Piezoelectric Measurement System Comparison: Charge Mode vs. Low Impedance Voltage Mode (LIVM)

Introduction

Piezoelectric sensors (Transducers) measure dynamic phenomena such as force, pressure and acceleration (including shock and vibration). Inside the sensor, piezoelectric materials such as quartz and man-made ceramics are stressed in a controlled fashion by the input measured i.e., the specific phenomena to be measured. This stress "squeezes" a quantity of electrical charge from the piezoelectric material in direct proportion to the input stress, creating analogous electrical output signals. ("Piezo" is from the Greek word meaning to "squeeze.")

Because of the high stiffness of piezoelectric materials, it is possible to produce sensors with very high resonant frequencies making them well-suited for measurement of rapidly changing dynamic phenomena such as shock tube pressure wavefronts, high frequency hydraulic and pneumatic perturbations, impulse (impact) forces, vibrations in machinery and equipment, pyrotechnic shocks, etc.

The task faced by the measurement system is to couple information, contained within the small amount of electrical charge generated by the crystals, to the outside world without dissipating it or otherwise changing it. (The quantity of charge generated by the piezo element is measured in units of picocoulombs, (pC) which is 1×10^{-12} Coulombs.)

Throughout the evolutionary process of piezoelectric sensor development, two types of systems have emerged as the main choices for dynamic metrology.

1. The Charge Mode System
2. The Low Impedance Voltage Mode (LIVM) System.

This section is intended to help make your choice between these systems a little easier by pointing out the advantage and limitation of each type.

The Charge Mode System

Dytran Charge Mode sensors are manufactured with both ceramic and crystalline quartz piezoelectric elements. Charge mode accelerometers used for vibration measurements utilize piezo-ceramic materials from the Lead Zirconium Titanate (PZT) family. These materials are characterized by high charge output, high internal capacitance, relatively low insulation resistance and good stability. Most charge mode pressure and force sensors use pure Alpha quartz in the sensing elements.

These sensors are normally used with a Charge Amplifier, a special type of amplifier designed specifically to measure electrical charge. The charge mode system is thus composed of the charge mode sensor, the charge amplifier and the interconnecting cable. (see Figure 1).

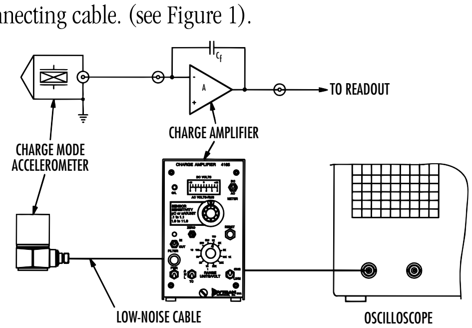


Figure 1: A Charge Mode Accelerometer System

Figure 1 is a symbolic and graphic representation of a typical charge mode vibration measurement system. The input stage of the charge amplifier utilizes a capacitive feedback circuit to balance or "null" the effect of the applied input charge signal. (This action is explained in more detail in the section "Introduction to Charge Mode Accelerometers".) The feedback signal is then a measure of input charge. This amplifier presents essentially infinite input impedance to the sensor and thus measures its output without changing it - the goal of all measurement processes.

The gain (transfer function) of the basic charge amplifier is dependent only upon the value of the feedback capacitor C_f (See Figure 1) and is independent of input capacitance, an important feature of the charge amplifier. Following stages may add voltage gain and attenuation, filtering, and other functions to further process and refine the data before coupling it to the readout instrument.

A Word About Cables

Because of the very high intput impedance of the charge amplifier, the sensor must be connected to the amplifier input with low-noise coaxial cable such as Dytran series 6013A. This cable is specially treated to minimize triboelectric noise, e.g., noise generated within the cable due to physical movement of the cable. Coaxial cable is necessary to effect an electrostatic shield around the high impedance input lead, precluding extraneous noise pickup.

Charge Mode System Advantages

• Since there are no electronic components contained within the sensor housing, the upper temperature limit of charge mode sensors is much higher than the +250˚F (121˚C) limit imposed by the internal electronics of LIVM sensors. Rather, the high temperature limit is set by the Curie temperature of the piezoelectric material or by the properties of insulating materials employed in the specific design. Check the individual product data information for the operating temperature limits of Dytran charge mode sensors.

• Laboratory type charge amplifiers currently available offer a wide range of signal augmentation choices such as filtering, ranging, standardization, integrating for velocity and displacement, peak hold and more - all conveniently contained in one package.

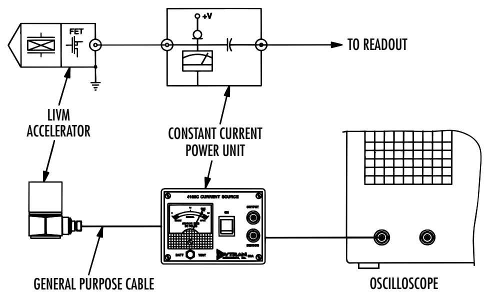
• Charge amplifier gain is independent of input capacitance, therefore system sensitivity is unaffected by changes in input cable length or type, an important point when interchanging cables.

• A special type of charge amplifier, the very long time constant "Electrostatic" type, used in conjunction with certain quartz element charge mode force and pressure sensors can, with certain precautions, be used to make near static (quasi-static) measurements of events lasting up to several minutes duration.

The LIVM System

Figure 2 contains a symbolic and a graphic representation of a typical LIVM system. We have a chosen to illustrate an accelerometer system in Figure 2 so that direct comparisons can be made with the charge mode system illustrated in Figure 1. LIVM systems are available for pressure and force measurements as well.

Figure 2: The LIVM System



Referring to Figure 2, the LIVM accelerometer, although of similar basic construction as the charge mode unit, uses crystalline quartz as the signal generating element instead of piezoceramic. Unlike the charge mode accelerometer, the LIVM accelerometer utilizes the voltage signal generated by the quartz element rather than the charge signal. The voltage signal is related to the charge signal by the following relationship:

$$V=Q/C \qquad \text{(Eq. 1)}$$

Where:
- Q = charge (pC)
- V = voltage (Volts)
- C = crystal capacitance, including any shunt capacitance added (pF)

Although the charge sensitivity of quartz is very low when compared to ceramics, the self capacitance is also very low resulting in a high sensitivity voltage signal, higher in fact than that from an equivalently proportioned ceramic element.

A miniature IC metal oxide silicon field effect transistor (MOSFET) amplifier built into the housing of the sensor, converts the high impedance voltage signal from the quartz element to a much lower output impedance level, so the readout instrument and long cable have little effect on the signal quality. Because the high impedance input to the IC amplifier is totally enclosed and thus shielded by the metal housing, the LIVM sensor is relatively impervious to external electrostatic interference and other disturbances. The sensor amplifier is a common drain, unity gain "source follower" circuit with the source terminal brought out through a coaxial connector on the sensor body.

The sensitivity of the LIVM sensor is fixed at time of manufacture by varying the total capacitance across the quartz crystal element (refer to Equation 1). The highest possible voltage sensitivity is obtained with no added capacitance across the element. To decrease sensitivity (increase range), capacitance is added to attenuate the voltage signal. Once the sensitivity is set in this manner, it cannot be changed by external means. External amplification performed in power units, or by other means can amplify or attenuate the signal but cannot change the fixed sensitivity (mV/g, psi or LbF) of the sensor.

The LIVM Power Unit

The LIVM sensor, unlike the charge mode sensor does not require a charge amplifier, but rather a much simpler Current Source Power Unit. The power unit contains a DC power source (batteries or a regulated DC power supply), a current source element (constant current diode or constant current circuit), and a means of blocking or otherwise eliminating the DC bias voltage that exists at the center terminal of the sensor connector, so the signal may be conveniently coupled to the readout instrument (oscilloscope, meter, recorder, analyzer, etc.)

Since the source load for the sensor IC (the constant current diode or circuit) is located in the power unit and not within the sensor housing, a single two-conductor cable is used to connect the sensor to the power unit. The low output impedance of the sensor makes it unnecessary to connect sensor to power unit with the more expensive low noise coaxial cable as with the charge mode system. Rather, we recommend the standard series 6010A coaxial cable. Twin lead cable with the 6115 solder connector adapter may also be used, a real cost-saving advantage for LIVM systems.

As with the charge amplifier, some dedicated signal augmentation can be accomplished within the LIVM power units such as gain, attenuation, filtering, etc., within the constraints of the fixed sensor sensitivity. With rare exceptions, full scale sensor output voltage is 5 Volts.

LIVM System Advantages

• Low output impedance (less than 100 ohms) makes the sensitivity of the LIVM sensor independent of cable length within the frequency response limits outlined in the chart (Figure 6) in the section "Introduction to Current Source Power Units". Basic system sensitivity does not change when cables are replaced or changed.

• The low output impedance precludes the use of expensive low noise cable allowing the use of inexpensive coaxial cable (or twin-lead ribbon cable) to connect sensor to power unit.

• Sensitivity and discharge time constant are fixed at time of assembly, setting full scale range and low frequency response. This makes LIVM sensors ideal for dedicated applications such as modal analysis and health monitoring.

• Sealed rugged construction, with high impedance connections contained within the sensor housing, makes LIVM sensors ideal for field use in dirty or moist environments.

• With proper considerations, very long cables (up to thousands of feet long) can be driven by LIVM sensors.

• LIVM power units are relatively simple and fractions of the cost of laboratory charge amplifiers. Multi-channel units with 3, 4, 6, 12 and 16 channels are available to greatly lower the per-channel cost of the system. Even the single-channel cost is a fraction of that of the typical charge mode system.

• The tiny IC amplifier chip built into LIVM sensors is very rugged, able to withstand shocks over 100,000 g's. This makes LIVM accelerometers, such as the Dytran 3200B series, excellent choices for measurement of very high shocks (e.g., those encountered in pyrotechnic testing). Dytran can supply ruggedized coaxial cable (series 6034A) or 2-pin solder connector adapters (model 6115 for use with very light 2-wire cable) to withstand the punishment of such severe applications.

Conclusion

We have attempted to help with your decision as to which type of system best suits your needs by pointing out the advantages and limitations of two types of dynamic measurement systems. We realize this decision is often determined or influenced by factors outside the control of the test engineer or technician. This may include having instruments already on hand which must be utilized for economic reasons, limited operating budgets, and personal preferences based upon years of familiarity with one type of instrumentation. All of these factors must be weighed.

Whatever your choice, we hope we have improved your ability to make an intelligent decision. We stand ready to offer technical assistance and to provide the best possible instrumentation at reasonable cost.

Low Frequency Phase Shift In LIVM Sensors As A Function Of Discharge Time Constant And Frequency

Abstract

Low Impedance Voltage Mode (LIVM) sensors are piezoelectric devices with integral FET impedance converting amplifiers. To bias the amplifier, a high value resistor is placed in parallel with the gate of the FET and the crystal element. The discharge time constant (TC) of the sensor is the product of this resistor and the total shunt capacitance of the crystal element. (See Figure 1). It is the discharge time constant which sets the low frequency amplitude and phase response of the sensor. This article presents a mathematical relationship for phase response as a function of frequency with discharge time constant as a parameter.

The LIVM Sensor

Figure 1 shows schematically, the LIVM sensor.

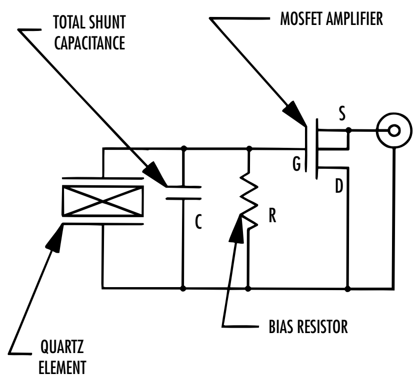


Figure 1

It can be shown that the sensor is actually a first order high pass filter with phase and amplitude parameters established by the discharge TC. The TC is the product of crystal capacitance C (includes stray C and the input capacitance of the FET) times the gate resistor R. The units of TC are seconds. The filter may be represented as shown in Figure 2 below.

