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Piezoelectric Accelerometers

Theory and Application

instrumentos de medida

50 years Metra accelerometers

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1 Introduction

1.1 Why Do We Need Accelerometers?

Vibration and shock are present in all areas of our daily lives. They may be generated and transmitted by motors, turbines, machine-tools, bridges, towers, and even by the human body.

While some vibrations are desirable, others may be disturbing or even destructive. Consequently, there is often a need to understand the causes of vibrations and to develop methods to measure and prevent them. The sensors we manufacture serve as a link between vibrating structures and electronic measurement equipment.

1.2 The Advantages of Piezoelectric Sensors

The accelerometers Metra has been manufacturing for over 40 years utilize the phenomenon of piezoelectricity. "Piezo" is from the Greek word πιέξειν meaning to squeeze. When a piezoelectric material is stressed it produces electrical charge. Combined with a seismic mass it can generate an electric charge signal proportional to vibration acceleration.

The active element of Metra's accelerometers consists of a carefully selected ceramic material with excellent piezoelectric properties called Lead-Zirconate Titanate (PZT). Specially formulated PZT provides stable performance and long-term stability. High stability similar to quartz accelerometers is achieved by means of an artificial aging process of the piezoceramic sensing element. The sensitivity of ceramics compared to quartz materials is about 100 times higher. Therefore, piezoceramic accelerometers are the better choice at low frequencies and low acceleration.

Piezoelectric accelerometers are widely accepted as the best choice for measuring absolute vibration. Compared to the other types of sensors, piezoelectric accelerometers have important advantages:

- Extremely wide dynamic range, almost free of noise - suitable for shock measurement as well as for almost imperceptible vibration
- Excellent linearity over their dynamic range
- Wide frequency range - very high frequencies can be measured
- Compact yet highly sensitive

- No moving parts - no wear
- Self-generating - no external power required
- Great variety of models available for nearly any purpose
- Integration of the output signal provides velocity and displacement

The following table shows advantages and disadvantages of other common types of vibration sensors compared to piezoelectric accelerometers:

Sensor Type	Advantage	Disadvantage
Piezoresistive	Measures static acceleration	Limited resolution because of resistive noise Only for low and medium frequencies Supply voltage required
Electrodynamic / Geophone	Cheap manufacturing	Only for low frequencies
Capacitive	Measures static acceleration Cheap manufacturing with semiconductor technology	Low resolution Fragile

1.3 Instrumentation

The piezoelectric principle requires no external energy.

Only alternating acceleration can be measured. This type of accelerometer is not capable of a true DC response, e.g. gravitation acceleration.

The high impedance sensor output needs to be converted into a low impedance signal first. In the case of IEPE compatible transducers this is the task of the built-in electronics. This electronic circuit is powered by the connected instrument. This can be a simple supply unit, for instance Metra's M28, or the signal conditioners M32, M72 and M208. For sensors with charge output, an external charge amplifier is required, for instance Model M72 or IEPE100.

For processing the sensor signal, a variety of equipment can be used, such as:

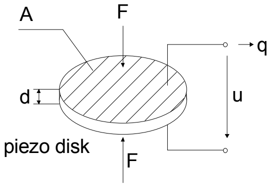
- Time domain equipment, e.g. RMS and peak value meters
- Frequency analyzers
- Recorders
- PC instrumentation

However, the capability of such equipment would be wasted without an accurate sensor signal. In many cases the accelerometer is the most critical link in the measurement chain. To obtain precise vibration signals some basic knowledge about piezoelectric accelerometers is required.

2 Operation and Designs

2.1 Piezoelectric Principle

The active element of an accelerometer is a piezoelectric material. Figure 1 illustrates the piezoelectric effect with the help of a compression disk. A compression disk looks like a capacitor with the piezoceramic material sandwiched between two electrodes. A force applied perpendicular to the disk causes a charge production and a voltage at the electrodes.



$$q = d33\,F$$

$$u = \frac{d33\,d}{e33\,A}\,F$$

A	electrode area
d	thickness
F	force
q	charge
u	voltage
d33, e33	piezo constants

Figure 1: Piezoelectric effect, basic calculations

The sensing element of a piezoelectric accelerometer consists of two major parts:

- Piezoceramic material
- Seismic mass

One side of the piezoelectric material is connected to a rigid post at the sensor base. The so-called seismic mass is attached to the other side. When the accelerometer is subjected to vibration, a force is generated which acts on the piezoelectric element (compare Figure 2). According to Newton's Law this force is equal to the product of the acceleration and the seismic mass. By the piezoelectric effect a charge output proportional to the applied force is generated. Since the seismic mass is constant the charge output signal is proportional to the acceleration of the mass.

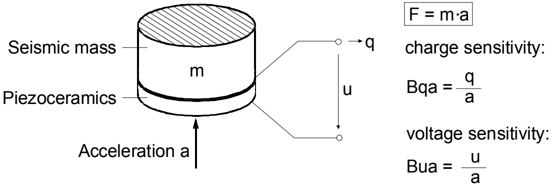


Figure 2: Principle of a piezoelectric accelerometer

Over a wide frequency range both sensor base and seismic mass have the same acceleration magnitude. Hence, the sensor measures the acceleration of the test object.

The piezoelectric element is connected to the sensor socket via a pair of electrodes. Some accelerometers feature an integrated electronic circuit which converts the high impedance charge output into a low impedance voltage signal (see section 2.3).

Within the useable operating frequency range the sensitivity is independent of frequency, apart from certain limitations mentioned later (see section 3.1).

A piezoelectric accelerometer can be regarded as a mechanical low-pass with resonance peak. The seismic mass and the piezoceramics (plus other "flexible" components) form a spring mass system. It shows the typical resonance behavior and defines the upper frequency limit of an accelerometer. In order to achieve a wider operating frequency range the resonance frequency must be increased.

This is usually done by reducing the seismic mass. However, the lower the seismic mass, the lower the sensitivity. Therefore, an accelerometer with high resonance frequency, for example a shock accelerometer, will be less sensitive whereas a seismic accelerometer with high sensitivity has a low resonance frequency.

Figure 3 shows a typical frequency response curve of an accelerometer when it is excited by a constant acceleration.

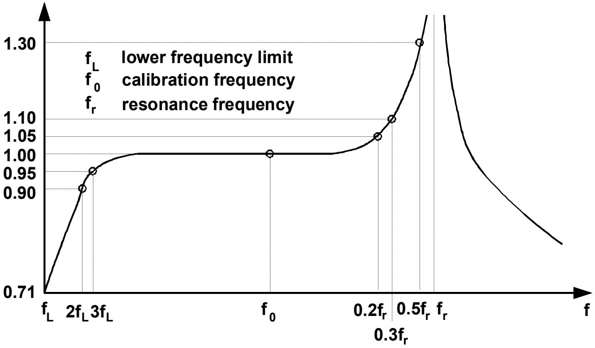


Figure 3: Frequency response curve

Some practical frequency ranges can be derived from this curve:

- At approximately 1/5 the resonance frequency the response of the sensor is 1.05. This means that the measured error compared to lower frequencies is 5 %.
- At approximately 1/3 the resonance frequency the error is 10 %. For this reason the "linear" frequency range should be considered limited to 1/3 the resonance frequency.
- The 3 dB limit with approximately 30 % error is obtained at approximately one half times the resonance frequency.

The lower frequency limit mainly depends on the chosen preamplifier. Often it can be adjusted. With voltage amplifiers the low frequency limit is a function of the RC time constant formed by accelerometer, cable, and amplifier input capacitance together with the amplifier input resistance (see section 4.3.4.)

