Gantner instruments

Whitepaper

Vibration Monitoring Essentials

An Overview of Acceleration Measurement Technologies

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Introduction

Vibration is, in general, the movement or mechanical oscillation of a machine or structure about a fixed position. Vibration is measured as acceleration and can be expressed in its physical unit m/s² or units of gravitational constant *g* where 1 g is 9.81 m/s².

The vibration of an object, machine, or structure can be measured using different types of sensors such as accelerometers, proximity probes (eddy current sensors), or displacement sensors such as LVDTs. For machine monitoring, one must distinguish between relative and absolute transducers.

Relative vibration transducers such as proximity probes or eddy current sensors are often used to measure shaft vibration in plain bearings where the rotating shaft has no direct contact with the bearing itself to transfer the vibration as a mechanical force into the bearing housing. For these fluid film sleeve bearings, the described contactless transducers are used for relative vibration measurements.

Absolute vibration transducers are accelerometers and, in the example of machinery monitoring, are mounted on the bearing housing of standard roller bearings. There are different types of accelerometers available that provide a raw acceleration output or convert the measured acceleration directly into vibration velocity (mm/s).

This whitepaper explains the various types of absolute vibration transducers – accelerometers with pure acceleration output and corresponding measurement chains.

Types of Accelerometers

The measurement of acceleration or vibration is generally made possible using accelerometers with different kinds of sensing elements. Depending on the sensor type used, signal conditioning may be performed within the sensor housing while the data acquisition is performed by I/O modules. In contrast, the sensor may not contain any type of electronics within its sensor housing; therefore, the signal conditioning and data acquisition are both performed by a specialized I/O module. This whitepaper provides an overview of the following sensor types, their required signal conditioning, and best-fit data acquisition systems:

- PE – Piezoelectric
- IEPE – Integrated Electronics Piezoelectric
- MEMS – Micro Electromechanical System

The sensing elements within PE and IEPE types of accelerometers are mostly the same: a piezoelectric crystal or quartz. The piezoelectric (PE) effect is the ability of certain solids to generate an electrical charge in response to mechanical stress. The applied force of pressure or tension causes the microscopic structures of the object to change, resulting in dipoles between which an electric field is generated.

The electrical charges that are produced in the piezo crystal are proportional to the force applied and can be used as measurement acquisition signals with the use of a charge amplifier.

In case the sensor has no inbuilt impedance converter or electronics, it is considered a piezoelectric sensor. When the sensor contains an electronic circuit that converts the charge from the sensing element to a voltage by use of an impedance converter, then it is considered an IEPE sensor.

MEMS sensors use two different kinds of sensing elements and are distinguished as either variable capacity or piezoresistive accelerometers. The sensing element in MEMS variable capacity accelerometers is comprised of a mass that is suspended between two parallel plates or flexures attached to a ring frame. This configuration forms two air-gap capacitors between the proof mass and the upper and lower plates. As the proof mass moves when acceleration is applied, one airgap decreases while the other gap increases, creating a change in capacitance proportional to the applied acceleration.

The sensing elements in MEMS piezoresistive accelerometers are comprised of flexures on a middle wafer sandwiched between an upper and lower wafer. The bending of these flexures causes a measurable change in resistance that is proportional to the applied acceleration.

In both cases, inbuilt electronic circuits convert capacity or resistance into a voltage signal that can be read by a data acquisition I/O module.

Annex A shows the advantages and disadvantages of each sensor type, and a comparison of the measurement chains and I/O-modules to be used.

Selecting an Accelerometer

To select the appropriate accelerometer, a clear understanding of the application and its measurement tasks are essential. First, determine the type of application: is it vibration testing, condition monitoring, or modal analysis? Depending on the application, further information must be determined, e.g., what is the necessary sensitivity, precision, and frequency range of the sensor? These points are especially crucial for vibration testing and modal analysis. Knowledge of environmental conditions is essential for selecting the appropriate accelerometer for industrial condition monitoring applications. For these types of applications, robustness is likely more of an interest than the maximum highest precision.

Explained:
Sensitivity is the indication of how much the sensor's output changes when the sensor is affected by acceleration. The minimum input of a physical parameter that will create a detectable output change. In some sensors, the sensitivity is defined as the input parameter change required to produce a standardized output change.

There are pros and cons for each of the three sensors types (PE, IEPE, MEMS) used for measuring acceleration. Sensors with inbuilt electronics, such as IEPE and MEMS, have a limited environmental temperature range in which they can be used. IEPE sensors can be used up to 150 °C and some variants up to 200 °C surface or environmental temperature. MEMS sensors have a little lower allowable temperature range but have the advantage of being able to measure quasi-static signals. In contrast, the measurement range of IEPE sensors typically starts at 0.5 Hz. The PE sensor can be used under very high environmental or surface temperatures and has a broad measurement range from just a few g up to tens of thousands g. It also has a frequency response from quasi-static to kilohertz. But these kinds of sensors need special cables and a charge amplifier for signal conditioning.

Explained:
Frequency response is often also referred to as bandwidth. It represents the lowest and highest frequency at which the output magnitude drops to about 3 dB (70%) of the actual magnitude. It represents the frequency range of a sensor in which the sensor signals can be measured.

The properties of each sensor type and their scope of application are summarized in Table 1.

Table 1: Sensor properties comparison

Sensor Type	Temperature Range	Size of the Sensor Casing	Frequency Response	Measurement Range	Sensitivity	Price Level of Sensor & DAQ	Application
Piezoelectric	Cryo up to >+300°C	Very small	DC to 10kHz+	2g to 50,000g	Very high	high	Production & Test, R&D, crash test, high temperature
IEPE	-50°C to +200 °C, Cryo possible	normal	Typically 0.5Hz to 10kHz	10g to 10,000g	normal	low	Industrial, monitoring
MEMS	-50°C to 120°C	normal	DC to 3kHz	0g to 250g	high	normal	Modal analysis, structural testing, and monitoring

Accelerometer Mounting and Handling

The mounting of a vibration sensor (accelerometer) directly impacts its performance. Incorrect mounting may give readings that relate not only to a change in conditions but also to the instability of the sensor itself, thus making the sensor's readings unreliable. The primary goal is to achieve a maximum useable frequency response for performing a vibration measurement. Since the mounting surface conditions affect transmissibility, a variety of adhesive mounting pads, clips, magnetic bases, studs, and triaxial cubes with accurately prepared mounting surfaces are available for use in a wide range of applications. Accelerometers should be mounted onto a surface that is free from oil and grease as close as possible to the source of vibration. The surface should be smooth, unpainted, flat and larger than the base of the accelerometer itself. For best results, sensors should be mounted via a drilled and tapped hole directly to the machine housing.