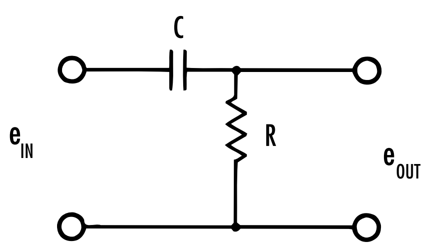


Figure 2

The transfer function of the filter shown in Figure 1 is:

$$\frac{e_{out}}{e_{in}} = \frac{R}{R + jX_C} \qquad \text{Eq. 1}$$

The vector diagram for this circuit is:

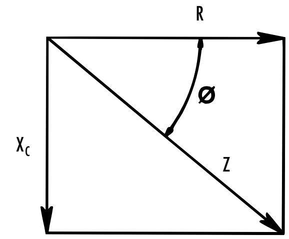


Figure 3

Regarding the phase angle Ø:

From the diagram, Figure 3,
we may write the relationship: $Ø = \tan^{-1} \dfrac{X_C}{R}$ Eq. 2

In equation 2, X_C is the capacitive reactance.

Capacitive reactance is: $X_C \; \dfrac{1}{2\pi fC}$ where: f = frequency (Hz), C = capacitance (Farads)

Substituting this relationship in Eq. 2,

$$Ø = \tan^{-1} \frac{1}{2\pi fRC}$$

Since RC = TC by definition:

$$Ø = \tan^{-1} \frac{1}{2\pi fTC}$$

reducing further,

$$Ø = \tan^{-1} \frac{0.16}{fTC} \qquad \text{Eq. 3}$$

Using the last equation, knowing the discharge TC of the sensor, this phase shift at any frequency may be calculated easily.

Example:
What is the phase shift of a sensor with a 2 second TC at 2 Hz?

$$\text{Phase shift } Ø = \tan^{-1} \frac{0.16}{2 \times 2} = \tan^{-1} 0.04 = 2.29 \text{ degrees}$$

Low Frequency Response and Quasi-Static Behavior of LIVM Sensors

First, let's define the terms "Low Frequency Response," " Quasi-static Behavior" and "Discharge Time Constant" as they apply to the context of this article.

Low Frequency Response - The ability of a sensor to measure very low frequency sinusoidal or periodic inputs (pressure, force and acceleration) with accuracy. This ability is best characterized by a graph of sensitivity vs. frequency with input amplitude held constant.

Quasi-Static Behavior - The response of a piezoelectric sensor to static (steady state) events, characterized by a graph of sensor output vs. time. This is a measure of the length of time meaningful information is retained after the initial application of a steady state measurand. ("Quasi" means "nearly or almost". Its use here is appropriate since piezoelectric sensors do not have true static response, but can only approximate static behavior.)

Discharge Time Constant - The time (in seconds) required for a sensor output voltage signal to discharge 63% of its initial value immediately following the application of a long term, steady state input change.

As we describe sensor discharge TC, its effect on quasi-static behavior will be quite apparent so we will relate these two topics first, then examine how TC relates to low frequency response.

Sensor Discharge Time Constant

The discharge time constant (TC) of the Low Impedance Voltage Mode (LIVM) sensor and the coupling time constant of AC coupled power units are very important factors when considering the low frequency and the quasi-static response capabilities of an LIVM system. For the time being we will consider only the sensor discharge TC and not the power unit coupling TC. As you will see, direct-coupled power units are available which remove the limiting effect of AC coupled power units on system behavior.

The term "Discharge Time Constant" or simply "TC", is referred to often on data sheets and specifications for piezoelectric sensors. It is important to understand the meaning of this term to understand how this influential design parameter controls both quasi-static behavior and low frequency response.

Discharge TC and Quasi-Static Response

In the following explanation, we will refer to the term "step function" input. This type of input is obtained, for example, by using static means such as a dead weight tester to calibrate a pressure sensor and a proving ring to calibrate a force sensor.

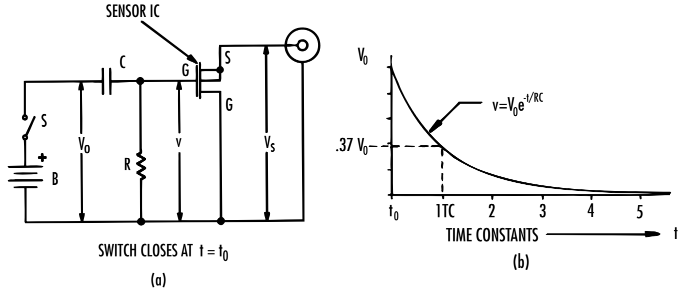


Figure 1: Discharge Time Constant (TC) Output vs. Time

For purposes of TC analysis, the sensor piezo element and internal IC amplifier may be represented schematically by the RC circuit, battery and switch shown in Figure 1a. Gate voltage (v) responds as shown in Figure 1b when voltage step (V_0) is impressed across the input terminals at time t_0. Such a step function voltage input would be generated by a sensor element in response to a sudden change in pressure or force input. At t_0, voltage (v) instantly assumes value V_0, then immediately begins to discharge (or decay) exponentially with time. The decay function is described by the following equation:

$$v = V_0e^{-t/RC} \qquad \text{(Eq. 1)}$$

Where:	v	= instantaneous gate voltage	(Volts)
	V_0	= initial voltage at time t_0	(Volts)
	e	= base of natural logarithm	
	R	= gate resistance	(Ohms)
	C	= total shunt capacitance	(Farads)

It is important to note here that the resistance (R) is the value of the resistor placed across the piezoelectric element to bias the MOSFET sensor IC.

The capacitance (C) is comprised of the self-capacitance of the piezo crystal, the input capacitance of the amplifier, stray capacitance and any ranging capacitance placed across the crystal to reduce sensitivity (if used).

The product RC is the sensor discharge TC, in seconds.

$$RC = TC\ (Ohms) \times (Farads) = (Seconds) \qquad \text{(Eq. 2)}$$

Referring again to Figure 1b, we should point out a few important features of the exponential decay curve. First, if we let time (t) equal TC, then Equation 1 reduces to:

$$v = V_0e^{-1} = V_0/e = .37V_0 \qquad \text{(Eq. 3)}$$

This result states that at time t=TC (one time constant) the signal has discharged to $.37V_0$, or put in another way, has lost .63 (63%) if its initial value V_0. In 5 x TC seconds (five time constants), the output will have decayed essentially to zero.

Another important point is that the curve shown in Figure 1b is relatively linear to about 10% TC, e.g., in 1% of the TC, the sensor will discharge 1% and so on up to 10% T.C. In fact, we may draw the conclusion that to have at least 1% accuracy in quasi-static force or pressure measurement, we must take the reading of the output within a time window of 1% of the sensor TC.

Static response is most closely approximated when the event time is a very small percentage of the sensor (or system) discharge TC. This situation is best illustrated by example:

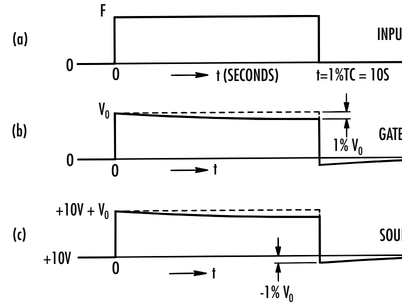


Figure 2: Approaching Static Response

Figure 2 illustrates a hypothetical situation where the static event lasts 1% of the sensor TC. (Assume a force sensor with a 1000 sec. TC and a 10 sec. event time.) Figure 2a is the force-time history showing input force F applied to the sensor, starting at time t_0, and holding steady for ten seconds. At time t_0 + 10 seconds, the force is removed.

Introduction to Piezoelectric Force Sensors

LIVM FORCE SENSORS

Low Impedance Voltage Mode (LIVM) force sensors contain thin piezoelectric crystals which generate analog voltage signals in response to applied dynamic forces. A built in IC chip amplifier converts the high impedance signal generated by the crystals to a low impedance voltage suitable for convenient coupling to readout instruments. (Refer to the articles "Introduction to LIVM Accelerometers" and "Introduction to Current Source Power Units" in this handbook for in-depth discussions of the LIVM principle.)

Construction and Operating Principles

Figure 1a is a typical cross-section of a Dytran LIVM force sensor with radial connector. Figure 1b is an axial connector sensor.

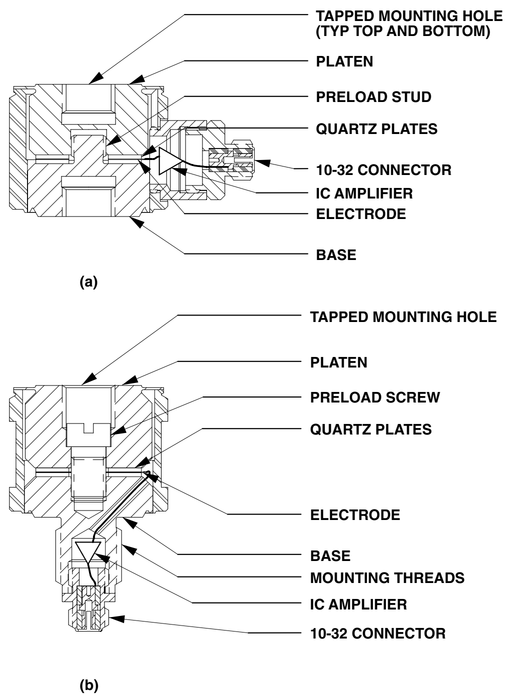


Figure 1: LIVM Force Sensors

Two quartz discs are preloaded together between a lower base and an upper platen by means of an elastic preload screw (or stud) as seen in Figure 1a and 1b. Preloading is necessary to ensure that the crystals are held in intimate contact for best linearity and to allow a tension range for the instruments. In the radial connector style (Figure 1a), both platen and base are tapped to receive threaded members such as mounting studs, impact caps or machine elements. Platen and base are welded to an outer housing which encloses and protects the crystals from the outside environment. A thin steel web connects the platen to the outer housing allowing the quartz element structure to flex unimpeded by the housing structure. The integral IC amplifier is located in the radially mounted connector housing.

Construction of the axial connector style (Figure 1b) is similar to the radial connector style except that the lower base contains a threaded integral mounting stud, which also serves as the amplifier housing and supports the electrical connector. This design allows the electrical connection to exit axially and is especially useful where radial space is limited. A typical application for the axial sensor is shown in Figure 4c (drop tube).

When the crystals are stressed by an external compressive force, an analogous positive polarity voltage is generated. This voltage is collected by the electrode and connected to the input of a metal oxide silicon field effect transistor (MOSFET) unity gain source follower amplifier located within the amplifier housing. The amplifier serves to lower the output impedance of the signal by 10 orders of magnitude so it can be displayed on readout instruments such as oscilloscopes, meters and recorders. When the sensor is put under tensile loads (pulled), some of the preload is released causing the crystals to generate a negative-going output signal. Maximum tensile loading is limited by the ultimate strength of the internal preload screw and is usually much less than the compression range.

Calibration

Before proceeding with this section, we suggest you read the article "Low Frequency Response and Quasi-Static Behavior of LIVM Sensors" in this series as it provides excellent background material for the following discussion.

Although Dytran LIVM force sensors are designed to measure dynamic forces, the discharge time constants of most units are long enough to allow static calibration. By "static calibration" we refer to the use of calibrated weights or ring dynamometers. An important rule of thumb for this type of calibration is that the first 10% of the discharge time constant (TC) curve is relatively linear vs. time. What this means is that the output signal will decay 1% in 1% of the discharge TC, and so on up to about 10 seconds. This tells us that in order to make a reading that is accurate to 1% (other measurement errors not considered) we must take our reading within 1% of the discharge TC (in seconds) after application of the calibration force.

The most convenient way to do this is by use of a digital storage oscilloscope and a DC coupled current source power unit such as the Dytran Model 4115B. The DC coupled unit is essential because the AC coupling of conventional power units would make the overall system coupling TC too short to perform an accurate calibration in most cases.