2.2 Accelerometer Designs

Metra employs three mechanical construction designs:

- Shear system ("KS" types)
- Compression system ("KD" types)
- Bending or flexure system ("KB" types)

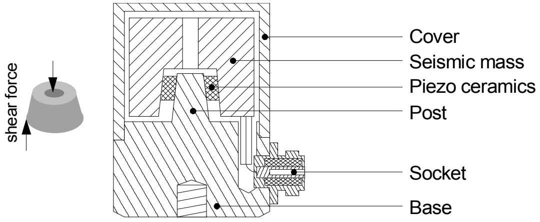
The reason for using different piezoelectric systems is their individual suitability for various measuring purposes and their different sensitivity to environmental influences. The following table shows advantages and drawbacks of the three designs:

	Shear	Compression	Bending
Advantage	Low temperature transient sensitivity Low base strain sensitivity	High sensitivity-to-mass ratio Robustness Technological advantages	Best sensitivity-to-mass ratio
Drawback	Lower sensitivity-to-mass ratio	High temperature transient sensitivity High base strain sensitivity	Fragile Relatively high temperature transient sensitivity

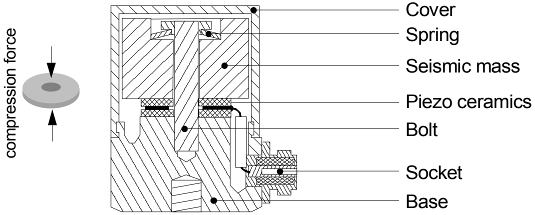
Shear design is applied in the majority of modern accelerometers because of its better performance. However, compression and bending type sensors are still used in many applications,.

The main components of the 3 accelerometer designs are shown in the following illustrations:

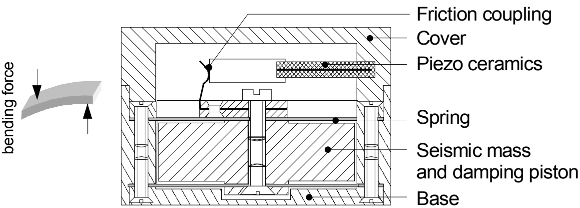
Shear Design:



Compression Design:



Bending Design:



2.3 IEPE Compatible Sensor Electronics

Metra manufactures many accelerometers featuring a built-in preamplifier. It transforms the high impedance charge output of the piezo-ceramics into a low impedance voltage signal which can be transmitted over longer distances. Metra uses the well-established IEPE standard for electronic accelerometers ensuring compatibility with equipment of other manufacturers. The abbreviation IEPE means "Integrated Electronics Piezo Electric". Other proprietary names for the same principle are ICP®, CCLD, Isotron®, Deltatron®, Piezotron® etc. The built-in circuit is powered by a constant current source (Figure 4). This constant current source may be part of the instrument or a separate unit. The vibration signal is transmitted back to the supply as a modulated bias voltage. Both supply current and voltage output are transmitted via the same coaxial cable which can be as long as several hundred meters. The capacitor C_C removes the sensor bias voltage from the instrument input providing a zero-based AC signal. Since the output impedance of the IEPE signal is typically 100 to 300 Ω, special low-noise sensor cable is not required. Standard low-cost coaxial cables are sufficient.

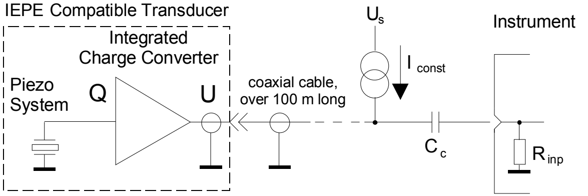


Figure 4: IEPE principle

The constant current may vary between 2 and 20 mA (not to be confused with 4 to 20 mA standard!). The lower the constant current the higher the output impedance and, therefore, the susceptibility to EMI. A constant current value of 4 mA is a good compromise in most cases.

The bias voltage, i.e. the DC output voltage of the sensor without excitation, is between 8 and 12 V. It varies with supply current and temperature. The output signal of the sensor oscillates around this bias voltage. It can never become negative. The upper limit is set by the supply voltage (U_S) of the constant current source. This supply voltage should be between 24 and 30 V. The lower limit is the saturation voltage of the built-in amplifier (about 0.5 V). Metra guarantees an output span of > ± 5 .. 6 V for its sensors. Figure 5 illustrates the dynamic range of an IEPE compatible sensor.

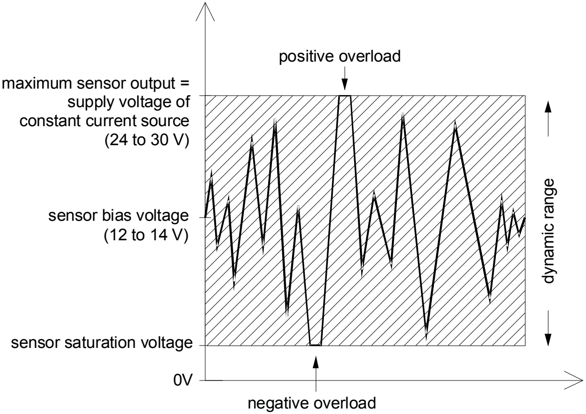


Figure 5: Dynamic range of IEPE compatible transducers

In addition to standard IEPE transducers Metra offers a low power version. These types are marked with "L". They are particularly suited for battery operated applications like hand-held meters or telemetry systems. Their bias voltage is only 5 to 7 V at a constant supply current of 0.1 to 6 mA. Due to the lower bias voltage the maximum output is limited to ± 2 V.

The lower frequency limit of Metra´s transducers with integrated electronics is 0.1 to 0.3 Hz for most shear and bender accelerometers and 3 Hz for compression sensors. The upper frequency limit mainly depends on the mechanical properties of the sensor. In case of longer cables, their capacitance should be considered. Typical coaxial cables supplied by Metra have a capacitance of approximately 100 pF/m.

The nomogram in Figure 6 shows the maximum output span of an IEPE compatible transducer over the frequency range for different cable capacitances and supply currents. With increasing cable capacitance the output span becomes lower. The reason for this influence is the reduced slew rate of the amplifier at higher load capacitances. With very long cables the full output span of ± 6 V can only be reached at frequencies up to a few hundred Hertz.

For a cable capacitance up to 10 nF (100 m standard coaxial cable) and 4 mA supply current the reduction of the output span can be neglected.

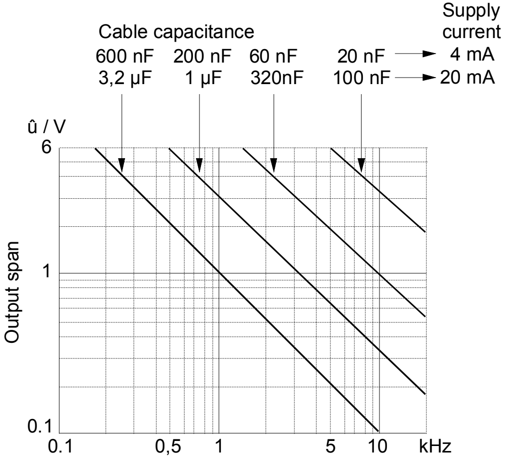


Figure 6: Output span of IEPE compatible accelerometers for different cable capacitances and supply currents

Figure 7 shows the frequency response of the sensor electronics under the influence of different cable capacitances and supply currents. At higher capacitances the upper frequency limit drops due to the low pass filter formed by the output resistance and the cable capacitance. At 4 mA the cable capacitance can be up to 50 nF (500 m standard coaxial cable) without reduction of the upper frequency limit.

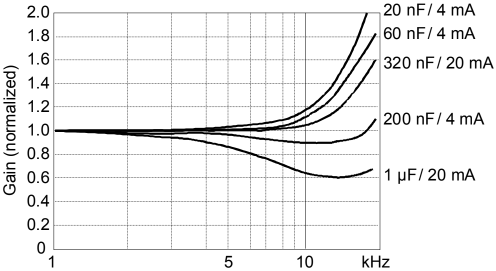


Figure 7: Frequency response of IEPE compatible accelerometers for different cable capacitances and supply currents

Today in most applications IEPE compatible accelerometers are preferred. However, charge mode accelerometers can be superior in some cases. The following table shows advantages and drawbacks of both sensor types.