When frequencies higher than 2 - 3 kHz are considered, refer to the accelerometer's instruction manual for specific recommendations for surface quality, sensor orientation, and mounting torque. Frequency response considerations are detailed in Figure 1 and should be considered during design and sensor installation.

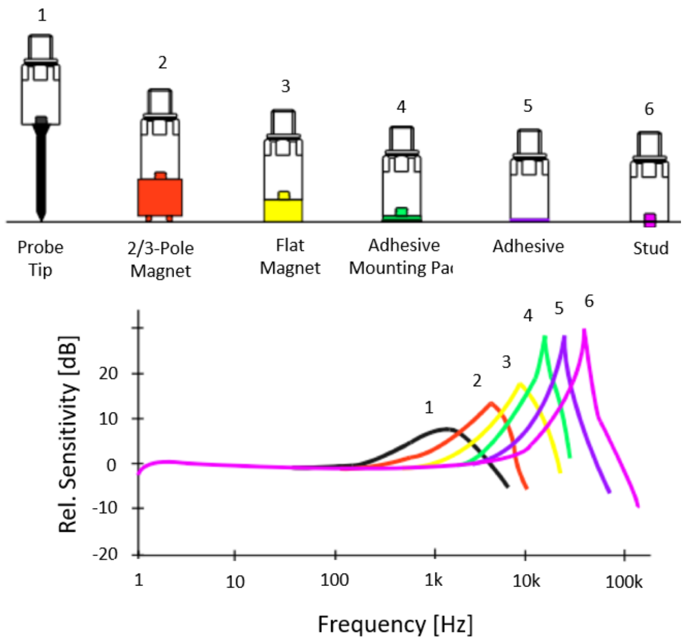


Figure 1: Accelerometer mounting options versus frequency and sensitivity

The sensor cable must also be laid with great care and needs fixation at several points, but most importantly, fixed at the sensor. With free-flying cables, vibration can be introduced by components other than the object measured. This introduced vibration affects the sensor and distorts the signal measured. Fixing the sensor cable directly to the sensor itself prevents external influences.

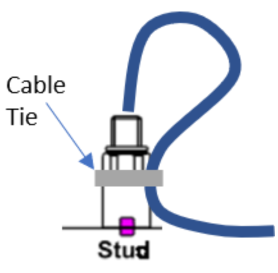


Figure 2: Sensor cable fixation

Avoiding Ground Loops

Cable screen or conductor grounding should be carefully considered during design and installation to provide proper shielding and prevent ground loops. Ground loops can transmit interference to the measurement signal as noise, usually at a line frequency of 50 / 60 Hz. Ground loops develop when a common line (e.g., signal return/shield of an IEPE accelerometer installation) is grounded at two points of differing electric potential. Figure 3 demonstrates the typical installation of an industrial IEPE accelerometer mounted by stud on a machine's surface. The sensing element itself is electrically isolated from the sensor casing and has two pins for sensor connections (signal and return line). These pins are electrically isolated from the sensor casing, but if using the wrong connector where the cable screen attaches to the sensor casing, a ground loop occurs due to the cable screen also being connected to the ground on the readout device.

For sensors with coaxial cable, the center conductor carries the signal and power, while the outer braid provides shielding and signal return. Typically, the cable shield is electrically isolated from the sensor housing and the mounting point of the machine, preventing ground loops (see Figure 3, right image). If a non-isolated sensor is used, it is recommended that an isolated mounting pad also be used to break possible ground loops.

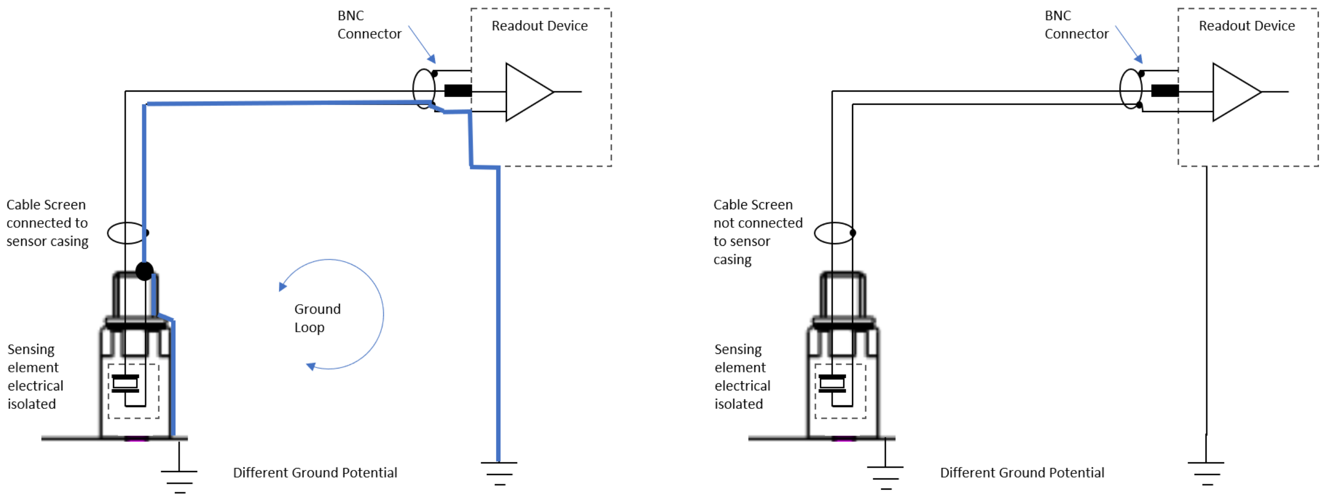


Figure 3: Ground loop due to improper cable screen connection (left), ground loop avoided by prober cable screen layout (right)

Measuring with PE Sensors

When it comes to special applications with limited installation space, or high surface or ambient temperature, PE (Piezo Electric) sensors are the method of choice. With their direct charge output (physical unit pC/g), these sensors do not have any electronic items in their housings, making them small and robust against high temperatures. However, these sensors require external signal conditioning to convert the charge output into a standard voltage signal. The required signal conditioning is provided by a device known as a charge amplifier. It converts the negative charge produced by the piezoelectric sensor when it is subjected to vibration into a positive voltage proportional to the vibration.