Natural Frequency Considerations

The natural frequency of force sensors is always specified as "unloaded" and for a good reason. Placing a load on a force sensor creates in effect, an accelerometer. The load can be considered a seismic mass (M) and the force sensor represents stiffness (K). The natural frequency of this new combination is now:

$$f_n = 1/2\pi\sqrt{K/M} \text{ (Hz)} \qquad \text{(Eq. 1)}$$

Where:
K = Force sensor stiffness, (LbF/in.)
M = Mass of load, (slugs)

It is easy to see by Equation 1 that the larger the mass, the lower the "loaded" natural frequency. Many people are misled by the natural frequency specifications of force sensors and consideration of this topic will enhance your understanding of force sensor behavior. Note: Equation 1 will yield a close approximation of the loaded natural frequency and should not be considered an exact relationship.

To perform the calculation described in Equation 1, obtain the stiffness of the force sensor from the specification sheet and convert the weight of the added

Introduction to Piezoelectric Pressure Sensors

LIVM PRESSURE SENSORS

Dynamic pressure sensors are designed to measure pressure changes in liquids and gasses such as in shock tube studies, in-cylinder pressure measurements, field blast tests, pressure pump perturbations, and in other pneumatic and hydraulic processes. Their high rigidity and small size give them excellent high frequency response with accompanying rapid rise time capability. Acceleration compensation makes them virtually unresponsive to mechanical motion, i.e., shock and vibration.

Figures 1a and 1b are representative cross sections of Dytran Model Series 2300V LIVM (Low Impedance Voltage Mode) acceleration compensated pressure transducers. This series is characterized by very high frequency response and fast rise time. These instruments contain integral impedance converting IC amplifiers which reduce the output impedance by many orders of magnitude allowing the driving of long cables with negligible attenuation.

Series 2300V utilizes thin synthetic quartz crystals stacked together to produce an analogous voltage signal when stressed in compression by pressure acting on the diaphragm. This pressure, by virtue of diaphragm area, is converted to compressive force which strains the crystals linearly with applied pressure producing an analog voltage signal.

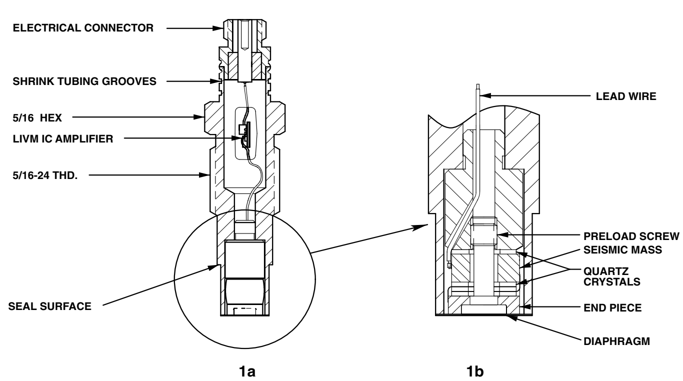


Figure 1: Low Impedance Voltage Mode (LIVM) pressure sensor.

As with all LIVM instruments, the voltage generated by the crystals is fed to the gate terminal of the FET input stage of an impedance converting IC amplifier which drops the impedance level 10 orders of magnitude. This allows these instruments to drive long cables with little effect on frequency response.

Referring to figure 1a and 1b, series 2300V contains an integral accelerometer built into the crystal stack. This accelerometer, consisting of one quartz crystal and a seismic mass, produces a signal of opposite polarity (to that produced by pressure on the diaphragm) when acted upon by vibration or shock. This signal cancels the signal produced by vibration or shock acting upon the diaphragm and end piece, negating the effects of mechanical motion on the output signal.

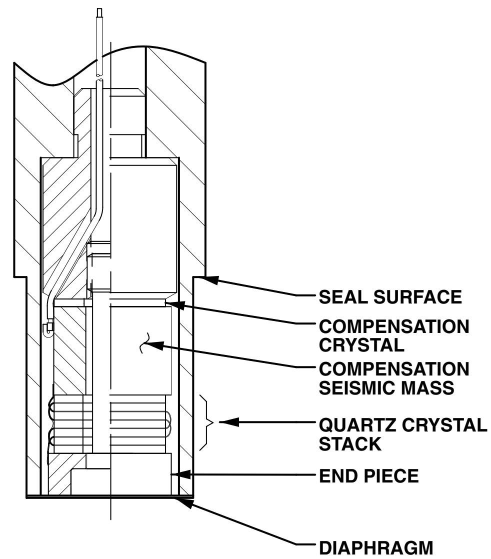


Figure 2: Model 2200V1 higher sensitivity pressure sensor.

Model 2200V1 (refer to figure 2) is constructed similar to series 2300V with the difference that model 2200V1 has several more quartz crystals in the stack to produce more voltage sensitivity for the lower pressure range sensor. The maximum sensitivity of series 2300V is 20 mV/psi whereas the sensitivity of model 2200V1 is 50 mV/psi. The resonant frequency is lower than that of Model series 2300V.

System Interconnection

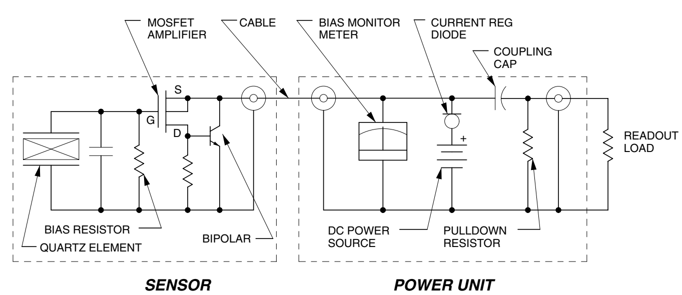


Figure 3: Schematic, typical system interconnect

Figure 3 is a schematic diagram of a typical LIVM system consisting of pressure sensor, cable and power unit. To complete the LIVM measurement system, choose the current source power unit needed to power the internal sensor amplifier and select the input and output cables.

Introduction to LIVM Accelerometers

Construction

Low Impedance Voltage Mode (LIVM) accelerometers are designed to measure shock and vibration phenomena over a wide frequency range. They contain integral IC electronics that converts the high impedance signal generated by the piezo crystals to a low impedance voltage that can drive long cables with excellent noise immunity. These accelerometers utilize quartz and piezoceramic crystals in compression and shear mode.

Figure 1 is a representative cross section of a typical LIVM compression design accelerometer with central preload, strain isolation base and integral impedance converting IC amplifier. The amplifier utilizes a metal oxide silicon field effect transistor (MOSFET) in its input stage, coupled to a bipolar output transistor for improved line driving capability.

The LIVM concept eliminates the need for expensive charge amplifiers and low noise cable, allows the driving of long cables for field use and lowers the per-channel cost of the measurement system.

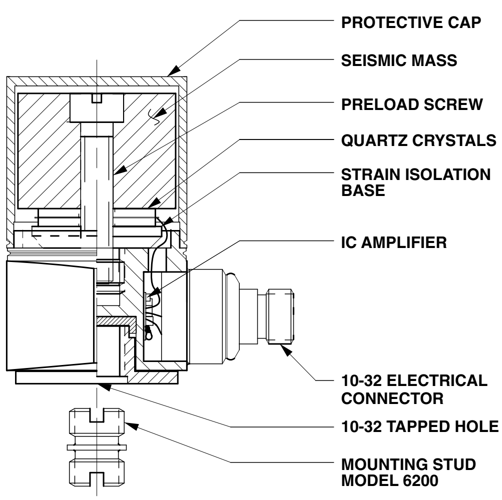


Figure 1: Compression design LIVM accelerometer.

Powering

All Dytran LIVM accelerometers may be powered by any constant current type power unit capable of providing 2 to 20 mA of constant current at a DC voltage (compliance) level of +18 to + 30 Volts. NEVER connect a power supply that has no current limiting to an LIVM accelerometer. This will immediately destroy the integral IC amplifier.

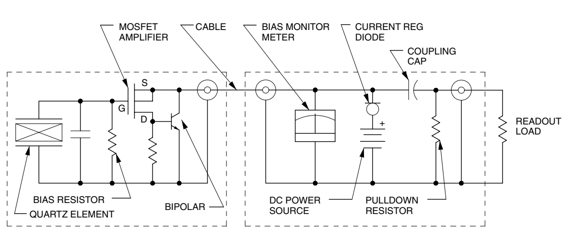


Figure 2: Typical LIVM system

The quiescent DC bias level (turn-on voltage), at the power input to the accelerometer, may fall within the range of +8 to +12 Volts DC, depending upon the specifications of the particular model. The actual measured value is reported on the calibration certificate supplied with each instrument. The dynamic signal from the accelerometer is superimposed on the DC bias level and is extracted in the power unit.

Each LIVM accelerometer is ranged to produce ±5 Volts output for ±full scale (g level) input. The magnitude of the DC voltage source (compliance voltage) in the power unit determines the overrange capability, i.e., the point where clipping will occur on the positive waveform.

System Low Frequency Response

Piezoelectric accelerometers are effectively AC coupled devices (see Figure 2) and as such, do not posses true DC response. However, with certain considerations and precautions, these devices may be used to measure events at frequencies as low as fractions of one Hertz.

The low frequency response of LIVM systems may be limited by the accelerometer or by the power unit but more likely by the combination of both. Referring again to Figure 2, it will be seen that an LIVM system contains two high pass first order RC filters in cascade as described here:

1. Inside the accelerometer, the shunt capacitor and bias resistor located at the gate of the amplifier and,

2. In the power unit, the coupling capacitor and the pulldown resistor/readout load in parallel.

These low pass filters may be represented by the following equivalent circuit (see Figure 3).

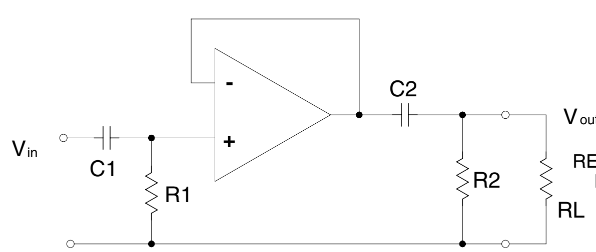


Figure 3: Equivalent LIVM system schematic.

While exact analysis of this circuit is well known, certain helpful observations can be quickly made. The time constant of each filter is the product of the appropriate R and C as follows:

Introduction to Charge Mode Accelerometers

Dytran charge mode accelerometers are designed to measure shock and vibration phenomena over a broad temperature range. These accelerometers, unlike the Low Impedance Voltage Mode (LIVM) types, contain no built-in amplifiers. Dytran's charge mode accelerometers utilize high sensitivity piezoceramic crystals, of the lead zirconate titinate (PZT) family, to produce a relatively high charge output in response to stress created by input vibration or shock acting upon the seismic system.

Because of the high impedance level of the charge mode signal generated by the crystals, a special type of amplifier, called a charge amplifier, is used to extract the very high impedance electrostatic charge signal from the crystals. The charge amplifier has the ability to convert the charge signal to a low impedance voltage mode signal without modifying it.

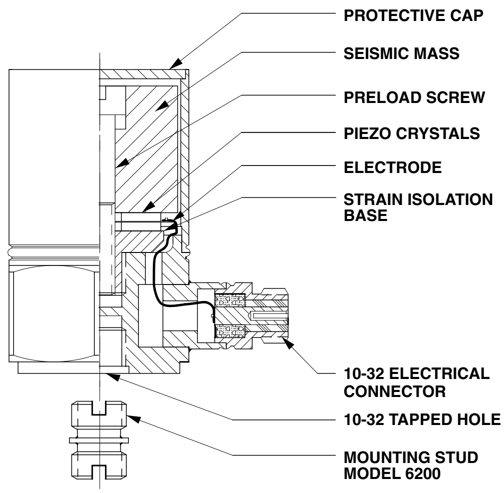


Figure 1: Typical compression design, charge mode accelerometer

Figure 1 is a cross-section of a typical charge mode compression design accelerometer, model 3100C6. The sensitivity is 100 pC/g (pC = pico coulomb = 1 x 10^{-12} Coulomb) and the useful frequency range is up to 5 kHz. The 3100C6 operates at temperatures up to +500˚F.