	IEPE Compatible Sensors	**Charge Mode Sensors**
Advantage	Fixed sensitivity regardless of cable length and cable quality Low-impedance output can be transmitted over long cables in harsh environments Inexpensive signal conditioners and cables Intrinsic self-test function Better withstands harsh conditions like dirt and humidity	No power supply required - ideal for battery powered equipment No noise, highest resolution Wide dynamic range Higher operating temperatures Smaller sensors possible
Drawback	Constant current excitation required (reduces battery operating hours) Inherent noise source Max. operating temperature limited to <120 °C	Limited cable length (< 10 m) Special low noise cable required Charge amplifier required

Further details on IEPE compatible accelerometers can be found in section 4.1.2 on page 25.

3 Characteristics

Metra utilizes for factory calibration a modern PC based calibration system. The calibration procedure is based on a transfer standard which is regularly sent to Physikalisch-Technische Bundesanstalt (PTB) for recalibration.

Metra sensors, with few exceptions, are supplied with an individual calibration chart (Figure 8). It shows all individually measured data like sensitivity, transverse sensitivity, isolation resistance, IEPE bias voltage and frequency response curve. Additionally, all available typical characteristics for the transducer are listed.

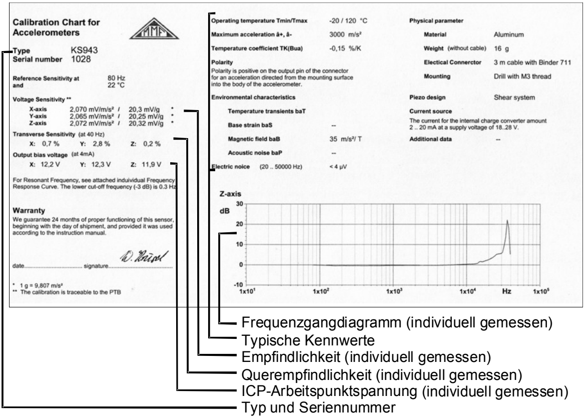


Figure 8: Individual calibration chart of Metra accelerometers

The following sections explain the parameters used in the individual calibration sheets.

3.1 Sensitivity

A piezoelectric accelerometer with charge output can be regarded as either a charge source or a voltage source with very high impedance. Consequently, charge sensitivity or voltage sensitivity are used to describe the relationship between acceleration and electrical output. In the individual characteristics sheet Metra states the charge sensitivity at 80 Hz and room temperature in picocoulombs per g and per m/s² (1 g = 9.81 m/s²).

The sensitivity of accelerometers with IEPE compatible output is stated as voltage sensitivity in millivolts per g and per ms^{-2}.

The total accuracy of this calibration is 1.8 %, valid under the following conditions:
f = 80 Hz, T = 21 °C, a = 10 m/s², C_{CABLE} = 150 pF, I_{CONST} = 4 mA.

The stated accuracy should not be confused with the tolerance of nominal sensitivity which is specified for some accelerometers. Model KS80, for example, has ± 5 % nominal sensitivity tolerance. Standard tolerance window for sensitivity, if not stated otherwise, is ± 20 %. Hence the exact sensitivity of production accelerometers may vary from the nominal sensitivity within the specified tolerance range.
Charge sensitivity decreases slightly with increasing frequency. It drops approximately 2 % per decade. For precise measurements at frequencies differing very much from 80 Hz a recalibration in the desired frequency range should be performed.

Before leaving the factory each accelerometer undergoes a thorough artificial aging process. Nevertheless, further natural aging can not be avoided completely. Typical are -3 % sensitivity loss within the first 3 years. For a high degree of accuracy recalibration should be performed (see section 4.3.5).

3.2 Frequency Response

Measurement of frequency response requires mechanical excitation of the transducer. Metra uses a specially-designed calibration shaker which is driven by a sine generator swept over a frequency range from 20 (80) up to 40 000 Hz. The acceleration is kept nearly constant at 3 m/s² over the entire frequency range by means of a feedback signal from a reference accelerometer. Most accelerometers are supplied with an individual frequency response curve. It shows the deviation of sensitivity in dB. For example the upper 3 dB limit can be derived from this curve. The 3 dB limit is often used in scientific specifications. It marks the frequency where the measuring error becomes 30 %. It is usually at about 50 % of the resonance frequency (compare Figure 3). The 1 dB limit marks an error of approximately 10 %. It can be found in the range of 1/3 the resonance frequency. The mounted resonance frequency, which is the largest mechanical resonance, can also be identified from this curve. Usually there are sub-resonances present at lower frequencies.

Metra performs frequency response measurements under optimum operating conditions with the best possible contact between accelerometer and vibration source. In practice, mounting conditions will be less than ideal in many cases and often a lower resonance frequency will be obtained.

The frequency response of IEPE compatible transducers can be altered by long cables (see section 2.3, page 8).

The lower frequency limit of IEPE accelerometers can be found in the linear frequency range given in the data sheet. It is stated for limits of 5 %, 10 % and 3 dB (see also page 5). For accelerometers with charge output we do not state a lower frequency limit since it is mainly determined by the external electronics.

3.3 Transverse Sensitivity

Transverse sensitivity is the ratio of the output due to acceleration applied perpendicular to the sensitive axis divided by the basic sensitivity in the main direction. The measurement is made at 40 Hz sine excitation rotating the sensor around a vertical axis. A figure-eight curve is obtained for transverse sensitivity. Its maximum deflection is the stated value. Typical are <5 % for shear accelerometers and <10 % for compression and bender models.

3.4 Maximum Acceleration

Usually the following limits are specified:

- $\hat{a}_+$ maximum acceleration for positive output direction
- $\hat{a}_-$ maximum acceleration for negative output direction
- $\hat{a}_q$ maximum acceleration for transverse direction (only for shock accelerometers)

The maximum acceleration is given for frequencies within the operating frequency range and at room temperature. At higher temperatures it may be lower.

For charge output accelerometers these limits are determined solely by the sensor's construction. If one of these limits is exceeded accidentally, for example, by dropping the sensor on the ground, the sensor will usually still function.

However, we recommend recalibrating the accelerometer after such incidents. Continuous vibration should not exceed 25 % of the stated limits to avoid wear. When highest accuracy is required, acceleration should not be higher than 10 % of the limit. Transducers with extremely high maximum acceleration are called shock accelerometers.

If the accelerometer is equipped with built-in IEPE electronics, the limits $\hat{a}_+$ and $\hat{a}_-$ are usually determined by the output voltage span of the amplifier (see section 2.3).

3.5 Linearity

The mechanical sensing elements of piezoelectric accelerometers have very low linearity errors. Within the stated measuring range the linearity error will be less than 1 % usually.

Another issue is the linearity of IEPE transducers. The sensor electronics will contribute additional errors, particularly at higher output voltages. Typically the linearity error will be less than 1 % at within 70 % of the maximum output voltage.

3.6 Non-Vibration Characteristics

3.6.1 Temperature

3.6.1.1 Operating Temperature Range

The maximum operating temperature of a charge transducer is limited by the piezoelectric material. Above a specified temperature, the so-called Curie point, the piezoelectric element will begin to depolarize causing a permanent loss in sensitivity. The specified maximum operating temperature is the limit at which the permanent change of sensitivity exceeds 3 %. Other components may also limit the operating temperature, for example, adhesives, resins or built-in electronics. Typical temperature ranges are -40 to 250 °C and -10 to 80 °C. Accelerometers with built-in electronics are generally not suitable for temperatures above 120 °C. For such applications Metra offers the remote charge converter IEPE100.

3.6.1.2 Temperature Coefficients

Apart from permanent changes, some characteristics vary over the operating temperature range. Temperature coefficients are specified for charge sensitivity ($TK(B_{qa})$) and inner capacitance ($TK(C_i)$). For sensors with built-in electronics only the temperature coefficient of voltage sensitivity $TK(B_{ua})$ is stated.