The measurement chain of a piezoelectric sensor with a charge amplifier is visualized in Figure 4. The main components are:

- Range capacitor C_r
- Time constant resistor R_t
- Reset / Measure switch

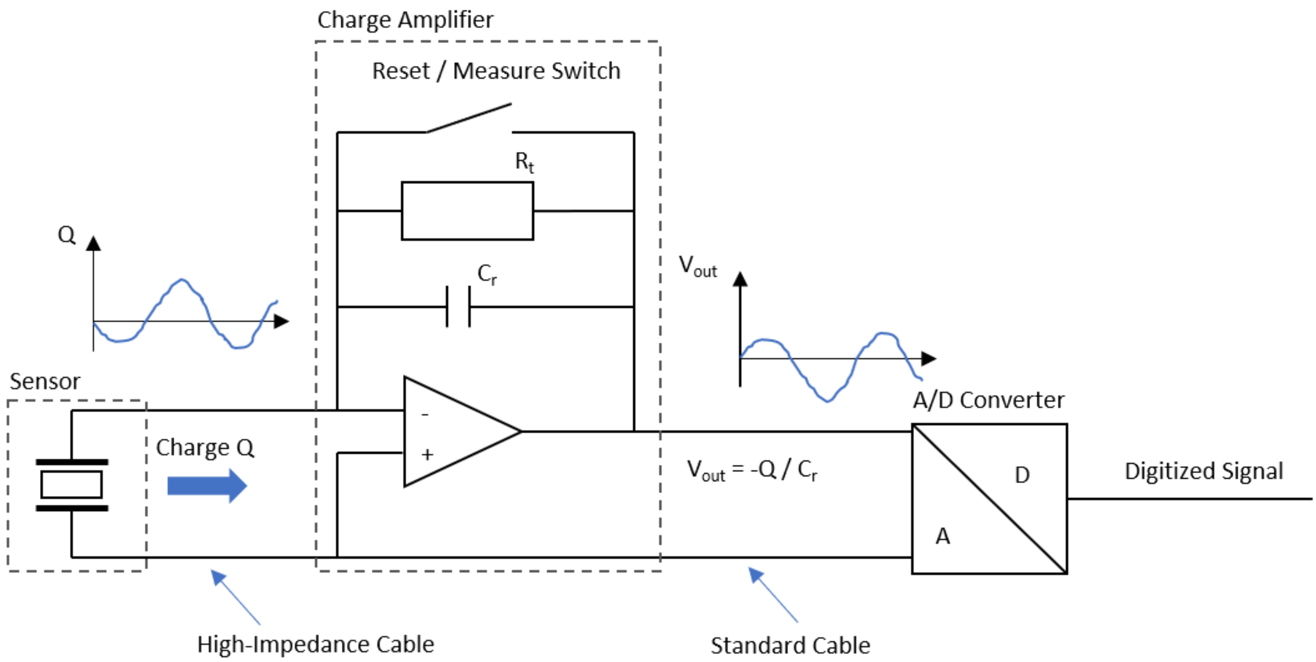


Figure 3: Measurement chain for piezoelectric sensors with a charge amplifier

The range capacitor, C_r, is used to set the measurement range of the amplifier by switching between different capacitors. With the switched or changed measurement range, it is possible to measure across several decades with a remarkable signal-to-noise ratio. It is possible to measure low frequencies down to DC as well as high frequencies up to 20 kHz, just by switching the measurement range. The signal-to-noise ratio is still outstanding.

Explained:
Signal-to-Noise Ratio (SNR) is defined as the ratio of the power of a signal (meaningful input) to the power of background noise (unwanted input):
$SNR = P_{signal} / P_{noise}$
Often specified in decibel (dB).

The time constant resistor, R_t, determines the cut-off frequency for the high-pass filter of the amplifier. It also defines the behavior of the charge amplifier in the lower frequency range. Different time constants are used for quasi-static measurements down to DC level and for high dynamic measurements.

The Reset / Measure Switch is used to control the start of measurement or to reset the signal to zero-point. For quasi-static measurements, the switch between Reset and Measure is essential to avoid signal drift. The switch is open during measurement and closed to “discharge” the range capacitor and reset the signal.

In the past, this measurement chain was achieved by external devices such as inline charge amplifiers, and their voltage output was connected to a data acquisition system. Gantner Instruments provides a 4-channel charge amplifier in the Q.series X product line that has the A/D converter integrated into the charge amplifier. Figure 5 demonstrates a measurement chain with an A141 charge amplifier that produces a digitized signal, directly.