A heavy metal seismic mass is preloaded against the piezoceramic crystals with an elastic preload screw. The mass converts the input acceleration into analogous stress on the crystals producing an output charge signal in direct proportion to instantaneous acceleration.

When to Use Charge Mode Accelerometers

The question may be asked, "When should I consider using charge mode accelerometers vs. LIVM types with built-in electronics?"
Charge mode accelerometers should be considered:

1. when making measurements at temperatures above +250˚F, the maximum temperature for most LIVM instruments,

2. when the versatility of the laboratory charge amplifier is desired for system standardization, ranging, filtering, integrating for velocity and displacement, etc. and,

3. when adding or replacing accelerometers where existing charge amplifiers must be used for economic or other reasons.

Two System Concepts

Charge mode accelerometers may be combined with a variety of electronic components to create two basic measurement system classifications:

1. The conventional charge mode system, and
2. The Hybrid system.

The conventional charge mode system utilizes a sophisticated laboratory charge amplifier while the hybrid system features simple dedicated range miniature in-line charge and voltage amplifiers operating in conjunction with LIVM current source power units.

The Conventional Charge Mode System

The versatile laboratory charge amplifier is the main feature of the conventional charge mode system. This section will familiarize you with the theory, operating characteristics and features of the basic laboratory charge amplifier.

Figure 2: Elements of the conventional charge mode system

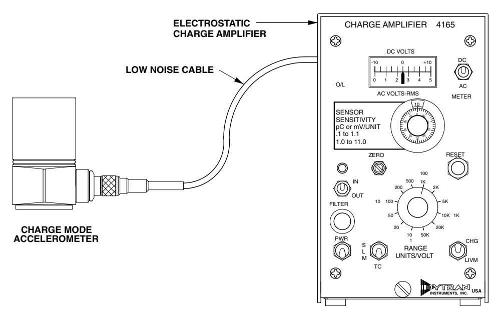


Figure 2 illustrates a laboratory charge amplifier, model 4165 in use with a model 3100C6 charge mode accelerometer. Series 6019A low-noise coaxial cable is used to minimize triboelectric noise generated by cable motion. This is a very versatile system whose signal conditioning options include:

1. Standardization of system sensitivity
2. Full Scale range selection
3. Discharge time constant choices
4. Filter options
5. 0-10 VDC out for sinusoidal input
6. Overload indication
7. Instant system zeroing (or reset)
8. External calibrate signal insertion
9. Front panel meter for observation of DC level of output signal

Accelerometer Mounting Considerations

An accelerometer is an instrument that senses the motion of a surface to which it is attached, producing an electrical output signal precisely analogous to that motion. The ability to couple motion, (in the form of vibration or shock), to the accelerometer with high fidelity, is highly dependent upon the method of mounting the instrument to the test surface. For best accuracy, it is important that the mounting surface of the accelerometer be tightly coupled to the test surface to ensure the duplication of motion, especially at higher frequencies. Since various mounting methods may adversely affect accuracy, it is important to understand the mechanics of mounting the accelerometer for best results.

Calibration

Throughout the article we will refer to "back-to-back" calibration at times. It will be informative to explain what is meant by this and to show how this type of calibration is performed at Dytran.

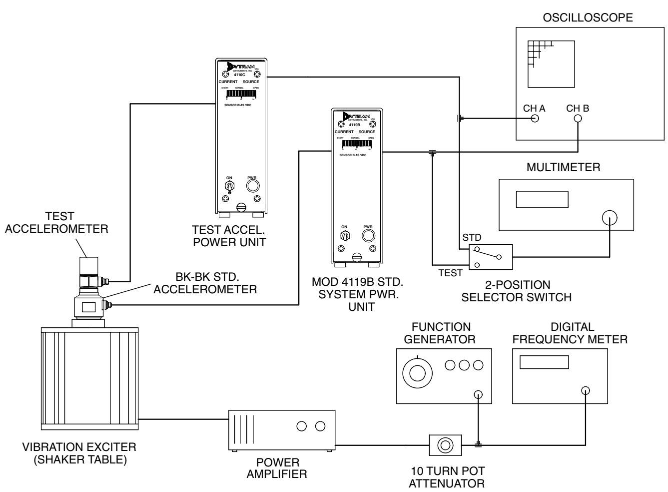


Figure 1: Back-to-back calibration set-up

Figure 1 illustrates the components of a simple accelerometer calibration system utilizing the Dytran Model 3120BK back-to-back accelerometer calibration system, a small electrodynamic shaker, a signal generator, a power amplifier and the readout instruments.

To perform a calibration, the test instrument is attached to the top surface of the back-to-back standard accelerometer, (model 3120B) using the method to be used in the actual application, i.e., adhesive or stud mount. At each frequency of interest, the input amplitude (in g's RMS) is set precisely by the back-to-back standard system and the corresponding output from the test system is recorded. To learn more about this topic, refer to the article "Back-to-Back Accelerometer Calibration" in this series.

For purpose of analysis, a piezoelectric accelerometer may be considered to be a second order spring-mass system with essentially zero damping. (Refer to Figure 2).

The spring (K) is the crystal stack and the mass (M) is the seismic mass that stresses the crystals to produce an electrical output proportional to acceleration. The dynamic characteristics of this system determine the frequency response of the accelerometer.

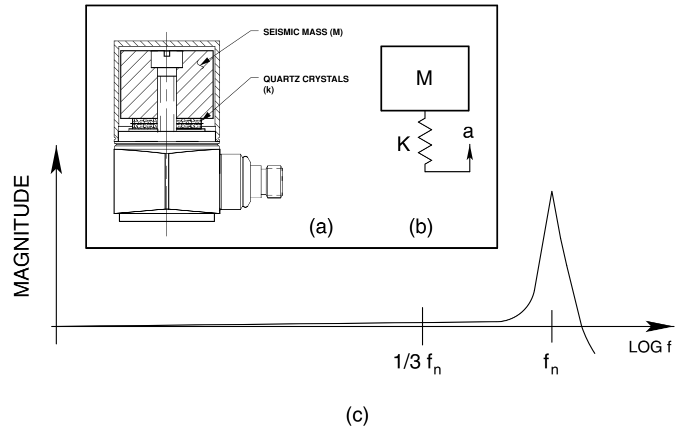


Figure 2: The accelerometer as a spring-mass system.

Figure 2a illustrates the accelerometer. Its spring-mass analogy is Figure 2b and Figure 2c is a typical frequency response plot for such a system. The plot is obtained by graphing accelerometer output vs. frequency with input vibration level held constant at each frequency setting. Every such system has a mounted resonant (or natural) frequency, f_n characterized by a very high peak of output at resonance. The solution for the differential equation of motion yields the definitive expression for the resonant frequency as follows:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \qquad \text{(Eq 1)}$$

where: f_n = system natural frequency (Hz)
K = spring constant of the crystal stack (lbs/in)
M = mass of the seismic system (Slugs)

Examination of the response graph (Fig 2b) shows that the lower frequency portion of the curve is sufficiently flat to provide a useable range up to approximately 1/3 of the resonant frequency. This will not be the case however, if, during the mounting, other "springs" are inadvertently interposed between mating surfaces creating secondary spring-mass systems with lower natural frequencies than that of the accelerometer itself. The following section is an attempt to explain how this can happen if care is not exercised during mounting of the test accelerometer. We start by exploring the various mounting methods commonly used to mount accelerometers.

Stud Mounting

The preferred method of mounting an accelerometer to the test object is the stud mount method. (See Figure 3). The stud may be integral, i.e., machined as part of the accelerometer or it may be separate (removable). The stud mount method yields the best results because when the instrument is installed in this fashion, the accelerometer and the test surface are essentially "fused" together by virtue of the high clamping force of the stud, ensuring the exact duplication of motion of both bodies at all frequencies.

The inclusion of a thin layer of silicone grease between mating surfaces aids in the fidelity of motion by filling in any voids due to slight imperfections in the mounting surfaces.

Back-to-Back Accelerometer Calibration

To calibrate a vibration accelerometer is to accurately determine its sensitivity (in mV/g or pC/g) at various frequencies of interest. The ISA approved back-to-back comparison method is probably the most convenient and least expensive technique.

At Dytran, back-to-back calibration involves coupling the test accelerometer directly to a (NIST) traceable double-ended calibration standard accelerometer and driving the coupled pair with a vibration exciter at various frequencies and acceleration (g) levels. The assumption here is that since the accelerometers are tightly coupled together, both will experience exactly the same motion, thus the calibration of the back-to-back standard accelerometer can be precisely "transferred" to the test accelerometer.

The Dytran model 3120BK vibration calibration system used in conjunction with a small electrodynamic shaker, a signal generator, a frequency meter and several other pieces of equipment provides an inexpensive means to set up a calibration facility. The 3120BK may also be used with more sophisticated computer driven automatic calibration systems.

The 3120BK Back-to-Back Calibration System

The model 3120BK vibration calibration system consists of a double ended calibration accelerometer, (model 3120B), a standardization amplifier, (model 4119B), and the necessary interconnect cables and accessories. (See figure 1).

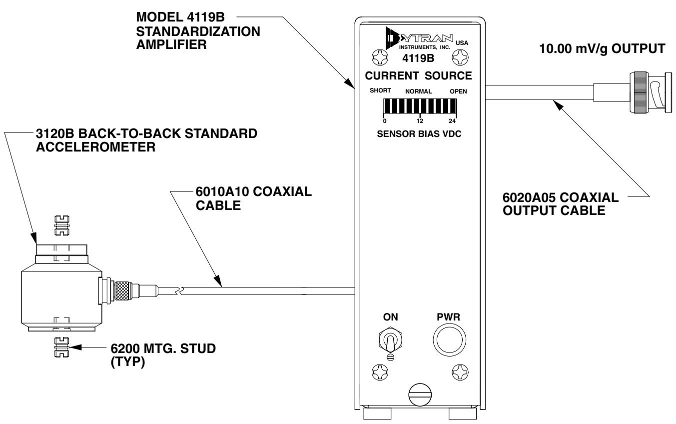


Figure 1: Model 3120BK system

Model 3120B Back-to-Back Standard Accelerometer

Figure 2 is a representative cross section of the model 3120B back-to-back standard accelerometer. This type of accelerometer is also known as a "double ended" standard because of its two mounting surfaces. The lower surface attaches to the shake table armature and the test accelerometer is attached to the upper surface.

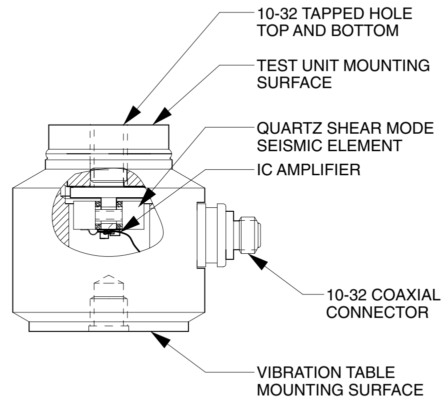


Figure 2: Model 3120B back-to-back calibration accelerometer

The quartz shear seismic element in the 3120B is mounted directly to the underside of the upper mounting surface to position it in closest possible proximity to the unit under test. This location ensures the tightest possible coupling to the test accelerometer. The excellent strain isolation of the quartz shear element serves to minimize the effect of the mass of the test accelerometer on the sensitivity of the standard. Subsequent sections of this article will address this phenomenon, known as "mass loading".

Within the 3120B, the electrical output of the self generating quartz shear seismic element is connected directly to the input of an integral IC impedance converting amplifier. (See the article "Introduction to LIVM Accelerometers" for a complete treatment of the Dytran internal amplifier concept). This amplifier buffers the signal making it impervious to outside interference and to cable generated noise.