Some transducers have a non-linear temperature / sensitivity curve. Figure 9 shows an example. In this case the temperature coefficient may be stated for several temperature intervals or graphically as a diagram.

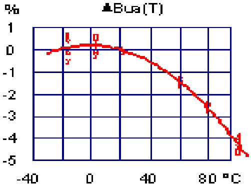


Figure 9: Example of non-linear temperature / sensitivity curve

There is a simple way to reduce the temperature coefficient of charge mode accelerometers. Since the temperature coefficients of B_{qa}, B_{ua} and C_i are different, the temperature behavior can be compensated by a serial capacitor at charge amplification or a parallel capacitor in case of high impedance voltage amplification. This capacitor is calculated to:

$$C = C_i \frac{TK(C_i) - TK(B_{qa})}{TK(B_{qa})}$$

This can be a useful at very changeable temperatures. Please note that the total sensitivity will become lower by this measure.

3.6.1.3 Temperature Transients

In addition to the temperature characteristics mentioned above, accelerometers exhibit a slowly varying output when subjected to temperature transients, caused by so-called pyroelectric effect. This is specified by temperature transient sensitivity b_{aT}. Temperature transients produce frequencies below 10 Hz. Where low frequency measurements are made this effect must be considered. To avoid this problem, shear type accelerometers should be chosen for low frequency measurements. In practice, they are approximately 100 times less sensitive to temperature transients than compression sensors. Bender systems are midway between the other two systems in terms of sensitivity to temperature transients. When compression sensors are used the amplifier should be adjusted to a 3 or 10 Hz lower frequency limit.

Temperature transient sensitivity is measured with the sensor mounted on a 200 g aluminum block which is immersed in containers with water at 20 and 50 °C.

3.6.2 Base Strain

When an accelerometer is mounted on a structure which is subjected to strain variations, an unwanted output may be generated as a result of strain transmitted to the piezoelectric material. This effect can be described as base strain sensitivity b_{as}. The stated values are measured by means of a bending beam oscillating at 8 or 15 Hz. Base strain output mainly occurs at frequencies below

500 Hz. Shear type accelerometers have extremely low base strain sensitivities and should be chosen for strain-critical applications.

3.6.3 Magnetic Fields

Strong magnetic fields often occur around electric machines and frequency converters. Magnetic field sensitivity b_{aB} has been measured at B=0.01 T and 50 Hz for some accelerometers. It is very low and can be ignored under normal conditions.

Generally, accelerometers with stainless steel cases provide better protection against magnetic fields than accelerometers with aluminum cases.

Stray signal pickup can be avoided by proper cable shielding. This is of particular importance for sensors with charge output.

Adequate isolation must be provided against ground loops. They can occur when a measuring system is grounded at several points, particularly when the distance between these grounding points is long. Ground loops can be avoided using accelerometers with insulated bases (for instance Models KS74 and KS80) or insulating mounting studs. More information on ground loops can be found in section 4.3.5).

3.6.4 Acoustic Noise

If an accelerometer is exposed to a very high noise level, a deformation of the sensor case may occur which can be measured as an output. Acoustic noise sensitivity b_{ap} as stated for some models is measured at an SPL of 154 dB which is beyond the pain barrier of the human ear. Acoustic noise sensitivity should not be confused with the sensor response to pressure induced motion of the structure on which it is mounted.

3.6.5 Inner Capacitance

Inner capacitance is stated in the individual calibration sheet only for accelerometers with charge output. It can be relevant if the transducer is used with a high impedance voltage amplifier (compare section 4.1.1.2 on page 23). The stated value includes the capacitance of the sensor cable used for calibration. This cable capacitance is stated separately in the calibration sheet. Its value has to be deducted from the sensor capacitance to obtain the actual inner capacitance.

3.6.6 Intrinsic Noise and Resolution

A piezoelectric sensing element can be regarded as purely capacitive source. The sensor itself is practically free of intrinsic noise. The only noise is contributed by the temperature motion of electrons in the built-in the IEPE compatible charge converter. Consequently, a noise specification makes only sense for IEPE compatible sensors.

The intrinsic noise determines the resolution limit of the sensor. Signals below the noise level cannot be measured.

The signal-to-noise-ratio S_n is a measure of the error caused by noise. It is the logarithm of the ratio of the measured signal level (u) and the noise level (u_n):

$$S_n = 20 \log \frac{u}{u_n}$$

The intrinsic noise of IEPE compatible accelerometers mainly depends on the frequency.

Below about 100 Hz it has the typical 1/f characteristics. Above 100 Hz the noise level is nearly independent of the frequency. The following picture shows a typical noise spectrum of an IEPE compatible accelerometer:

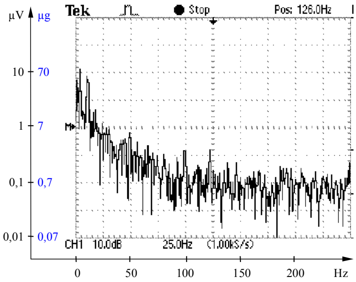


Figure 10: Typical noise spectrum of an IEPE compatible accelerometer

It is useful to state the noise of an accelerometer as equivalent acceleration level. For this purpose, the noise voltage (u_n) is divided by transducer sensitivity (B_{ua}) yielding the equivalent noise acceleration (a_n):

$$a_n = \frac{u_n}{B_{ua}}$$

While u_n only depends on the electronic circuit which is similar for all sensor types, the sensitivity of the piezoelectric sensing element will directly influence the equivalent noise acceleration. It can be seen that a transducer with a very sensitive piezo system provides a high resolution.

The characteristics of most accelerometers show noise accelerations for several frequency ranges.

Example of a noise statement (KS48C):

Wide-band noise:	a_{nwb}	0.5 to 1000 Hz	< 13 µg
Noise densities:	a_{n1}	0.1 Hz	1 µg/√Hz
	a_{n2}	1 Hz	0.6 µg/√Hz
	a_{n3}	10 Hz	0.1 µg /√Hz
	a_{n4}	100 Hz	0.06 µg /√Hz

Wide-band noise is the RMS acceleration noise measured over the usable frequency range of the sensor.

Noise densities show the noise performance at specific frequencies which is of particular interest at low frequencies. To obtain the actual noise acceleration within a certain frequency range, noise density is multiplied by the square root of the difference between upper and lower frequency.

Example: Calculation of the intrinsic noise of Model KS48C with the noise data shown above for a frequency range from 0.1 Hz to 1 Hz:

Choose the stated noise density at 0.1 Hz (worst case) and multiply by the square root of the frequency range:

$$a_n = 1\ \mu g/\sqrt{Hz} \cdot \sqrt{(1\ Hz - 0.1\ Hz)} = 0.95\ \mu g\ (RMS)$$

For the evaluation of the intrinsic noise of an entire measuring chain the noise of all components including signal conditioners and other instruments must be considered.

4 Application Information

4.1 Instrumentation

4.1.1 Accelerometers With Charge Output

4.1.1.1 Charge Amplifiers

Accelerometers with charge output generate an output signal in the range of some picocoulombs with a very high impedance. To process this signal by standard AC measuring equipment, it needs to be transformed into a low impedance voltage signal.

Preferably, charge amplifiers are used for this purpose. The input stage of a charge amplifier features a capacitive feedback circuit which balances the effect of the applied charge input signal. The feedback signal is then a measure of input charge. Figure 11 shows a typical charge input stage.

