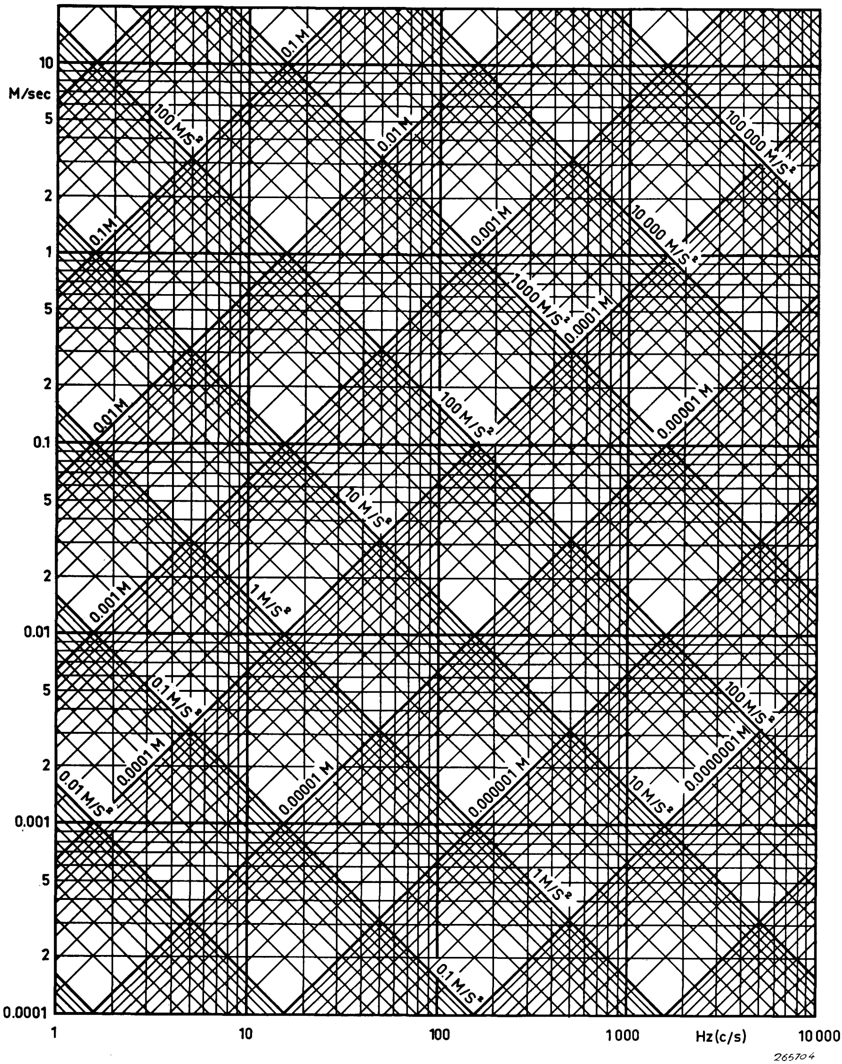
$-31.8 = (-2) \times 20 + 8.2.$

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)



265704

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

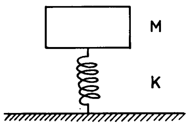
Conversion of Weight (Mass)

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



265703

M = mass (kg)

K = stiffness (Newt/m)

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

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

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

10. Specifications

The accelerometers are available as Accelerometer Sets Type 4319, 4323 and as Accelerometer Packages Type 4359, 4363 containing the following parts: (See Fig. 10.1).

The Accelerometer Sets Type 4319 and Type 4323 contain:

One Accelerometer Type 4339 or Type 4343	
One low noise cable for operation to 100°C (212°F)	AO 0037
Five threaded steel studs, 10–32 NF	YQ 2960
One electrically isolated stud, 10–32 NF	YS 0420
One nut, 10–32 NF	YM 0414
One cemeting stud	DB 0756
One mica washer	YO 0534
Electrically isolated permanent magnet	UA 0070
Cable clip	DL 3014
Wax	YJ 0216
Probe with round tip	YP 0080
Sharp tip for probe	DB 0545
Screw tap, 10–32 NF	QA 0029
Allen key for studs	QA 0013
Microplug to B & K plug adaptor	JP 0028
Individual calibration chart	

The Accelerometer Packages Type 4359 and Type 4363 contain:

Five Accelerometers Type 4339 or Type 4343	
Five low noise cables for operation to 100°C (212°F)	AO 0037
Five threaded steel studs, 10–32 NF	YQ 2960
Five individual calibration charts	

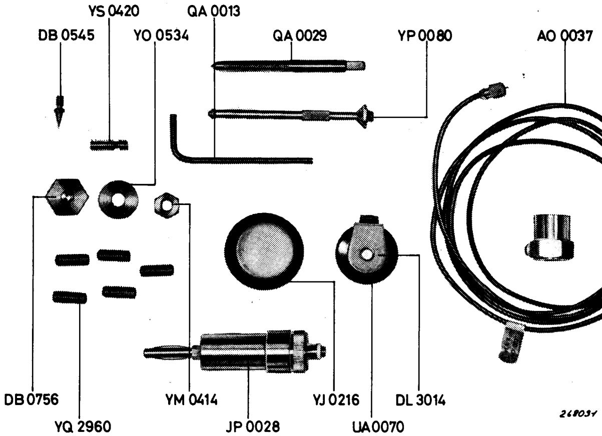


Fig. 10.1. Photograph of an accelerometer set (excl. mahogany case).

Fig. 10.2. Photograph of an accelerometer package

Specifications

Accelerometer Type	*4339*	*4343*
Contained in Accelerometer Set	4319	4323
Contained in Accelerometer Package	4359	4363
*Sensitivity (mV/g)	10 ± 0.2	approx. 10
*Charge Sensitivity (pC/g)	approx. 10	10 ± 0.2
*Free Resonance (kHz)	75	75
*Capacity Includ. Cable (pF)**	1000	1000
*Transverse Sensitivity (%)***	< 3	< 3
Max. Ambient Temperature (°C)	260	260
*Temperature Stability (dB/°C)	0.02	0.02
Lowest Leak Resistance at 20°C (MΩ) Typical value at 250 °C (MΩ)	$>2 \times 10^4$ 2×10^4	$>2 \times 10^4$ 2×10^4
Magnetic Sensitivity (μV/Gauss)	< 0.5	< 0.5
Acoustic Sensitivity (μV/μbar)	< 0.1	< 0.1
Torque Sensitivity, 6–60 kgcm (%)	< 1	< 1
Max. shock (g's)	10,000	10,000
Max. g with Magnetic Attachment	200	200
*Frequency Range (Hz) 2 % 10 %	0^+–10,000 0^+–15,000	0^+–10,000 0^+–15,000
Type of Connection	Side	Side
Height (mm)	17	17
Weight (grams)	16	16
Material of Base	Stainless steel	Stainless steel
Provision for Water Cooling	No	No
Mounting thread	10-32 NF	10-32 NF
Sensitivity time stability	< 2 % per year	< 2 % per year
Design	Single ended, all welded	

* Individual values given on the calibration chart.
** With standard low-noise cable, 1.2 m (4 feet) long.
*** Axis of minimum transverse sensitivity indicated by red dot on the accelerometer.
\+ The low frequency cut-off is determined by the preamplifier.

ORBOE PRINT . COPENHAGEN . DENMARK

October 1968