The electrical connector of model 3120B is the convenient 10-32 coaxial type which has become the industry standard.

Model 4119B Standardization Amplifier

The line-powered model 4119B supplies constant current power to operate the IC amplifier in the 3120B and standardizes the system sensitivity to precisely 10.00 mV/g at 100 Hz. It also provides the necessary low-pass filtering to suppress the rising high frequency characteristic of the 3120B to provide flat frequency response to 10 kHz. (See Figure 3).

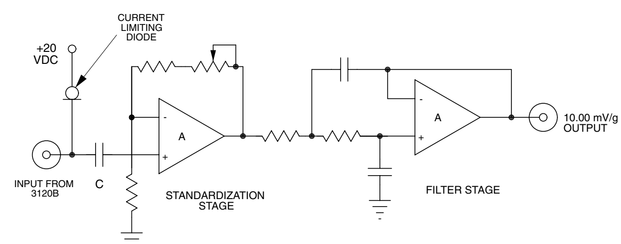


Figure 3: Block Diagram Model 4119B amplifier

The constant current source, a 2 mA current limiting diode, is powered by an internal 20 VDC power supply. A coupling capacitor C blocks the DC bias voltage which exists on the 3120B line, and connects the vibration signal (AC) to the input of the standardization stage.

This variable gain stage adjusts the system sensitivity to exactly 10.00 mV/g at the 100 Hz reference frequency. The next stage of the 4119B is a second order Butterworth low-pass filter with adjustable frequency characteristics. This filter is adjusted to exactly match the high frequency characteristics of the 3120B. The rolloff characteristics of the 4119B cancel the rising characteristics of the 3120B at higher frequencies.

Performing the Calibration

Assemble the system elements as shown in Figure 4. Couple the test accelerometer to the top surface of the 3120B. By setting the vibration frequency and the amplitude (using the output of the 3120BK system) a frequency response curve may be plotted for the test accelerometer. At each frequency, set the amplitude (in RMS g's) and read the corresponding amplitude from the test accelerometer (in RMS mV).

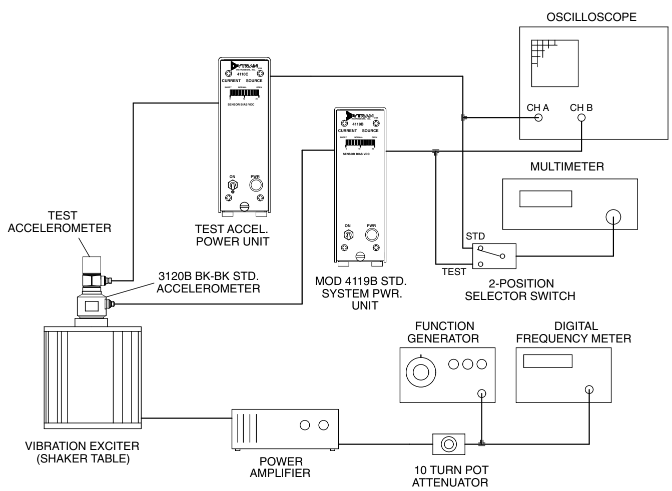


Figure 4: The complete calibration system

Mass Loading Compensation

It is appropriate at this time to discuss a very important but little emphasized phenomenon associated with back-to-back accelerometers known as "mass loading".

The 3120B is initially calibrated with a single ended accelerometer, model 3010B, which has been calibrated by an NIST certified calibration station. This accelerometer weighs 19 grams. When accelerometers (or velocity pickups), weighing considerable more that 19 grams, are placed atop the 3120B, the increased inertial loading due to the increase in mass, actually changes the effective sensitivity of the 3120B inserting a small calibration error. This error increases at higher frequencies.

These errors are negligible when calibrating units weighing up to 30 grams but over this weight, correction curves should be constructed to compensate for this effect. The following section shows how to establish the compensation curve for test units of varying weights.

Mass Loading Compensation Curves

The mass loading effect is frequency dependent as illustrated in Figure 5a. This figure shows a typical family of correction curves as plotted with various masses atop the 3120B.

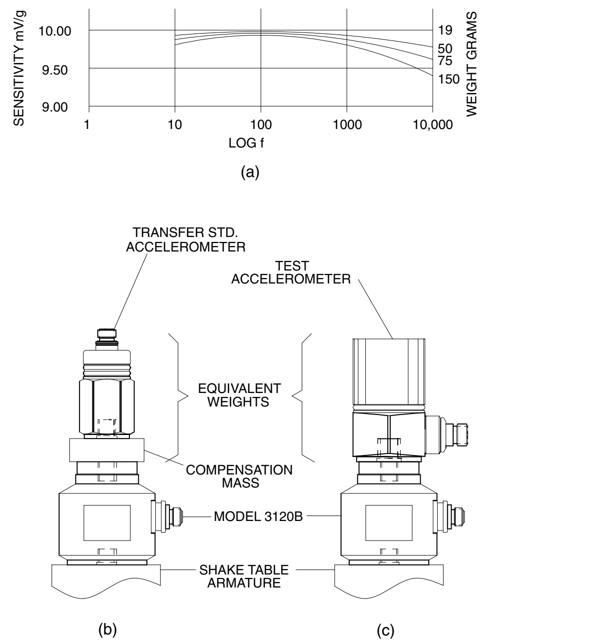


Figure 5: Typical correction curves and a compensation weight

To plot a mass loading correction curve for a model 3120BK system, proceed as follows:

1. Select a single-ended accelerometer to use as a transfer standard (preferably a model 3010B). Weigh the instrument precisely and record this weight, in grams.

2. Attach this accelerometer to the 3120B and determine its sensitivity at all frequencies of interest using the 3120B as the standard. Record the sensitivity at each frequency.

3. Weigh the new instrument to be calibrated. (If it weighs less than 30 grams, you do not need mass loading correction.

4. If it weighs more (say 50 grams) subtract the weight of the transfer standard from 50 grams and record. This is the needed weight of the compensation mass.

5. Calculate the dimensions of a steel (or tungsten) cylinder required to equal the result of step 4 and fabricate a compensation mass as shown in Figure 5b.

Note: It is important that the mating surfaces of the compensation mass be very flat (optical flatness is preferred). This degree of flatness is best obtained by a lapping process. Dytran has the equipment and skills to produce compensation masses at reasonable cost.

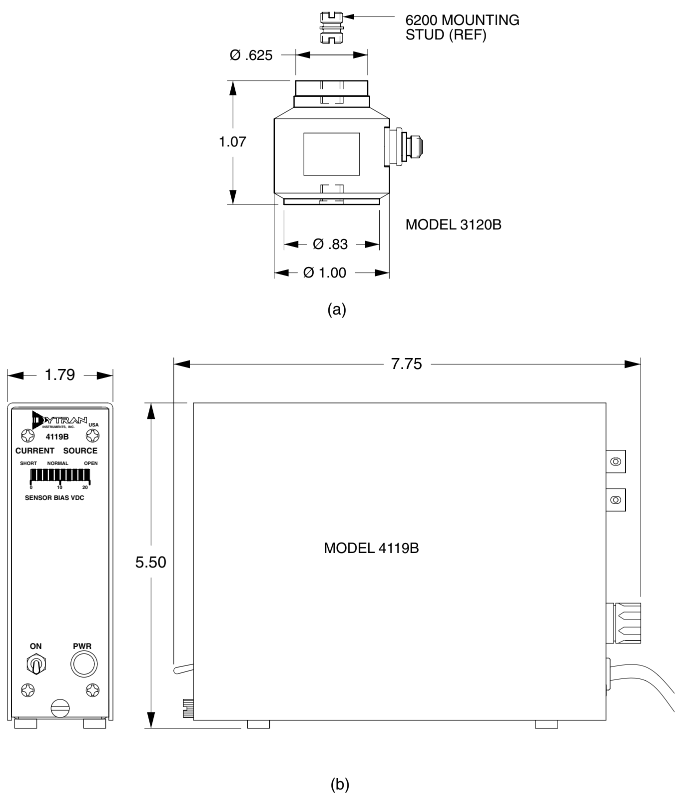
6. Attach the transfer accelerometer and compensation mass together as shown in Figure 5b, placing a light coating of silicone grease between all mating surfaces. Torque in place.

7. Using the sensitivity of the transfer standard (obtained in step 2) to determine the amplitude at each frequency point, determine the loaded sensitivity of the back-to-back standard accelerometer and record each of these values. These new sensitivity values plotted against frequency represent the correction curve for that particular mass of test instrument.

8. Mount the test instrument atop the 3120B, as shown in Figure 5c and, using the new values obtained in step 7, proceed to calibrate the test instrument by setting the amplitude at each frequency using the corrected output from the 3120BK system and reading the corresponding output from the test instrument at each frequency point.

NOTE: When using an RMS reading voltmeter to read amplitude values, you may convert to equivalent peak g levels by multiplying the RMS values by 1.414. This will only be necessary when calibrating velocity or displacement pickups.

Figure 6: System dimensions



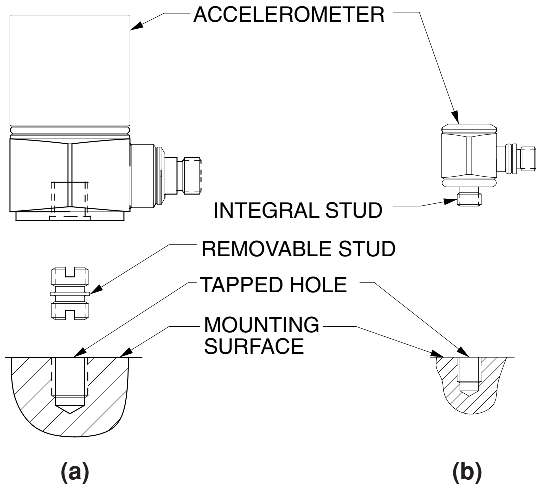


Figure 3: The threaded stud mount

Two stud mount designs are illustrated in Figure 3, the separate stud in Figure 3a and the integral stud in Figure 3b. The separate stud style accelerometer is the most popular for several reasons:

1. The removable stud allows easy access to the mounting surface of the accelerometer for restoration of surface flatness should this become necessary. Even with normal care, in time, after many installations, the mounting surface of the accelerometer may become worn or damaged to a point where it is no longer flat enough to affect a satisfactory mount and frequency response will be compromised. It is a simple matter to restore flatness if the stud can be removed and the accelerometer base can be applied directly to a lapping plate for restoration of flatness. When the stud is integral and cannot be removed, refurbishment of the mounting surface becomes very difficult and can only be performed at the factory.

2. If the integral stud is broken or the threads become stripped or otherwise damaged, the instrument may be essentially destroyed. On the other hand, the separate stud can be easily replaced.

3. At times, with radial connector style accelerometers like the model 3100B, it is important during installation, to orient the connector so that nearby obstacles may be avoided. By exchanging mounting studs, the desired orientation may be obtained.

4. The separate stud type accelerometer may be adhesive mounted without using a mounting adapter, should this be desired.

The Mounting Stud

The mounting stud itself is a very important factor of the performance of the accelerometer. Most Dytran mounting studs are fabricated from heat treated beryllium copper because of its high tensile strength and its low modulus of elasticity. This means that the stud will be very strong and relatively elastic, a perfect combination for the task of holding two surfaces together under a high preload.

The collar that is machined into the stud (see Figure 3a) prevents the stud from bottoming in either mounting hole. This ensures that the stud will be centered between the two mounting holes so that both sides have adequate thread engagement.

All Dytran accelerometers have a recess machined into the mounting surface to accommodate this collar allowing both surfaces to be in intimate contact.

When installing the stud, it is best to first thread the stud into the accelerometer to ensure that the stud enters the threaded port fully, then thread the accelerometer into the mounting port until the surfaces meet and torque in place.

In the design of miniature accelerometers such as the models 3030B, 3144A and the 3200B et.al., interior space is at a premium and the only alternative for stud mounting is the integral stud as shown in Figure 3b. This style of accelerometer with reasonable care, will provide a long lifetime of normal operation.