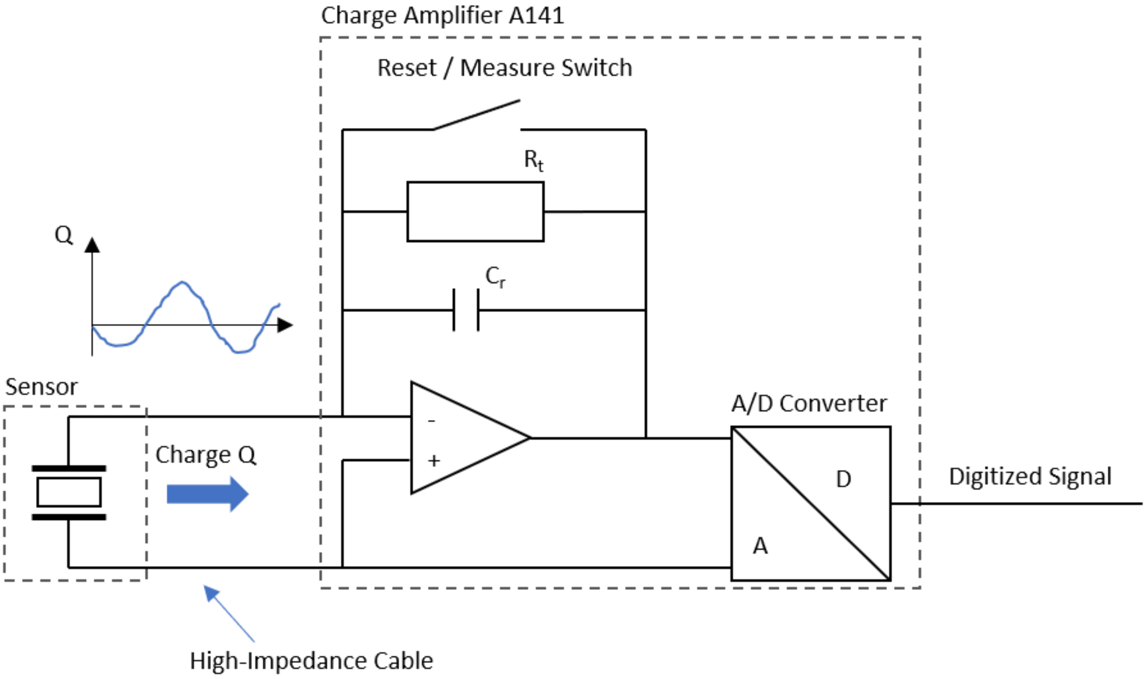


Figure 4: measurement chain for piezoelectric sensors with A141

The Two Operating Modes of Charge Amplifiers

The two operating modes of charge amplifiers are for quasi-static and dynamic measurements. Most charge amplifiers support both measurement types, but before setting up a vibration measurement chain, a clear understanding of the type of measurement involved is essential to selecting the correct charge amplifier.

For example, measurements in a low-frequency range <0.5 Hz should be performed in the quasi-static mode. The quasi-static mode can also sometimes be necessary when measuring low frequency pressure fluctuations in high-temperature applications. Typical vibration measurements have higher frequency content in the signal; therefore, the dynamic mode is used.

Nevertheless, charge amplifiers that support both modes are also often used for other piezoelectric sensors to measure force or pressure instead of acceleration. In any case, when changing the sensor or using the charge amplifier in a new application, the configuration mode of the amplifier is essential.

As explained, the time constant resistor determines the cut-off frequency for the high-pass filter characteristic of the charge amplifier, so it also determines the operating mode. For quasi-static measurements, the time constant resistor is not used. The amplifier is instead set to the time constant “long.” Signals with very low-frequency content or constant signals can then be measured, but since drift becomes visible after an extended period, and a reset signal is necessary to reset the signal to zero.

For dynamic measurements, the time constant resistor is used, and the amplifier is set to the time constant “short.” The input stage acts as a high-pass filter, so no signals lower than the cut-off frequency are visible in the measured signal. The reset switch is not used in this operating mode.

Figure 6 demonstrates the two different operating modes within a circuit diagram of a charge amplifier.

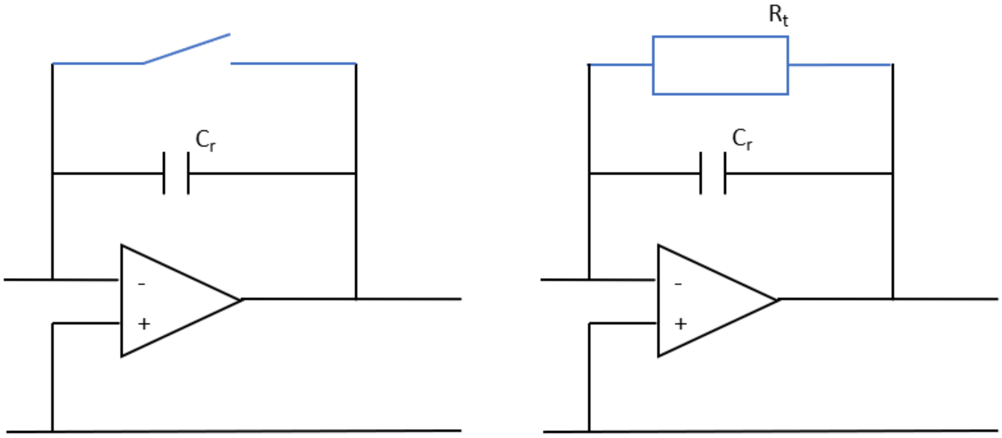


Figure 5: Circuit diagram of a charge amplifier in operating mode quasi-static (left) and dynamic (right)

Tips and Tricks

For best measurement results, only use high impedance cable and keep the connectors dry and clean.

As a mandatory requirement, piezoelectric sensors and charge amplifiers must be connected using a high-insulation cable (high impedance cable). In contrast to standard coaxial cables, the innermost wire of high-insulation cables is insulated with PTFE, which reduces the drift effect to the absolute minimum. Also, a special graphite sheathing minimizes the triboelectric effect. There are various versions (with comparable properties) of sensor cable available. Check out, e.g., Kistler (www.kistler.com) for more information.

In addition to using high-insulation cables when working with piezoelectric measuring chains, it is also essential to ensure that all connectors and sockets are always clean. It is recommended to leave the protective caps on the sockets of sensors and charge amplifiers until they are connected. The protective caps should be fitted again whenever components are disconnected or placed in storage.

Measuring with IEPE / ICP Sensors

Robust and relatively inexpensive acceleration measurements in industrial environments are possible with IEPE sensors. Sensors according to the IEPE standard are always used if the surface or ambient temperature at the measuring object is less than 150 °C, or in some cases, less than 200 °C and no quasi-static measurements below 0.5 Hz are required.

The abbreviation IEPE means Integrated Electronics Piezo Electric. IEPE sensors are piezoelectric sensors with inbuilt electronics that have set the standard for a wide range of industrial applications. In addition to acceleration, other parameters such as force and pressure can be measured with sensors according to the IEPE standard. Also, acoustic measurements with IEPE microphones are common as well.

Other brand names for sensors based in the IEPE standard are ICP®, ISOTRON®, DeltaTron, Piezotron, or PiezoStar. A good criterion for deciding whether it is a sensor according to the IEPE standard is the indication of the sensitivity of the sensor in mV/g. Standard accelerometers sensitivities are, e.g., 10 mV/g, 100 mV/g, while the typical sensitivities for shock sensors are, e.g., 0.1 mV/g and 1 mV/g.