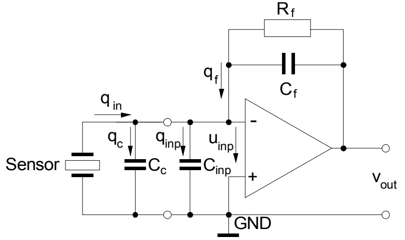


Figure 11: Charge amplifier

The input charge q_{in} flows into the summing point at the inverting input of the amplifier. It is distributed to the cable capacitance C_c, the amplifier input capacitance C_{inp} and the feedback capacitor C_f. The node equation of the input is therefore:

$$q_{in} = q_c + q_{inp} + q_f$$

Using the electrostatic equation:

$$q = u \cdot C$$

and substituting q_c, q_{inp} and q_f:

$$q_{in} = u_{inp} \cdot (C_c + C_{inp}) + u_f \cdot C_f$$

Since the voltage difference between the inverting and the non-inverting input of a differential amplifier becomes zero under normal operating conditions, we can assume that the input voltage of the charge amplifier u_{inp} will be equal to GND potential. With $u_{inp} = 0$ we may simplify the equation:

$$q_{in} = u_f \cdot C_f$$

and solving for the output voltage u_{out}:

$$u_{out} = u_f = \frac{q_{in}}{C_f}$$

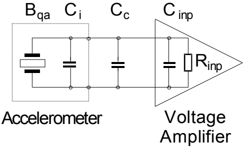
The result shows clearly that the output voltage of a charge amplifier depends only on the charge input and the feedback capacitance. Input and cable capacitances have no influence on the output signal. This is a significant fact when measuring with cables of different lengths and types.

Referring to Figure 11, the feedback resistor R_f has the function to provide DC stability to the circuit and to define the lower frequency limit of the amplifier. The circuit in Figure 11 represents only the input stage of a charge amplifier. Other parts like voltage amplifiers, buffers filters and integrators are not shown.

Typical charge amplifiers are, for example, the **M68** series Signal Conditioners and the **IEPE100** series Remote Charge Converters made by Metra.

4.1.1.2 High Impedance Voltage Amplifiers

Instead of charge amplifiers, high impedance voltage amplifiers can be used with charge mode transducers. In this case, however, the capacitances of sensor, cable, and amplifier input must be considered (Figure 12).



B_{qa} Charge sensitivity of the accelerometer
C_i Inner capacitance of the accelerometer
C_c Cable capacitance
R_{inp} Input resistance of the amplifier
C_{inp} Input capacitance of the amplifier

Figure 12: Charge accelerometer at high impedance voltage input

The voltage sensitivity of an accelerometer with known charge sensitivity B_{qa} and inner capacitance C_i is calculated to:

$$B_{ua} = \frac{B_{qa}}{C_i}$$

B_{qa} and C_i can be found in the sensor data sheet.

Taking into account the capacitance of the sensor cable C_c and the input capacitance C_{inp} of the voltage amplifier, the resulting voltage sensitivity B'_{ua} will become lower than B_{ua}:

$$B'_{ua} = B_{ua} \frac{C_i}{C_i + C_c + C_{inp}}$$

A typical 1.5 m low noise cable Model 009 has a capacitance of approximately 135 pF.

The lower frequency limit f_l will also be influenced by C_c, C_{inp} and R_{inp}:

$$f_l = \frac{1}{2\pi R_{inp}(C_i + C_c + C_{inp})}$$

The lower frequency limit increases with decreasing input resistance.

Example: A charge mode accelerometer Model KS56 with an inner capacitance of $C_i = 400$ pF is connected to a typical scope input with $R_{inp} = 10$ MΩ and $C_{inp} = 20$ pF. The sensor cable capacitance is 135 pF.
Result: The lower frequency limit will be at approximately 30 Hz.

4.1.2 IEPE Compatible Accelerometers

A special feature of the IEPE compatible sensor circuit is that power supply and measuring signal are transmitted via the same cable. So, an IEPE compatible transducer requires, like a transducer with charge output, only one single-ended shielded cable.
Figure 13 shows the principle circuit diagram.

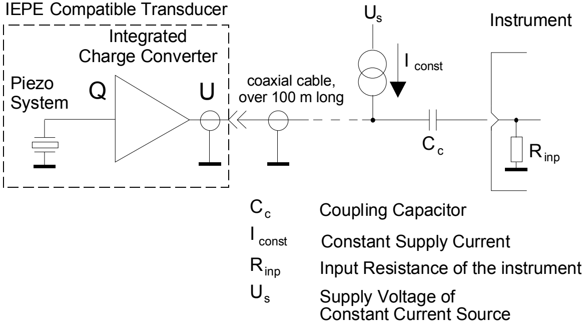


Figure 13: IEPE principle

The integrated sensor electronics is powered with constant current in the range between 2 and 20 mA. A typical value is 4 mA.
For battery powered applications Metra has developed a low-power version of the IEPE standard, which is applied in the accelerometers KS72L, KS94L, KS943L and in the vibration meters VM12 and VM15. Low Power IEPE accelerometers usually have a bias voltage of 4 to 6 V. So a supply voltage (U_s) of 9 to 12 V is sufficient. The constant current supply may be as low as 0.1 mA, depending on the transducer model. This can reduce the power consumption of the transducer by up to 99 %.

The constant current I_{const} is fed into the signal cable of the sensor. The supply current and the length of the cable may influence the upper frequency limit (compare section 2.3 on page 8).

The de-coupling capacitor C_c keeps DC components away from the signal conditioner input. The combination of C_c and R_{inp} acts as a high pass filter. Its time constant should be sufficiently high to let all relevant low frequency components of the sensor signal pass.

Important:

- A voltage source without constant current regulation must never be connected to an IEPE compatible transducer.
- False polarization of the sensor cable may immediately destroy the built-in electronics.

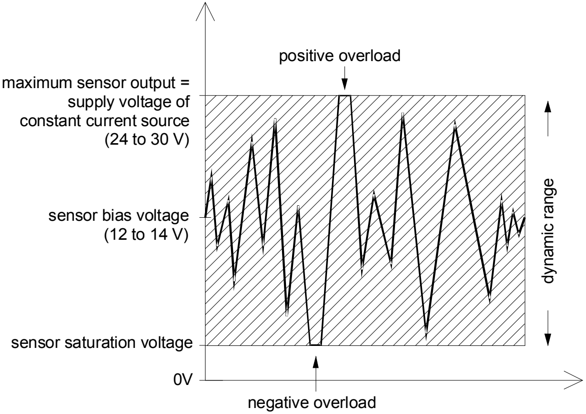


Figure 14: Dynamic range of IEPE compatible transducers

In Figure 14 can be seen that IEPE compatible transducers provide an intrinsic self-test feature. By means of the bias voltage at the input of the instrument the following operating conditions can be detected:

- $U_{BIAS} < 0.5$ to 1 V: short-circuit or negative overload
- $1\ V < U_{BIAS} < \approx 18$ V: O.K., output within the proper range
- $U_{BIAS} > 18$ V: positive overload or input open (cable broken or not connected)

IEPE transducers have an internal time constant which resembles a first order RC filter. When a step signal is applied to the input the output will be an exponentially decreasing voltage (see Figure 15).

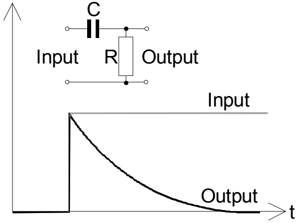


Figure 15: Step response of IEPE transducers

Step input signals can be caused by connecting the sensor to the IEPE current source or by shock acceleration. The decay time can reach up to one minute, depending on the lower frequency limit of the sensor. This should be considered when low frequencies are to be measured.

A variety of instruments are equipped with a constant current sensor supply. Examples from Metra are the Signal Conditioners of **M68** series, **M208** and **M32**, the Vibration Monitor **M12,** the Vibration Meter **VM30** or the Vibration Calibrating System **VC110**. The constant current source may also be a separate unit, for example Model **M28**.