When Mating Surfaces Are Not Flat

As previously stressed, flatness of mating surfaces between accelerometer and mounting surface, is of prime importance for best frequency response.. Here we will examine the mechanics of a poor mount and its effect on frequency response.

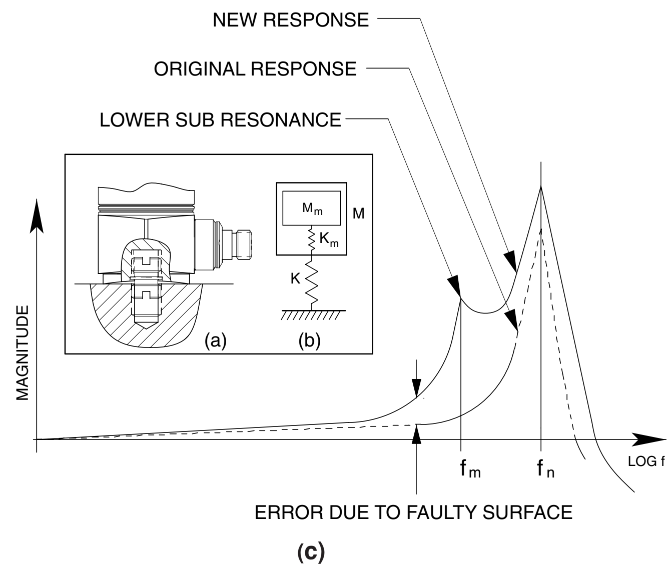


Figure 4: Non-flat accelerometer mounting surface

Figure 4a illustrates schematically, a condition where the accelerometer has acquired a "dished" shape thru heavy usage. The mechanical analogy of this is a leaf spring with spring rate K_m as shown in Figure 4b. There are now two spring-mass systems with this type of anomaly and both will affect frequency response.

The new spring-mass system is formed by spring K_m and the mass of the entire accelerometer M_m. The resonant frequency f_m of this new system will most likely be lower than that of the accelerometer and may affect the response curve as illustrated in Figure 4c.

Even though the new resonant frequency is higher than the actual resonance of the accelerometer, its effect will be to increase the output of the accelerometer at the high frequency end of the accelerometer response.

We have chosen for purpose of this explanation, a hypothetical non-flat condition to illustrate the mechanics of response degradation. This analogy can be extended to include other situations where mating surfaces are precluded from intimate contact such as when foreign particles are entrapped between mating surfaces or when other types of surface irregularities exist. The results of all such imperfections will be more or less similar in nature to the example chosen here.

Surface Preparation

It is difficult to overemphasize the importance of flatness of mating surfaces in the mounting of piezoelectric accelerometers, especially with regard to frequency response. All Dytran accelerometer mounting surfaces are lapped optically flat where possible or machined to very tight flatness tolerances. The test object surface must be as carefully prepared. Although lapping is usually not possible, other machining processes such as spotfacing, grinding, milling, turning, etc., can produce acceptably flat mounting surfaces (flat to .001 TIR).

After machining the surface and preparing the tapped mounting hole, clean the area thoroughly with compressed air and a solvent to remove all traces of metal chips, cutting oil, and any other surface contaminants. Before installing the accelerometer, spread a light coating of silicone grease on either mating surface. The grease will lubricate the surface and ensure intimate contact by filling in tiny surface imperfections, maximizing high frequency transmissibility to the accelerometer.

Mounting Torque

Although every Dytran accelerometer is designed to minimize the effect of mounting torque variations on sensitivity, it is good practice to set the torque level, using a torque wrench, to the value recommended on the installation drawing provided with the instruments. This will ensure that the instrument is properly mounted and will preclude the expense and delays that may result from overtorquing and breaking or stripping the threads of mounting studs. This practice will also eliminate one of the main causes of calibration inaccuracy.

Adhesive Mounting

Situations often arise where the stud mount method is impractical, even impossible, such as when mounting the accelerometer to thin sheet metal or to other surfaces where drilling a mounting hole is not allowable. In such cases, an adhesive mount installation can be the only practical way to install an accelerometer.

Some accelerometers are designed to be adhesive mounted directly to the test surface. (models 3115A, 3105A, 3053A, etc.). Others utilize mounting adapters or bases for adhesive mounting. These adapters are normally first glued to the test surface, then the accelerometers are stud mounted to them.

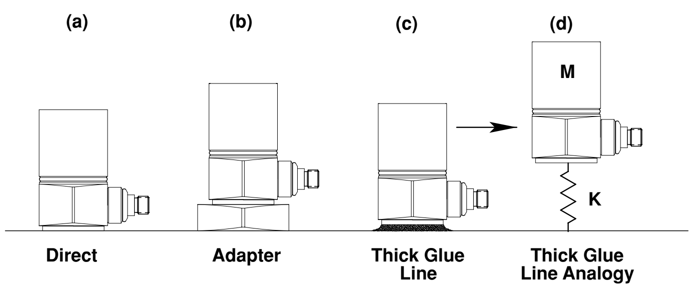


Figure 5: The adhesive mount, direct and with adapter

Figures 5a and 5b illustrate two adhesive mount installations, one direct mount and the other with adhesive adapter. Figure 5c shows the undesirable thick glue line and figure 5d illustrated the mechanical analogy of the thick glue line mount. The thick layer of adhesive is actually a spring and has the effect of creating a new spring mass system as previously described in the section "When mating surfaces are not flat", with a similar result as shown in figure 4c.

To avoid the thick glue line, we recommend the use of a cyanoacrylate adhesive, sometimes known as "Instant Bond" adhesives. These types of adhesives are readily available and are recommended because:

1. They set very quickly,

2. Not much adhesive is required for a strong bond so glue lines will necessarily be very thin,

3. Cleanup is easy because these types of adhesives are easily dissolved with acetone.

Some users report good results with dental cement. Because of its high rigidity, acceptable transmissibility can be obtained even with the slightly thicker glue line that results. However, the problem with dental cement lies with its tenacity. We know of no solvent that readily dissolves it so removal of the accelerometer can result in damage to the instrument.

In conclusion, when using the adhesive mount method, expect problems at high frequencies in direct relationship to the mass of the accelerometer. If possible, calibrate your accelerometer using a back-to-back accelerometer system (such as the 3120BK calibration system) using the exact adhesive that will be used in the actual test. In this manner, you can determine the precise behavior of your measurement system at the expected frequencies.

Removal (unmounting) of Adhesive Accelerometers

Many accelerometers and adhesive adapters have been damaged or destroyed by improper removal. The only sure way to avoid such damage is to torque the accelerometer or adapter with a wrench using the flats provided. Adhesives are generally weakest in shear strength and will yield under steady torque. Under no circumstances should you strike an accelerometer or adapter to remove it. The accelerometer would most likely sustain damage and may, at best, change calibration after such trauma. All Dytran adhesive mount adapters have hex or other flats to facilitate removal.

Electrical Isolation Bases

Isolation bases are used to electrically insulate the housing of an accelerometer from the test surface. This may be necessary to avoid annoying "ground loops" which can interfere with the measurement process when the test surface is an elevated electrical potential.

Be aware of the fact that the use of any such base will effect the high frequency response in the same manner as previously described in the section "The Adhesive Mount". Again, we recommend calibration with the actual adapter to determine the effect on high frequency response.

The model 6220 is an example of a well-designed isolation adapter with some exceptional features. The design incorporates stainless steel upper and lower bases with an insulating anodized aluminum disc sandwiched between them under high preload. The lower base has an integral threaded stud and the upper has a 10-32 tapped hole. The upper and lower bases are interlocked together to withstand high levels of mounting torque without damage. Both upper and lower bases can be refinished to restore flatness without affecting insulation.

Several anodized aluminum bases are also available for less demanding applications, (models 6226, 6244, 6245, and 6261 for example). These bases must be handled carefully to avoid scratching the anodized surfaces that will compromise the insulating properties.

Magnetic Mounting Adapters

Magnetic mounting adapters are used to attach accelerometers to ferromagnetic surfaces such as machinery and structures where the instrument is to be moved quickly from place to place. The accelerometer is attached to the magnetic adapter (usually by stud mount) and the assembly is applied to the test surface. While this method is certainly convenient, the user may be misled by this convenience.

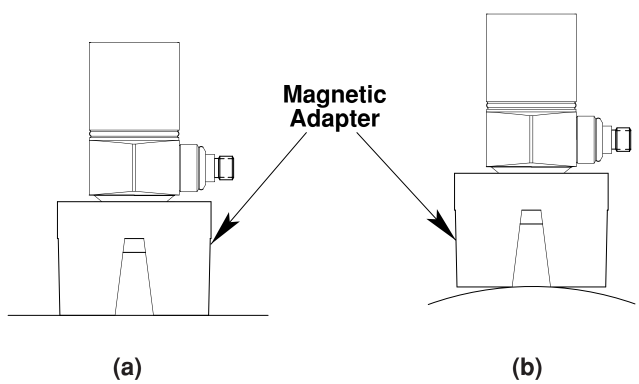


Figure 6: Magnetic mounting adapters

In general, magnetic adapters should be used with caution and rarely trusted at frequencies above 1 kHz. Expect response degradation in direct proportion to the weight of the accelerometer. There are some things the user can do to ensure the best possible accuracy from the magnetic mount installation:

1. If possible, attach the magnet to a flat, bare, ferromagnetic metal surface (See Figure 6a). A thick layer of paint on the test surface will lessen the holding force of the magnet and could lower the effective high frequency response.

2. Clean the mounting area to remove any oil, grease and other foreign matter which could preclude the intimate contact necessary to ensure a strong magnetic bond.

3. Select a flat area if possible, to achieve maximum surface contact. Avoid situations as illustrated in Figure 6b.

4. Attach the magnet to the test surface CAREFULLY. Remember that the pull of a magnet rises sharply just before contact with the ferromagnetic surface and this force could pull the assembly from your grip resulting in a very severe metal-to-metal impact. This could overrange the accelerometer beyond its maximum shock range and permanently damage it.

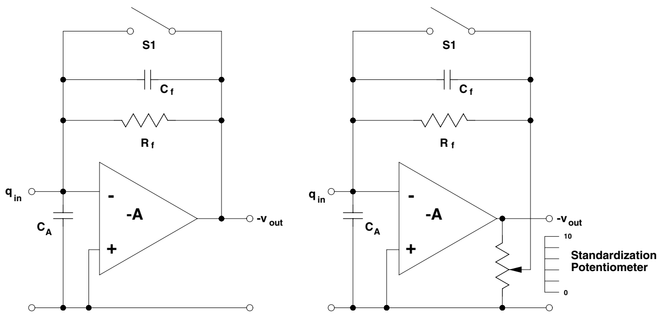
If possible, calibrate the accelerometer/magnet assembly by use of the back-to-back calibration method.

Mounting Wax

Mounting wax is very convenient to use but we do not recommend this method as a viable means of mounting an accelerometer. It should only be used when no other alternatives are feasible. The inconsistency in thickness and the low modulus (rigidity) of wax make the results unreliable at higher frequencies. As previously mentioned, calibration with the exact wax to be used will give the best indication of the expected results.

Charge Amplifier, Basic Theory

A charge amplifier is a special high gain, high input impedance inverting voltage amplifier with capacitive feedback. The amplifier is usually an operational amplifier (op-amp) with near infinite voltage gain.



(a) (b)

Figure 3: The charge amplifier

Referring to Figure 3, the input charge q_{in} is applied to the summing junction (inverting input) of the charge amplifier and is distributed to the input capacitance of the amplifier C_A and the feedback capacitor C_f. We may write the equation:

$$q_{in} = q_A + q_f \qquad \text{Eq 1}$$

Using the electrostatic equation $q = Cv$ and substituting in equation 1:

$$q_{in} = v_A C_A + v_f C_f \qquad \text{Eq 2}$$

Using equation 2 and making the appropriate substitutions and solving for the output voltage of the amplifier in terms of input charge, amplifier loop gain, and input and feedback capacitance we have:

$$V_{out} = \frac{-q_{in}}{C_A / A + C_f (A+1)} = \frac{-q_{in}}{C_f (1 + 1/A)} \times \frac{1}{1 + C_A / C_f (A+1)} \qquad \text{Eq 3}$$

where A is the open loop gain of the op-amp.