The inbuilt electronics inside the sensor housing converts the charge signal into a voltage signal. Technically the high impedance signal is converted to a low impedance signal by an impedance converter. According to the IEPE standard, the sensor power supply and the sensor signal are transmitted with one standard 2-wire cable.

For the power supply of an IEPE sensor, a constant current source is needed. In general, there are two ways, or two types of typical measurement chains used to acquire data from IEPE sensors. In older measurement chains, often, an additional constant current source from an external device inline with a data acquisition module is used. The state-of-the-art variant is an IEPE signal conditioning I/O module with an inbuilt constant current source such as the A111 from Gantner Instruments.

The measurement chain of an IEPE sensor with an external constant current source can be seen in Figure 7. The main components of the IEPE coupler are a constant current source at 24-30 VDC, a diode providing 2-20 mA of constant current, and a decoupling capacitor.

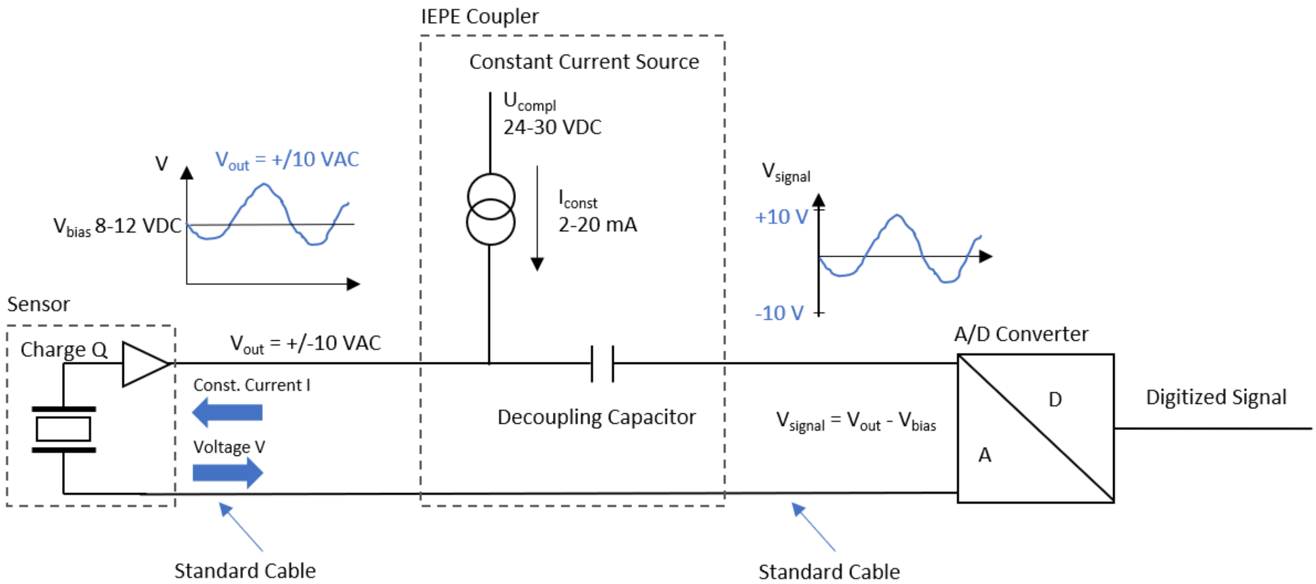


Figure 6: Measurement chain for IEPE sensors with an IEPE coupler as an external constant current source

The constant current source supplies the sensor with power with 2–20 mA and 24–30 VDC.

The sensor's inbuilt electronics superimpose the measurement signal as an AC signal to the bias voltage of the sensor. The decoupling capacitor is used to remove the constant bias voltage from the AC signal. It acts as a high-pass filter element.

Modern IEPE signal conditioning I/O modules such as the A111, for example, combine the constant current source and the A/D converter within a single module that produces a digitized signal, directly. Figure 8 shows the measurement chain with the A111 I/O module.