4.2 Intelligent Accelerometers to IEEE 1451.4 (TEDS)

4.2.1 Introduction

The standard IEEE 1451 complies with the increasing importance of digital data acquisition systems. IEEE 1451 mainly defines the protocol and network structure for sensors with fully digital output. Part IEEE 1451.4, however, deals with "Mixed Mode Sensors", which have a conventional IEPE compatible output but contain, in addition, a memory for an "Electronic Data Sheet". This data storage is named "TEDS" (Transducer Electronic Data Sheet). The memory of 64 + 256 bits contains all important technical data which are of interest for the user. Due to the restrictions of memory size the data is packed in different coding formats.

The Transducer Electronic Data Sheet provides several advantages:

- When measuring at many measuring points it will make it easier to identify the different sensors as belonging to a particular input. It is not necessary to mark and track the cable, which takes up a great deal of time.
- The measuring system reads the calibration data automatically. Till now it was necessary to have a data base with the technical specification of the used transducers, like serial number, measured quantity, sensitivity etc.
- The sensor self-identification allows to change a transducer with a minimum of time and work ("Plug & Play").
- The data sheet of a transducer is a document which often gets lost. The so called TEDS sensor contains all necessary technical specification. Therefore, you are able to execute the measurement, even if the data sheet is just not at hand.

The standard IEEE 1451.4 is based on the IEPE standard. Therefore, TEDS transducers can be used like common IEPE transducers. Figure 16 shows the principle of TEDS.

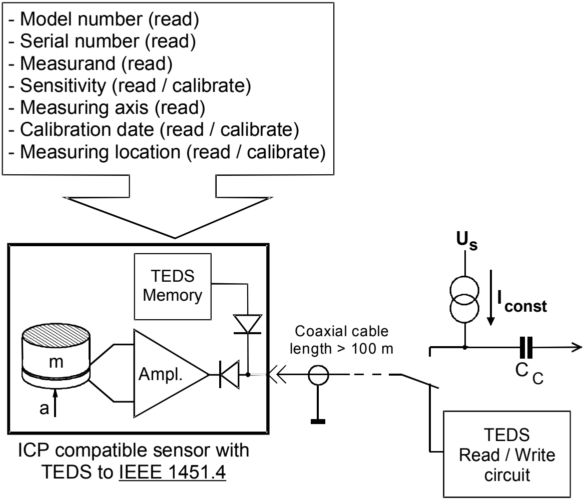


Figure 16: TEDS principle

If a constant current source is applied, the sensor will act like a normal IEPE compatible sensor. Programming and reading the built-in non-volatile 64 + 256 Bit memory DS2430 is also done via the sensor cable. The communication uses Maxim's 1-Wire® protocol . For data exchange TTL level with negative polarity is used. This makes it possible to separate analog and digital signals inside the sensor by two simple diodes.

Metra's 8-channel IEPE signal conditioner M208A provides full TEDS support with automatic transducer sensitivity normalization.

4.2.2 Sensor Data in TEDS Memory

4.2.2.1 Basic TEDS

A 64 bit portion of the memory is called application register. It includes the so-called Basic TEDS with general information to identify the sensor:

- Model and version number: Metra stores in this location a coded model number. The actual model number, for example "KS78.100", can be decoded by means of a *.xdl file to IEEE 1451.4 standard, the so-called "Manufacturer Model Enumeration File" which can be found in the download section of our web pages.
- Serial number: This is the actual serial number of the sensor which can be found on its case.
- Manufacturer code: A manufacturer-specific number assigned by IEEE. Metra's manufacturer number is 61. A complete list of manufacturer codes can be found here: http://standards.ieee.org/develop/regauth/manid/public.html

Basic TEDS can exclusively be modified and stored by the manufacturer.

4.2.2.2 Template No. 25

Calibration data is stored in a 256 byte section. The arrangement of data is defined in TEDS templates. For accelerometers in most cases the standard template no. 25 will be applied. Some switch bits determine whether the memory includes a transfer function or not. Metra stores, if no other format is desired by the customer, the version with transfer function including data like resonance or lower frequency limit.
Template no. 25 includes the following data:

- Sensitivity in V/m/s²: Sensitivity value at reference conditions according to the supplied calibration chart
- Calibration frequency of sensitivity in Hz
- Lower frequency limit in Hz: Typical value according to sensor data sheet

- Measuring direction: Relevant for triaxial accelerometers (0 = X; 1 = Y; 2 = Z; 3 = no data)
- Sensor weight in grams
- Polarity of output signal for positive acceleration: 0 = positive, 1 = negative
- Low pass frequency in Hz (if the sensor includes a low pass filter)
- Resonance frequency in Hz: Typical value according to sensor data sheet
- Amplitude slope in percent per decade
- Temperature coefficient in percent per Kelvin: Typical value according to sensor data sheet
- Calibration date (DD.MM.YY)
- Initials of calibrating person (3 capital letters)
- Calibration interval in days: Recommended time until next calibration

  This data can be modified by the calibration lab of the manufacturer or later by other calibration labs.
  In addition, TEDS memory provides some bytes for application specific data which may be entered by the user:
- Measurement point ID (1 to 2046)
- User text: 13 characters
- Note: In the download section of our web site

http://www.new.mmf.de/software_download.htm

we offer e TEDS editor for reading and modifying the contents of the TEDS memory. A suitable hardware interface can be ordered from Metra.

4.3 Preparing the Measurement

4.3.1 Mounting Location

In order to achieve optimum measurement conditions, the following questions should be answered:

- Can you make at the selected location unadulterated measurements of the vibration and derive the needed information?
- Does the selected location provide a short and rigid path to the vibration source?
- Is it allowable (considering warranty restrictions) and possible in technical respects to prepare a flat, smooth, and clean surface with mounting thread for the accelerometer?
- Can the accelerometer be mounted without altering the vibration characteristics of the test object?
- Which environmental influences (heat, humidity, EMI, bending etc.) may occur?

4.3.2 Choosing the Accelerometer

The following chart shows a summary of the most important criteria for selecting an accelerometer:

Criteria	**Accelerometer Properties**
Amplitude and frequency range	Choose appropriate sensitivity, max. acceleration and resonance frequency, shock accelerometers for extreme magnitudes, seismic accelerometers for lowest vibration
Weight of test object	Max. weight of accelerometer <1/10 the weight of test object, choose miniature accelerometers for light test objects
Temperature transients, strain, magnetic fields, extreme acoustic noise	Assess influence, choose sensor according to characteristics, choose shear type accelerometers when temperature transients or base strain may occur, stainless steel versions for strong magnetic fields
Humidity and dust	Use industrial accelerometers with IP67 protection grade
Measurement of vibration velocity and displacement	For integration below 20 Hz preferably use shear accelerometers
Mounting Quick spot measurement below 1000 Hz Temporary measurement without alteration of test object Long-term measurement	 Use accelerometer probe[1] Use clamping magnet, wax or adhesive Use mounting stud or screw
Grounding problems	Use insulated accelerometer or insulating flange
Long distance between sensor and instrument	Use accelerometer with built-in electronics (IEPE compatible)

1 Metra offers the probe accelerometer Model KST94 with a movable tip which is mechanically isolated from the sensor case.

4.3.3 Mounting Methods

Choosing the optimum mounting arrangement will significantly improve the accuracy.

For best performance, particularly at high frequencies, the accelerometer base and the test object should have clean, flat, smooth, unscratched, and burr-free surfaces.

A scratched accelerometer base can be applied to a lapping plate for restoration of flatness. If lapping is not possible, other machining processes such as grinding, spotfacing, milling, turning, etc., can produce acceptably flat mounting surfaces.

The transmission of higher frequencies can be improved by a thin layer of silicon grease at the coupling surface.
It is also important to provide a stiff mechanical connection between the sensor and the source of vibration. Sheet metal or plastic parts and other thin and flexible components are unsuited for accelerometer mounting.