Now, letting gain A approach infinity, we have:

$$V_{out} = \frac{-q_{in}}{C_f} \qquad \text{Eq 4}$$

This result (Eq 4) shows clearly that the transfer function (gain) of a charge amplifier is a function only of the value of the feedback capacitor C_f. Notice that input capacitance C_A has no effect on the sensitivity of the charge amplifier. This means that cable capacitance, for example, has no effect on the sensitivity, a significant find when switching cable lengths and types.

Adding Versatility to The Charge Amplifier

Standardization of system sensitivity, say to exactly 10.00 or 100.00 mV/g is accomplished by adjusting the amount of feedback with a potentiometer as shown. Standardization is often necessary because accelerometers are rarely ever made to exact sensitivities. The use of a precision multi-turn potentiometer with turns counting dial allows the standardization of the system sensitivity by dialing in the accelerometer sensitivity.

Referring to Figure 3b, changing the range of the charge amplifier is accomplished by switching various values of feedback capacitor into the feedback path. This is accomplished with a rotary switch which has maybe 10 values of precision capacitor arrayed around it.

Again referring to Figure 3b, feedback resistor R_f gives DC stability to the circuit and establishes the discharge time constant (TC) of the amplifier thereby setting the low frequency response of the amplifier. A momentary reset switch (S1) discharges the residual charge in the feedback capacitor returning the system output to zero.

The circuit shown in Figure 3b represents only the first stage of a rudimentary charge amplifier. One or more stages of filtering, integration and other features can be added all in one compact package.

The Hybrid System

A Dytran hybrid system combines charge mode accelerometers with miniature in-line fixed sensitivity charge amplifiers. These charge amplifiers are powered by standard 2-wire LIVM power units.

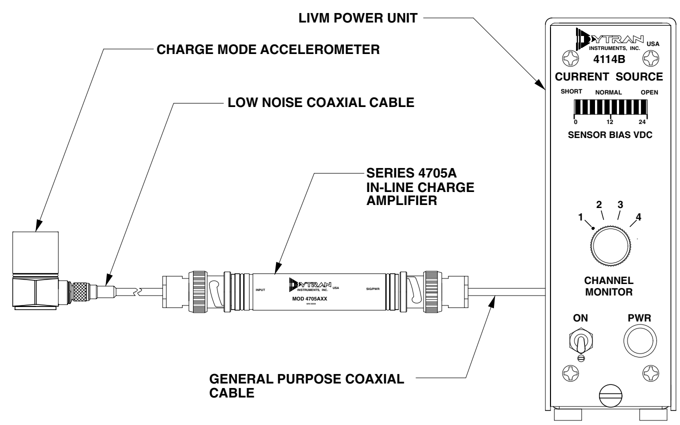


Figure 4: A hybrid system with in-line charge amplifier

The hybrid system, (refer to Figure 4) is ideal for field use because of its small size and rugged construction of the miniature charge amplifiers, for example, Models 4751B and 4505A. These amplifiers are powered by conventional LIVM constant current power units and transmit the output signal over the same two wires as do conventional LIVM systems. The power unit separates the signal information from the DC bias of the amplifier and couples it to the readout instrument. As with conventional charge mode systems, low noise coaxial cable is used to couple the accelerometer to the charge amplifier to minimize triboelectric noise.

When to Use The Hybrid System

The hybrid system should be considered when:

1. The accelerometer is used to measure events at a temperature which is above that recommended for LIVM instruments, i.e., instruments that have built-in amplifiers and the environment is not favorable to laboratory charge amplifiers.

2. System cost is an important factor. Per channel cost of the hybrid system is a fraction of that for the conventional charge amplifier system.

3. LIVM current source power units are in-hand and must be utilized.

4. Ruggedness and small size of the measurement system is imperative.

5. A dedicated system without the versatility of a laboratory charge is sufficient for the measurement task.

τ_1 = R1 x C1 (Seconds) and τ_2 = R2 x C2 (Seconds)
Consider 3 possible relationships between τ_1 and τ_2:

1. $\tau_1 << \tau_2$ In this case, the lower cutoff (-3db) frequency for the system is:

$$f_0 = \frac{.16}{\tau_1} \quad \text{(Hz)} \qquad \text{(Eq. 1)}$$

The lower -5% frequency is:

$$f_{-5\%} = 3 \times f_0 \quad \text{(Hz)} \qquad \text{(Eq. 2)}$$

The sensor is controlling the low frequency entirely in this case.

2. $\tau_1 >> \tau_2$ In this case, the output load and coupling capacitor determine the low frequency response as follows:

The lower cutoff frequency (-3db) is:

$$f_0 = \frac{.16}{\tau_2} \quad \text{(Hz)} \qquad \text{(Eq. 3)}$$

The lower -5% frequency is:

$$f_{-5\%} = 3 \times f_0 \quad \text{(Hz)} \qquad \text{(Eq. 4)}$$

3. $\tau_1 = \tau_2$ In this case, where τ_1 and τ_2 are equal or close in value, the combined time constant, $\tau_3 = (\tau_1 + \tau_2) / 2$

The -6db frequency is:

$$f_{-6db} = \frac{.16}{\tau_3} \quad \text{(Hz)} \qquad \text{(Eq. 5)}$$

The -3db frequency is:

$$f_0 = 1.6 \times f_{-6db} \quad \text{(Hz)} \qquad \text{(Eq. 6)}$$

The -5% frequency is:

$$f_{-5\%} = 1.6 \times f_{-6db} \quad \text{(Hz)} \qquad \text{(Eq. 7)}$$

These values are approximate and are to be used as a guide only.

Getting the Most From the Low Frequency Response of the Accelerometer

To measure ultra low frequencies with a very long TC LIVM accelerometer where the AC coupling TC of the power unit is the limiting factor, a DC coupled LIVM power unit (Model 4115B) is available. This unit utilizes a direct-coupled summing amplifier to null the DC bias of the accelerometer by summing an equal absolute value negative DC voltage at the input stage. The result is a zero DC voltage level at the output, achieved with no coupling capacitor.

Using this power unit, the accelerometer discharge time constant alone determines the low frequency response of the system in accordance with previously mentioned equations 1 and 2.

High Frequency Response

Another important consideration in selecting an accelerometer may be its high frequency response.

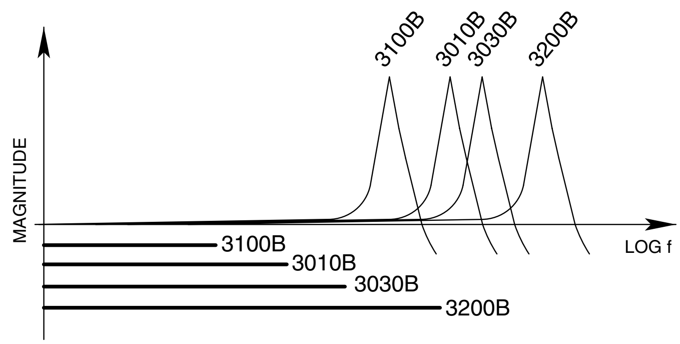


Figure 4: High Frequency Response Comparison

Figure 4 shows the typical high frequency characteristics of four Dytran accelerometers. These curves illustrate the undamped 2nd order system response characteristic of the accelerometers and the bar graphs illustrate the comparative useful frequency range of each model, the comparison criterion being the +5% deviation from the 100 Hz reference sensitivity.

The high frequency response of any accelerometer is sensitive to mounting techniques and may be modified by any anomaly that reduces the mechanical coupling between accelerometer and mounting surface such as the use of an adhesive, magnetic or ground isolation base, dirty or non-flat mounting surface and too thick glue lines in adhesive mount installations. Follow the mounting instructions outlined in the manual supplied with each accelerometer for best results.

Sensitivity Standardization

The reference sensitivity (mV/g) of all Dytran vibration accelerometers is measured at 100 Hz at an input amplitude of 1g, RMS unless otherwise specified. This is measured by the back-to-back comparison method. The sensitivity of shock accelerometers (such as series 3200B) is determined by a drop-shock technique developed by Dytran. All calibrations are NIST traceable. "Standardized" models are considered to be those models whose sensitivities are specified to be within ±2% of the nominal sensitivity value at 100 Hz. Shock accelerometers, because of their nature, are not standardized. Consult the product data sheet to determine which units have standardized sensitivity.

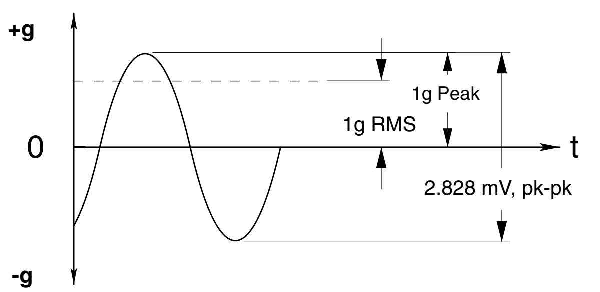
Piezodyne[tm] Technology

Dytran has perfected an advanced patented concept in LIVM technology that increases the voltage output from piezo crystals using a feedback technique with the standard unity gain IC LIVM amplifier. This concept, called Piezodyne[tm], (Patent no. 4,816,713) spawned a line of miniature, high sensitivity, high resolution accelerometers.

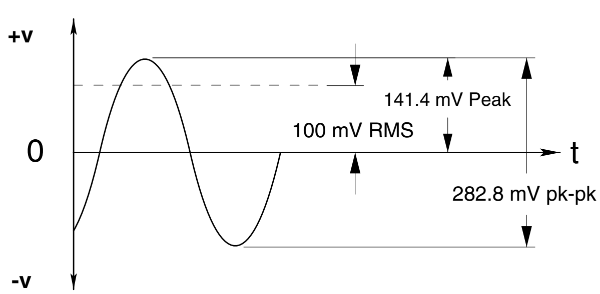
Because there is no gain amplifier used in Piezodyne, output noise does not increase in proportion to the increase in output signal amplitude. The result is a 6db improvement in signal-to-noise ratio and up to 8 times increase in sensitivity.

RMS to Peak Conversion

The output voltage generated by an LIVM accelerometer has a direct correlation with input acceleration. A 1g RMS sinusoidal input will produce a 1g RMS output signal as illustrated in Figure 5. A 100 mV/g accelerometer (Model 3100B) is used here as an example. Refer to figure 5.



Input Acceleration to 3100B



Corresponding Output voltage Signal from 3100B @ 100 mV/g

Figure 5: Input/Output Waveforms

For sinusoidal vibration input, it is convenient to read the output with a true RMS reading AC voltmeter. To convert this value to peak g's, simply multiply by 1.414. Example:

g's peak + 1.414 x g's RMS. and,

g's peak-to-peak = 2.828 x g's RMS

Shock Accelerometers

Shock accelerometers are designed to measure very rapidly changing high level unidirectional transient acceleration inputs as might be generated by pyrotechnic devices, crash tests, impact tests, etc. They are characterized by small size, high stiffness (for high natural frequency) and ruggedness. Model 3200B is one such accelerometer.

The resonant frequency of series 3200B shock accelerometers is greater than 100 kHz resulting in excellent rise time and minimal ringing. These rugged 6 gram instruments feature integral 10-32 or 1/4-28 threaded integral mounting studs (6 mm is also available) and hardened 17-4 steel housings. The sensing element utilizes an exclusive 2-piece element base for stain isolation and high natural frequency.