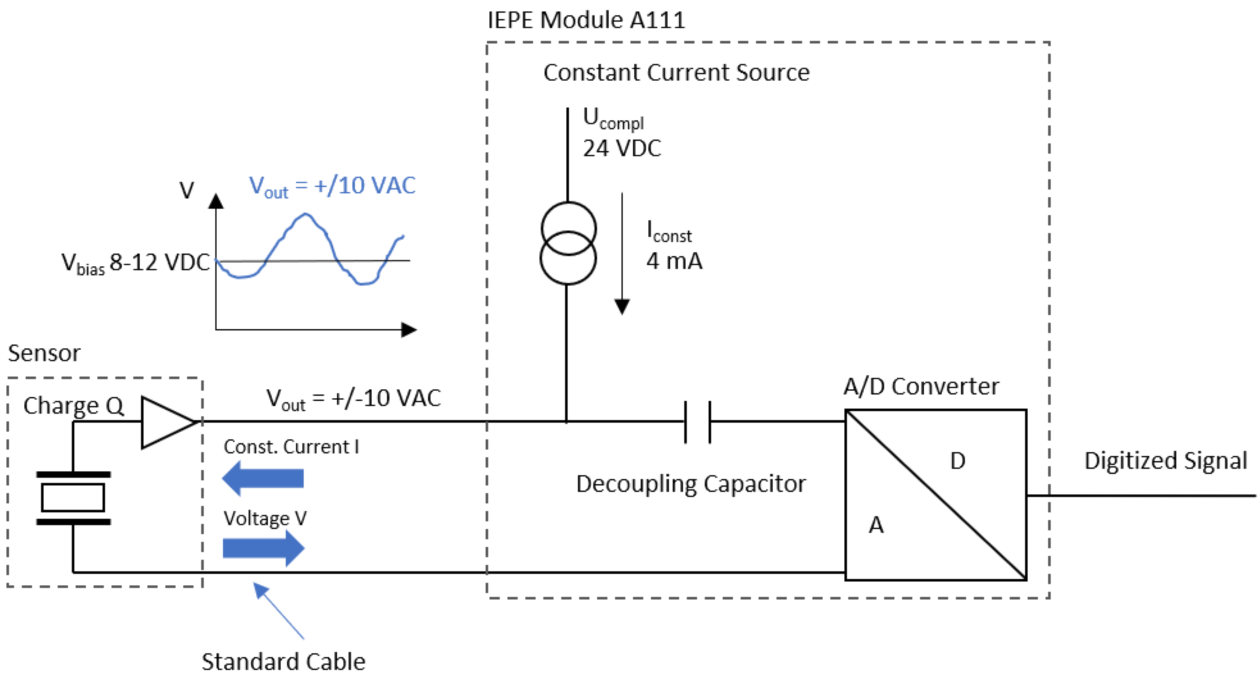


Figure 7: Measurement chain for IEPE sensors with A111

IEPE Signal Conditioning

According to the IEPE standard, a constant current source with 2 – 20 mA output current is required for sensor supply. For very long cables (>100 m) and high frequencies, a higher current is used. At high signal frequencies, the increasing cable capacitance with long cables leads to a deterioration of the drive capability of the inbuilt amplifier of the sensor. For high-temperature sensors, the lowest possible constant current of 2 mA is typically used to keep the heating caused by the power dissipation in the sensor as low as possible.

Most IEPE I/O modules offer a fixed constant current source of 4 mA and thus forms a very good optimum between noise immunity, cable length, signal frequency, and current consumption. Also, high-temperature sensors can be measured with a 4 mA constant current source even when 2 mA is stated in the sensor datasheet. But in that case, the maximum allowable ambient temperature should not be reached.

IEPE sensors generate a constant DC bias voltage (zero voltage or U_{bias}) of typically 8 – 12 V in standby state when the compliance voltage of the constant current source is in the range of 24 – 30 V. Depending on the acceleration of the sensor, an analog AC voltage generated in proportion to the movement - the actual acceleration signal - is added to the U_{bias}. For example, a deflection with amplitude 1 g (9.81 m/s^2) with a 10 Hz sine wave for a sensor with sensitivity 100 mV/g provides an output voltage of AC +/-100 mV with 10 Hz sine wave + U_{bias}. The maximum output signal of a sensor is usually AC +/-10 V (+ U_{bias}).

The compliance voltage should be two times higher than the bias voltage to ensure maximum amplitudes of the measured signal in the positive and negative directions. That is why, for example, the A111 has 24 V compliance voltage.

Sensor Failure Indication

Most IEPE I/O modules are equipped with a sensor wire break detection and indicate a faulty or missing sensor by an LED on the module front or by software. The modules use the sensor bias voltage for sensor detection. A voltage close to the compliance voltage or close to zero (short-circuit) indicates a sensor's failure.

Measuring with MEMS Sensors

MEMS (Micro Electromechanical System) sensors are often used for low-frequency vibration measurements down to DC. The variable capacity-based accelerometer is used for applications requiring a measurement range up to 250 g, while piezoresistive accelerometers are often used for shock or crash testing due to their extensive measurement range.

Both types of sensors have inbuilt electronics for signal conditioning with AC excitation and synchronous demodulation. Also, the signal conditioner provides the power conditioning for the accelerometer element and outputs an analog voltage proportional to the acceleration signal. That means, in general, the output voltage can be measured by any I/O module with the appropriate voltage input. Figure 9 shows a highly simplified measurement chain for a MEMS accelerometer.

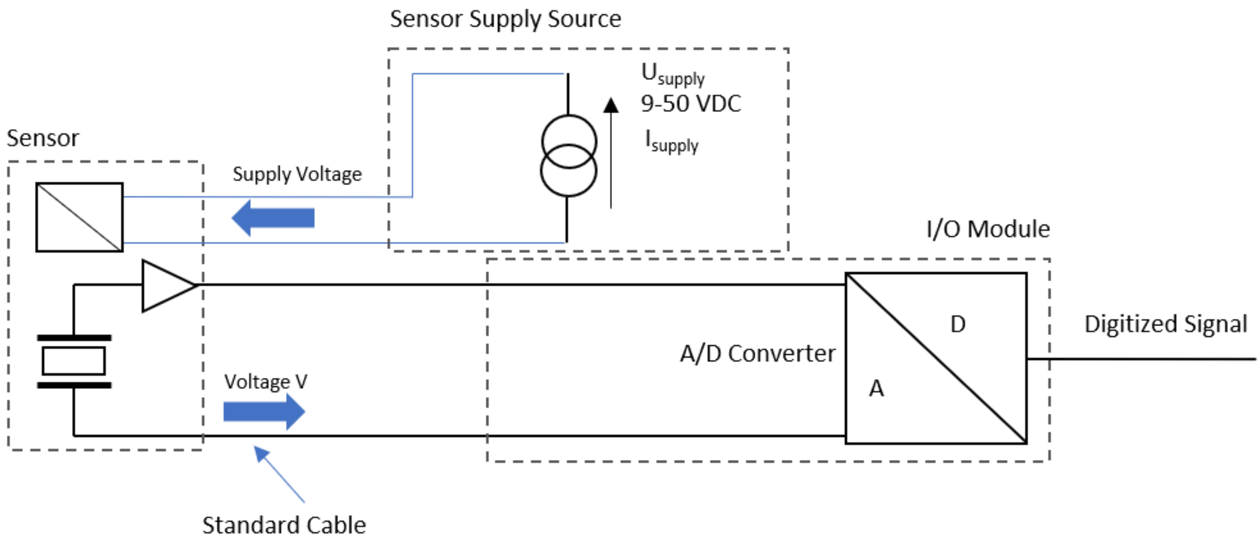


Figure 8: Measurement chain for MEMS sensors

The necessary sensor supply is provided by an external voltage source. Typical MEMS accelerometers can work with a broad range of supply voltage, e.g., 8 – 30 V or even up to 50 V. The voltage source must be of high quality but should be regulated within +/-0.1 %, while the noise and ripple cannot exceed 1.5 mV RMS.

Some I/O modules specially designed for MEMS-based sensors provide an inbuilt stable power supply like the A108-2M3 / 4M1 from Gantner Instruments (see Figures 10 and 11).