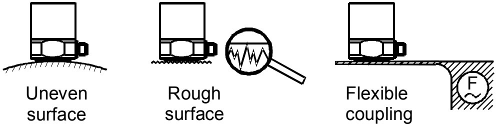


Figure 17: Typical reasons of coupling errors

Errors due to unwanted sensor vibrations can be reduced by symmetric mounting. The weight of the sensor including all mounting components should be low compared to the weight of the test object. As a rule the sensor should not weigh more than 10 % of the test object.

Misalignment of the sensor axis and the measuring directions should be kept as low as possible, particularly if transverse vibration of high magnitude occurs. When using screw mounting, make sure that the screw is not longer than the threaded hole. The must be no gap under the sensor.

The following mounting methods are used for accelerometers:

- Stud mounting with stud bolt, insulating flange or adhesive pads
- Magnetic base
- Adhesive by bee wax, cyanoacrylate, epoxy glue or dental cement
- Probe by hand pressure
- Automated coupling by a spring loaded tip (Figure 19)

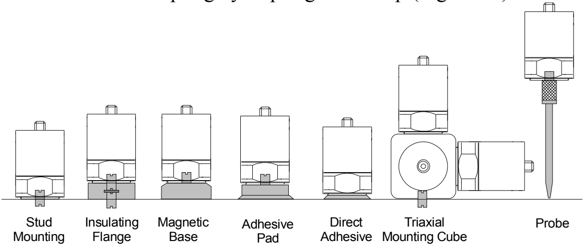


Figure 18: Mounting methods for accelerometers

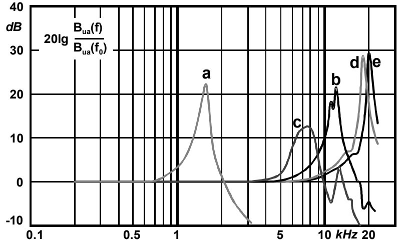
Figure 19: Probe accelerometer KST94 with movable tip

The following table compares some typical mounting techniques for piezoelectric accelerometers with regard to different criteria (Source: ISO 5348).

	Resonant frequency	Tempe-rature	Sensor weight and coupling stiffness	Resonance peak (Q)	Relevance of surface quality
Stud mounting	●	●	●	●	●
cyanoacry-late glue	●	●	●	●	◑
Bee wax	◑	○	◑	●	●
double sided adhesive tape	○	◑	○	○	●
Magnetic base	◑	●	○	○	●
Probe	○	○	○	○	○

● high ◑ medium ○ low

Figure 20 compares the typical high frequency performance of these methods as a result of added mass and reduced mounting stiffness.



a Probe

b Insulating Flange

c Magnetic Base

d Adhesive Mounting

e Stud Mounting

Figure 20: Resonance frequencies of different mounting methods

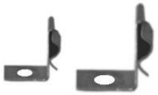
Metra accelerometers may have the mounting thread sizes M3, M5 and M8. Some Models have integral M4, M6 or M10 mounting studs or screws.

Many transducers are available with an accessory kit (ordering option “/01”) containing all suitable mounting parts.

The following list shows the mounting accessories offered by Metra:

Mounting Studs 021 (M3) 003 (M5) 043 (M8) 022 (M3 to M5) 044 (M5 to M8) 045 (M5 to 10-32) 046 (M5 to ¼”-28)	➔ For best performance, good for permanent mounting. Mounting thread required in the test object. A thin layer of silicon grease between mating surfaces aids in the fidelity of vibration transmission. Recommended torque: 1 Nm. Make sure that the mounting stud is not too long resulting in a gap between sensor and test object. 
Isolating Studs 106 (2 x M3) 006 (2 x M5) 206 (2 x M8) 129 (M3, adhesive) 329 (M3, adhesive) 029 (M5, adhesive)	➔ Avoid grounding problems. Limited performance at high frequencies. Model 006 not to be used above 100 °C. Models 029 and 129 for adhesive attachment using cyanoacrylate, (e.g. the gel-like Loctite 454) or epoxy glue. 
Non-Isolating Mounting Pads 229 (M8)	➔ Provides optimum coupling conditions on test objects without flat and smooth surfaces. For adhesive attachment using cyanoacrylate, epoxy glue or dental cement. 

Mounting Cubes 130 (M3) 030 (M5) 230 (M8) 330 (M10)	➔ For triaxial arrangements of uniaxial accelerometers. 
Handle Adapters 140 (M3)	➔ For the attachment of uniaxial or triaxial accelerometers with M3 thread on curved surfaces, for instance at machine tool handles. 
Han-held Adapters 142 (M3)	➔ For measurements with uniaxial or triaxial accelerometers with M3 thread on curved surfaces by hand pressure, for instance at machine tool handles. 
Rare-Earth Mounting Magnets 108 (small, M3 stud) 308 (large, M3 stud) 408 (M4 hole) 008 (M5 stud) 208 (M8 stud) 608 (2 x M5)	➔ For rapid mounting with limited high frequency performance. Ferromagnetic object with smooth and flat surface required. If not available, weld or epoxy a steel mounting pad to the test surface. **Caution:** Do not drop the magnet onto the test object to protect the sensor from shock acceleration. Gently slide the sensor with the magnet to the place. Do not use magnets for seismic accelerometers.

	  Foldable magnet model 608 for tubes etc.
Probe 001 (M5)	➔ For estimating and trending measurements above 5 Hz and below 1000 Hz. Attach the accelerometer via the M5 thread. Press onto the test object perpendicularly. Drilling a countersink will increase repeatability. 
Adhesive Wax 002	➔ For quick mounting of light sensors at room temperature and low acceleration. Soften the wax with the fingers. Apply thinly onto the test surface. Press sensor onto the wax. 
Cable Clamps 004 (M5) 020 (M3)	➔ Avoid introduction of force via the cable into the transducer. To be screwed onto the test object together with the accelerometer. 

4.3.4 Cabling

Cables and connectors are often the weakest part of a measuring system. In our sensor data sheets and catalogs you find recommendations for suitable cables for each accelerometer.

Choosing the right sensor cable is of particular importance for accelerometers with charge output. When a coaxial cable is subjected to bending or tension, this may generate local changes in capacitance. They will cause a charge transport, the so-called triboelectric effect. The produced charge signal cannot be distinguished from the sensor output. This can be troublesome when measuring low vibration with charge transducers. Therefore Metra supplies all charge transducers with a special low noise cable. This cable type has a particular dielectric with noise reduction treatment. However, it is recommended to clamp the cable to the test object.

As a rule, the cable length of sensors with charge output should not exceed 10 m.

Important: The connectors of low noise cables for charge transducers should be kept absolutely clean. Dirt or humidity inside the plug may reduce insulation resistance and will thereby increase the lower frequency limit of the sensor.

IEPE compatible transducers do not require special low noise cables. They can be connected with any standard coaxial cable.

Strong electromagnetic fields can induce error signals, particularly when charge transducers are used. Therefore it is recommended to route the sensor cable as far away as possible from electromagnetic sources, like generators, AC converters or motors. Do not route the cable along power lines and cross them right-angled.

Relative cable motion (cable whip) at the sensor body can cause erroneous sensor outputs. Miniature accelerometers and compression designs (i.e. Metra´s „KD“ models) are particularly susceptible to this. The problem can be avoided by proper cable tie-down. Metra offers the cable clamps 004 and 020 for this purpose. Adhesive cable clamps or “O”-Rings are also suited as shown in Figure 21.

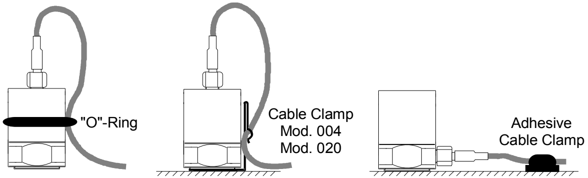


Figure 21: Methods of cable tie-down

When securing the cable, leave enough slack to allow free movement of the sensor.