Single-ended and Differential Output

MEMS sensors are available with single-ended and differential output, and a further distinction is made between bipolar and unipolar sensors.

The single-ended measurement setup uses a common line for both the ground and return signals of the sensor (see Figure 10). The differential output uses two wires for the sensor signal and two additional wires for the power supply to the sensor (see Figure 11). This method has, with some sensors, higher effective sensitivity, and an active rejection of common-mode noise.

The unipolar sensor provides a voltage at zero-g, and the full-scale output voltage depends on the sensor model but never falls below zero volts. The bipolar sensor provides a positive and negative output signal corresponding to positive and negative acceleration.

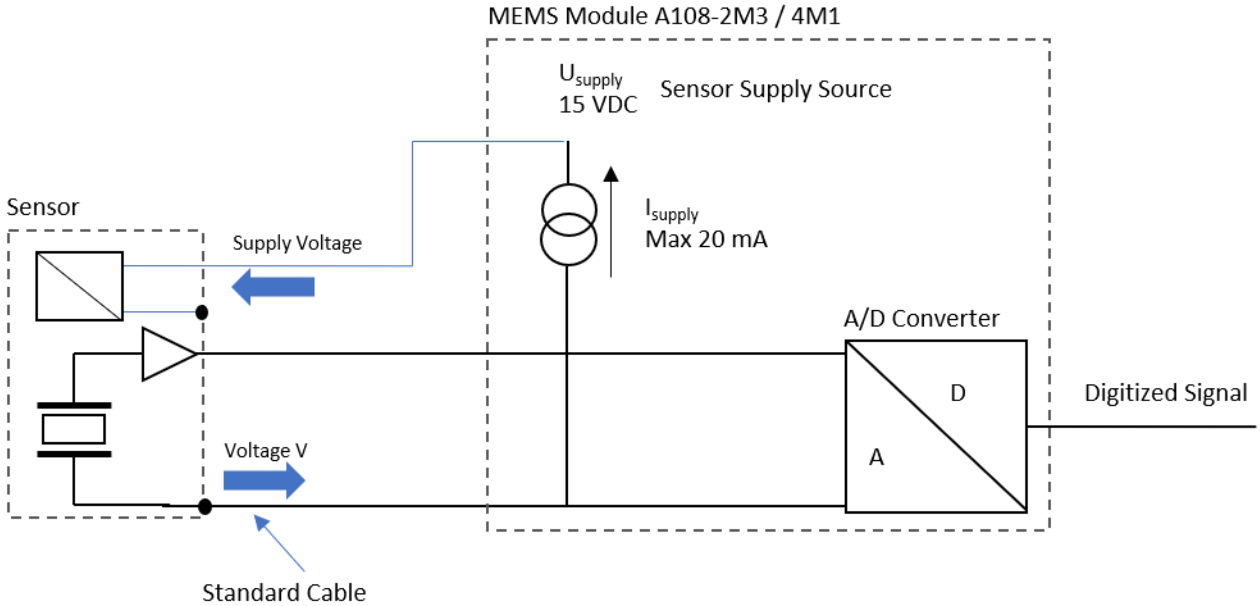


Figure 9: Measurement chain for MEMS sensors with A108-2M3 / 4M1 in single-ended mode

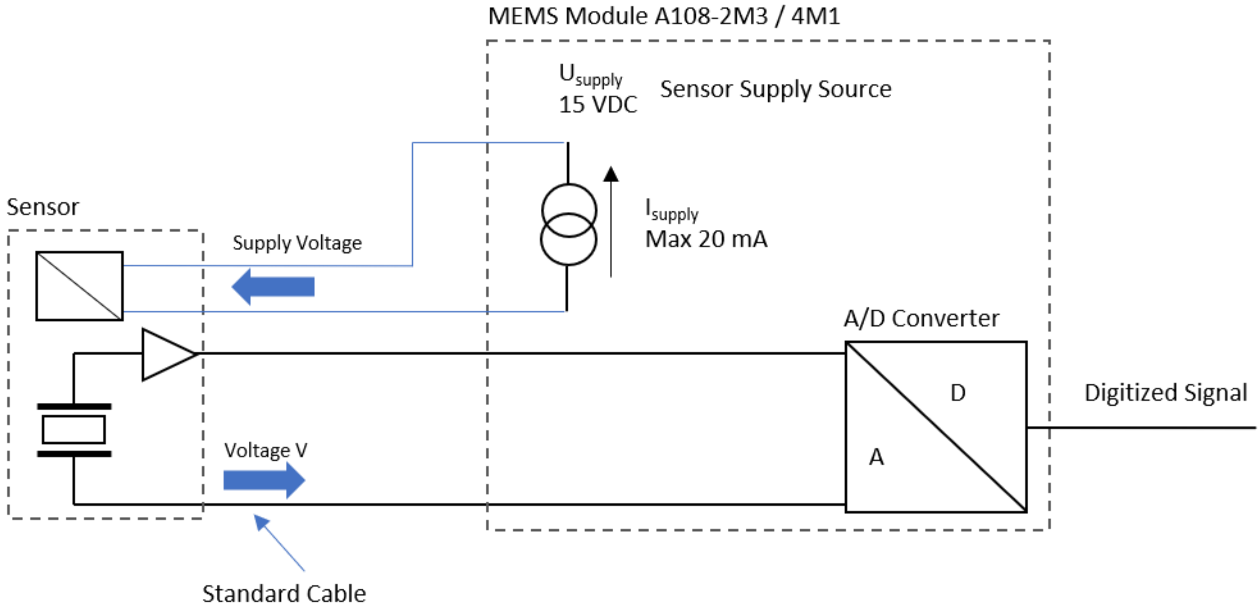


Figure 10: Measurement chain for MEMS sensors with A108-2M3 / 4M1 in differential mode

Measuring static acceleration

MEMS-based accelerometers provide an output signal like that produced by piezoelectric accelerometers. Unlike a piezoelectric accelerometer, a MEMS accelerometer is sensitive to static acceleration. Gravity is a factor in the output signal and must be considered when mounting the sensor. When the sensor is parallel to the ground, gravity produces an output equivalent to 1 g (or 9.81m/s² depending on the used physical values). When the sensor is rotated by 90°, the sensing element becomes insensitive to gravity, and a static output equivalent to 0 g is produced.

The “Correct” Sampling Rate

The best sensors and the perfect data acquisition system is not much use if signals are not correctly captured. “Correct” refers to both the amplitude level and the frequency components of the measurement signal.

For this purpose, the Nyquist-Shannon sampling theorem must be adhered to, which states that a continuous signal with a maximum frequency, f_{max}, must be sampled at a frequency greater than $2 \times f_{max}$ so the original signal can be reconstructed from the resulting discrete-time signal without loss of information.

In practice, this means that before digitizing, the maximum frequency must be known or determined, e.g., by Fourier analysis of a high frequency sampled signal. The signal must then be sampled at least twice the max frequency for digitization.

The Nyquist-Shannon sampling theorem applies to every digitization $0.5 \times f_{sampling}$ is called the Nyquist frequency. Signal components with a frequency higher than half of the sampling frequency must be filtered out of the signal with a low-pass filter before digitization; otherwise, artifacts occur. These artifacts are alias signals (interference pseudo signals), which are noticeable as interfering frequency components. For example, if a sine wave with 2000 Hz is digitized with a sampling frequency of 1500 Hz, you get a 500 Hz alias signal (2000-1500 Hz). A sampling frequency above 4000 Hz, however, does not produce the alias signal.

Explained:
At a sampling rate that is not at least twice the Nyquist frequency, false lower frequency components appear in the sampled data. This phenomenon is called the "aliasing effect". Typically, low-pass or anti-aliasing filters are used in data acquisition to filter high-frequency components from the signal so that they can be captured by a downstream AD converter without aliases, artifacts or distortion.

For an accurate reconstruction of the signal waveform, the sample rate, $f_{sampling}$, must be at least two times higher than the highest frequency component to be examined in the measured signal. Typically, a sample rate four or five times higher than the signal frequency is recommended.

Ordinary filters, and special low-pass or anti-aliasing filters, do not have an accurate cut-off or filter frequency, but always have a transition range. A 2.4- or 2.56-times sampling frequency ($2.56 \times f_{max}$) is often used in practice to keep the Nyquist-Shannon sampling theorem even with such a “non-ideal” filter.

Conclusion

The vibration of an object, machine, or structure can be measured using various transducers, and it is essential to be able to distinguish which sensor is the best fit for an application. There are pros and cons for each of the three sensors types (PE, IEPE, MEMS) used for acceleration measurement. Sensors with inbuilt electronics, such as IEPE and MEMS, have a limited environmental temperature range in which they are viable. In contrast, PE sensors can be used under very high environmental or surface temperatures and have a broad measurement range but require special cables and a charge amplifier for signal conditioning. Additional factors must be considered as well if attempting to achieve the best acceleration measurement results—elements like sensor mounting, cable fixation, avoiding group loop scenarios, sampling rate selection, and the data acquisition used.

Gantner Instrument's state-of-the-art Q.series X data acquisition systems are specially designed to accept all sensor types used for vibration measurement, as well as perform signal conditioning and charge amplification on the I/O level. Such qualities are ultimately necessary to achieve the best acceleration measurement results.

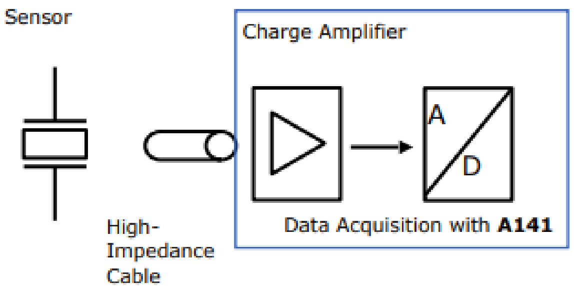
Gantner Instruments' specialists are committed to providing best-in-class, individualized sales, and technical application support. Gantner Instruments application support is free of cost and available without barriers to existing and potential customers. Let us help you achieve the best possible vibration measurement results!

The contact information for your domestic Gantner Instruments Sales and Service location is available at https://www.gantner-instruments.com.

ANNEX A: Overview of Acceleration Measurement Technologies

PE
(PiezoElectric)

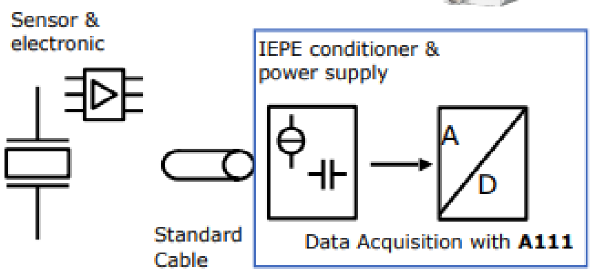
Q.Series X A141



- Sensor does not contain electronics
- Very wide temperature range
- Very broad measuring range
- Quasi-static up to very dynamic measurements possible
- High impedance cable required
- Charge amplifier required

IEPE (PiezoStar, Piezotron, DeltaTron, ICP®, ISOTRON®)
(Integrated Electronics PiezoElectric)

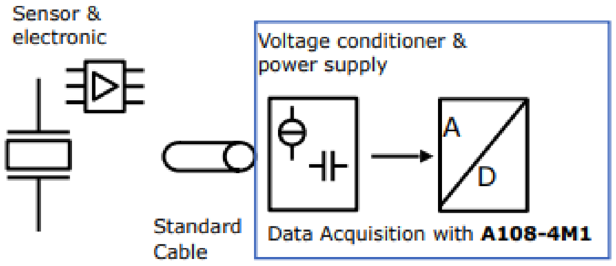
Q.Series X A111



- Sensor contains internal charge to voltage converter
- Standard cable for sensor connection
- DAQ system with integrated IEPE power supply (e.g. 4mA const.) required for operation
- Only dynamic measurements possible
- Measuring range is fixed
- Temperature range limited with integrated electronics

MEMS (K-Beam)
(Micro Electro Mechanical System)

Q.Series X A108-2M3 & A108-4M1



- Sensor contains internal charge to voltage converter
- Standard cable for sensor connection
- DAQ system with integrated power supply (e.g. 10-30V unregulated) required for operation
- Quasi-static (DC) measurements possible
- Measuring range is fixed
- Temperature range limited with integratedelectronics

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