Before starting the measurement, make sure that all connectors are carefully tightened. Loose connector nuts are a typical source of measuring errors. Do not use a pliers. Hand tightening is sufficient. A small amount of thread-locking compound can be applied on the male thread. Avoid contamination of the insulator.

Metra standard accelerometer cables may have the following connectors:

- *Microdot:* coaxial connector with UNF 10-32 thread
- *Subminiature:* coaxial connector with M3 thread
- *TNC:* coaxial connector with UNF7/16-28 thread and IP44
- *BNC:* coaxial connector with bayonet closure
- *Binder 707:* circular 4 pin connector with M5 thread and IP67
- *Binder 711:* circular 4 pin connector with M8 thread
- *Binder 713:* circular 4 pin connector with M12 thread and IP67
- *Binder 718:* circular 4 pin connector with M8 thread and IP67

4.3.5 Avoiding Ground Loops

The most typical source of errors in connection with sensors and AC measuring instruments are ground loops. They are a result of unwanted potential differences in the electric circuit between the sensor and the instrument. Such problems usually occur along ground or earth cables. Possible reasons are:

- Long distance between sensor and instrument

- Voltage drop over insufficient cable cross-sections in the grounding network
- Measurement close to powerful electric engines which may cause considerable current transients in the grounding system.

These potential differences may cause balancing currents through the shield of the sensor cable. The result are voltage drops which will be added as an error component to the sensor signal at the input of the instrument. Typically these error signals have strong frequency components at 50 or 100 Hz or, in the presence of pulsed drives, also at higher frequencies.

For this reason the current path between the sensor mounting location and the instrument should be interrupted.

The following practical method usually helps to avoid ground loops:

The entire measuring chain is grounded at only one point, if grounding cannot be avoided completely. The transducer, a preamplifier (if required) and the cable shield are insulated from ground / earth potential. The only connection to ground / earth potential is made at the input of the instrument, if necessary.

Poor grounding circuit:

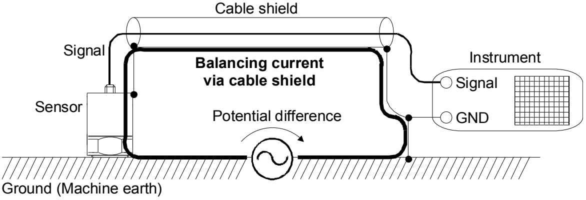


Figure 22: Sensor mounting without insulation causes ground loop

Better:

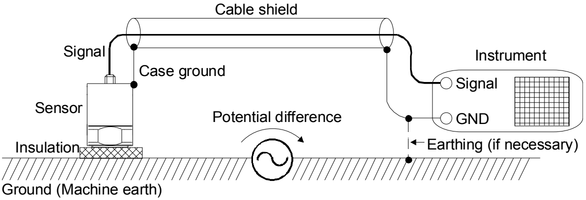


Figure 23: Insulated sensor mounting avoids ground loops

A central grounding point is of particular importance in multichannel measuring systems.

We recommend the use of accelerometers with insulated base to avoid grounding problems, for example Models **KS74**, **KS80, KS81 and KS813**. The insulating flanges **006**, **106**, **206**, **029**, **129** and 3**29** are also suited.

4.4 Calibration

Under normal conditions, piezoelectric sensors are extremely stable and their calibrated performance characteristics do not change over time. However, often sensors are exposed to harsh environmental conditions, like mechanical shock, temperature changes, humidity etc. Therefore it is recommended to establish a recalibration cycle. For applications where high accuracy is required, we recommend to recalibrate the accelerometer every time after use under severe conditions or at least every 2 years. In some less critical applications, for example in machine monitoring, recalibration may be unnecessary.

For factory recalibration service, please send the transducer to Metra. Our calibration service is based on a transfer standard which is regularly checked at Physikalisch-Technische Bundesanstalt (PTB).

Many companies choose to purchase own calibration equipment to perform recalibration themselves. This may save calibration cost, particularly if a larger number of transducers is in use. It may also be desirable to calibrate the vibration sensor including all measuring instruments as a complete chain by means of a constant vibration signal. This can be performed using a Vibration Calibrator of Metra's VC2x series. The **VC20** calibrator supplies a constant vibration of 10 m/s² acceleration, 10 mm/s velocity, and 10 µm displacement at 159.2 Hz controlled by an internal quartz generator. Model **VC21** has 7 frequencies of 15.92, 40, 80, 159.2, 320, 640 and 1280 Hz with up to 5 magnitudes between 1 and 20 m/s².

The **VC110** Vibration Calibrating System has an adjustable vibration frequency between 70 and 10,000 Hz at 1 m/s² vibration level. It can be controlled by a PC software. An LCD display shows the sensitivity of the sensor to be calibrated. The VC110 is also suitable for measuring frequency sweeps.

If no calibrator is at hand, a measuring chain can be calibrated electrically either by

- Adjusting the amplifier gain to the accelerometer sensitivity stated in the data sheet.
- Typing in the stated sensitivity when using a PC based data acquisition system.
- Replacing the accelerometer by a generator signal and measuring the equivalent magnitude.

Please understand the limitations of transducer calibration. Do not expect the uncertainty of calibration to be better than ± 2 %.

4.5 Evaluation of Measuring Errors

For the evaluation of measuring results it is very important to assess the measuring errors. The following three groups of errors occur with piezoelectric accelerometers:

- **Sensitivity Errors:**
  calibration errors, linearity errors, frequency and phase response errors, aging errors, temperature coefficients
- **Coupling Errors:**
  influence of transducer weight, quality of the coupling surfaces, transverse sensitivity
- **Noise and Environmental Influences:**
  noise, base strain, magnetic fields, temperature transients, intensive sound pressure, cable motion, electromagnetic interference in cables, triboelectric effect in cables

Systematical errors can be corrected arithmetically if their process of formation is known. The effect of these errors has been diminished and well described by the manufacturer.

Most of the systematical errors can be neglected if the measuring results are compared with another measurement under similar environmental conditions. This is of particular importance for unknown and undefined systematical errors.

Most errors, however, will occur accidentally in an unpredictable manner. They cannot be compensated by a simple mathematical model since their amount and their process of formation is unknown.

For practical measurements, systematical errors and accidental errors are combined in one quantity called measuring uncertainty.

The following example illustrates the contribution of several error components and their typical amounts:

- Accelerometer:

Basic error	2 %
Frequency error (band limits at 5 % deviation)	5 %
Linearity error	2 %
External influences	5 %

- Instrument with RMS calculation:

Basic error	1 %
Frequency error (band limits at 5 % deviation)	5 %
Linearity error	1 %
Waveform error	1 %

The addition of the squared error components yields for this example an uncertainty of $u = 9\ \%$.

<u>Please note that an uncertainty below 10 % will only be reached if all relevant errors are considered and if the used measuring equipment is of good quality.</u>

5 Standards

Selection of standards concerning piezoelectric accelerometers:

- **ISO 2041:** Vibration and shock – Vocabulary
- **ISO2954:** Mechanical vibration of rotating and reciprocating machinery - Requirements for instruments for measuring vibration severity
- **ISO 5347:** Methods of the calibration of vibration and shock pick-ups
- **ISO 5348:** Mechanical vibration and shock - Mechanical mounting of accelerometers
- **ISO 8041**: Human response to vibration - Measuring instrumentation
- **ISO 8042**: Shock and vibration measurements - Characteristics to be specified for seismic pick-ups
- **ISO 10816**: Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts
- **ISO 15242**: Rolling bearings - Measuring methods for vibration
- **ISO 16063**: Methods for the calibration of vibration and shock transducers
- **DIN 4150**: Vibration in buildings
- **DIN 5426**: Rolling bearings - Rolling bearing vibration and noise
- **DIN 45661**: Vibration measuring instrumentation - Vocabulary
- **DIN 45662**: Vibration measuring instrumentation - Fundamental requirements and verification
- **DIN 45669**: Measurement of vibration immission - Part 1: Vibration meters - Requirements and tests