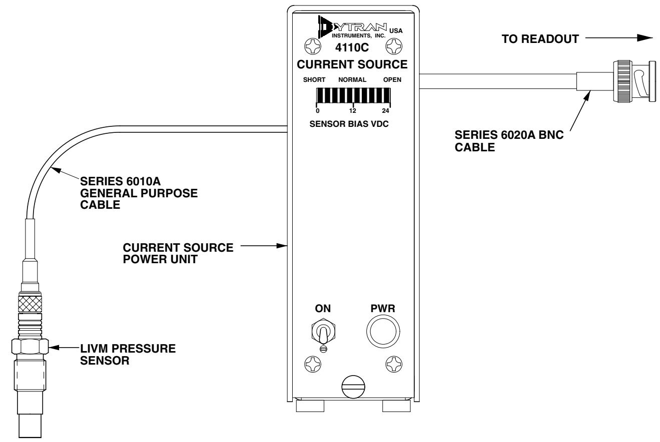


Figure 4: The complete measurement system

Figure 4 illustrates the components of a typical LIVM pressure measurement system. Pressure sensors may be used with a variety of current source power units depending upon the specific application. Consult the section "Introduction to Current Source Power Units" and the specification charts in that section for help in selecting the best power unit for your needs.

Low Frequency Response

Refer to the section "Low Frequency Response and Quasi-Static Behavior of LIVM Sensors" in this series for an explanation of these two parameters and how they relate to sensor discharge time constant (TC).

CHARGE MODE PRESSURE SENSORS

Dytran charge mode pressure sensors utilize pure synthetic quartz crystals to produce electrostatic charge signals analogous to pressure changes at the diaphragm. The very rigid structures of the charge mode quartz elements are similar to those of the LIVM sensors, however, there are no amplifiers built into the charge mode sensors.

Advantages of Charge Mode

The absence of internal electronics allows the charge mode sensor to be used at temperatures well above the 250°F upper limit of most LIVM sensors. Charge mode sensors must be used with charge amplifiers, special high input impedance amplifiers which have the ability to measure the very small charges (expressed in pC or 10^{-12} Coulombs) without modifying them.

Two distinctly different types of charge amplifiers for use with charge mode pressure sensors are available from Dytran:

1. The versatile laboratory type direct coupled electrostatic charge amplifier, Model 4156 which provides for easy standardization of system sensitivity and convenient range selection. Because of its long discharge time constant capability, Model 4165 is especially useful for calibration of sensors by quasi-static means (dead weight testers) and for very low frequency measurements. Model 4165 also features a reset (ground) button for returning the output to zero as well as interchangeable plug-in filters and variable discharge time constant settings for control of system "drift" in thermally active environments.

2. Series 4750A, 4750B and 4705A are miniature fixed range in-line type charge amplifiers designed for use in "Hybrid" systems. These amplifiers adapt charge mode sensors to LIVM power units and allow you to use these sensors in dirty and damp field environments, just like LIVM sensors, but at higher temperatures. These charge amplifiers are powered by standard LIVM current source power units and present a low cost field useable alternative to the expensive laboratory charge amplifier while providing the convenience of 2-wire LIVM operation.

When to Select Charge Mode

You will normally use charge mode pressure sensors in the following situations:

1. When making routine dynamic measurements above the +250°F limit of LIVM sensors.

2. When range switching capability and wide dynamic range of the laboratory charge amplifier are desired.

3. When calibrating charge mode pressure sensors by quasi-static methods such as a dead weight tester. The extremely long discharge TC obtainable with electrostatic charge amplifiers such as the Model 4165, make them ideal; for this purpose.

You would not choose charge mode pressure sensors in the following situations:

1. When operating in dirty or damp field environments driving very long cables from sensor to power unit or from power unit to readout with un-buffered power unit. (Buffered units are not affected by cable length from power unit to readout).

2. When you are making multi-channel measurements and cost is a factor.

3. When the fixed range simplicity of LIVM sensors is a positive factor such as when making multiple dedicated range measurements.

The Conventional Charge Mode System

In the charge mode system shown in Figure 5 below, the sensor is connected to the input of the electrostatic laboratory type charge amplifier using low-noise treated coaxial cable.

It is important to use coaxial cable for this purpose because the input to a charge amplifier is at a very high impedance level and as such, is susceptible to noise pickup if not continuously shielded.

The low noise treatment is also important because physical motion of untreated coaxial cable will generate electrostatic charges which will show up on the signal as spurious noise. This type of cable-generated noise is called triboelectric noise. Low noise cable is treated with a special coating within the layers of the cable which minimize the generation of this type of noise.

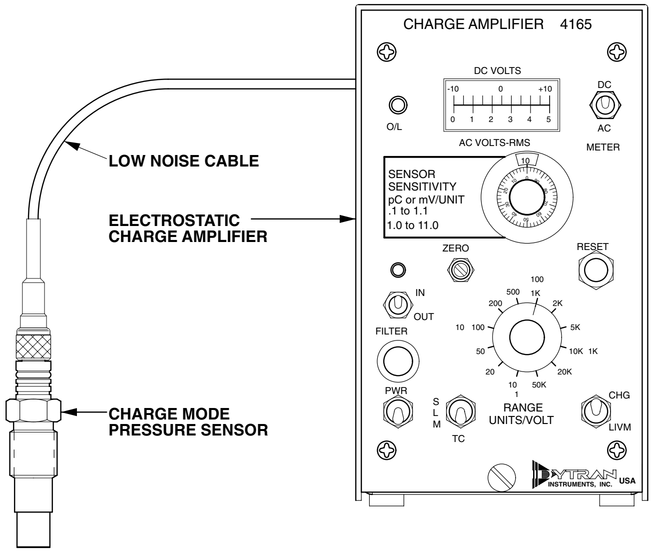


Figure 5: Conventional charge mode system.

In moist and dirty environments, it may be necessary to protect the high impedance cable connections at the sensor with shrink tubing over the cable connector. To facilitate this, most Dytran pressure sensors are designed with shrink tubing grooves just below the connector. It is recommended that you use about an inch of sealing type shrink tubing across the connection after the cable nut has been tightened securely by hand. This will seal the connection against moisture and other contaminants which can cause loss of insulation resistance at the input to the charge amplifier and which may cause annoying "drifting" of the charge amplifier output.

The Hybrid System

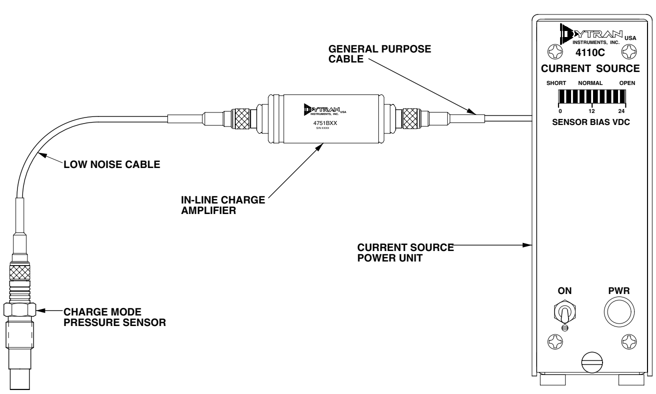


Figure 6: A hybrid pressure measurement system

The hybrid system combines charge mode and LIVM systems as shown in Figure 6. A charge mode sensor is connected to a miniature in-line charge amplifier which is driven by a conventional LIVM constant current power unit.

The in-line charge amplifier (so called because it is inserted in the line between the sensor and the power unit) is powered by constant current power from the LIVM power unit. These charge amplifiers, operating over two wires like LIVM sensors, convert the charge signal from the charge mode sensor to a voltage signal which appears at the output jack of the power unit.

High Frequency Response

The high frequency behavior of piezoelectric pressure sensors approximates that of a second order spring-mass system with close to zero damping. (See Figure 7 below)

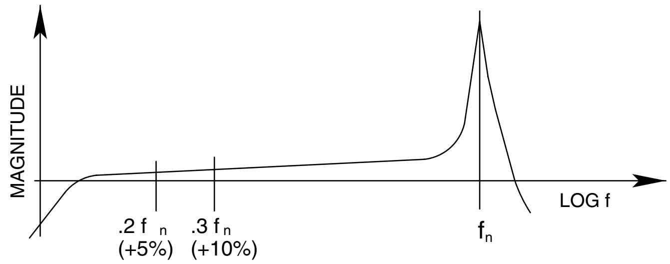


Figure 7: Frequency response of a piezoelectric pressure sensor.

Figure 7 is a graph of Magnification Factor vs. Log Frequency for a typical piezoelectric sensor. As shown by the graph, the sensitivity of the sensor will rise about .5db (5%) at 20% of the natural frequency fn and will rise about 1db (10%) at 30% of fn. The corresponding phase lag for these two points are one and two degrees respectively. These parameters will define the useable frequency range of the sensor based upon its natural frequency. The natural frequency of each sensor is recorded on the calibration sheet supplied with each instrument.

Installation

Installation instructions, including port preparation details, are supplied with every Dytran pressure sensor. Follow these instructions carefully. These sensors are precision measuring instruments and it is important for optimum accuracy, that they be properly installed. Prepare mounting ports carefully, paying particular attention to the seal seat. It is important that the sealing surface be smooth and free from chatter marks and other machining imperfections.

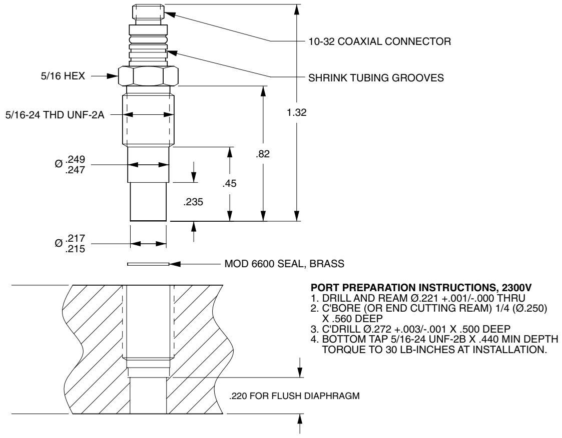


Figure 8: Typical flush diaphragm installation.

Use a torque wrench to monitor the mounting torque. All piezoelectric sensors are sensitive to mounting torque value to some degree so for highest accuracy, duplicate the torque value specified on the Outline/Installation drawing provided with the sensor. This is the torque value with which the sensor was calibrated at the factory. Always use the seal provided with the sensor to avoid damage to the mounting port or mounting adaptor from the hardened steel housing of the sensor.

Recessed Diaphragm Installation

A pressure sensor mounted with a passage in front of the diaphragm as shown in Figure 9 (recessed diaphragm mount) will exhibit impaired high frequency response and rise time characteristics when compared to the flush mount sensor characteristics. These limitations are due to the passage. The column of gas or liquid in the passage cavity ahead of the diaphragm is in itself a second order system with its own resonant frequency characteristic. Since we are using this column to couple the pressure event to the sensor diaphragm, its frequency characteristics are most important.

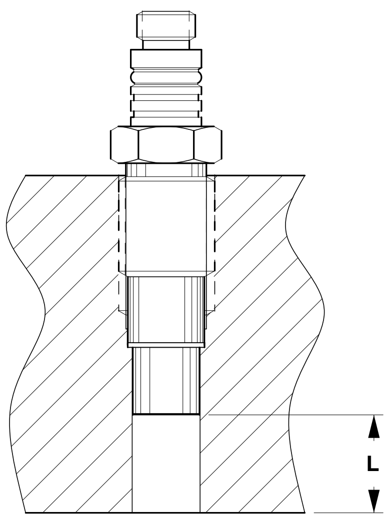


Figure 9: The recessed diaphragm installation.

The following chart (Figure 10) displays the theoretical effect of various length passages formed by the diaphragm recess. The formula used to calculate the chart value is the well-known pipe organ formula. The approximate fastest rise time that will pass through the passage is also related to the passage resonance.

$$fn = \frac{v}{4L} \quad \text{where:} \qquad \text{(Eq. 1)}$$

fn = passage resonant frequency (Hz)
v = velocity of sound in air (in./Sec)
L = cavity length (in.)

Note: The value for sound in air at sea level, 20˚C is 13,512 in./Sec.

As a general rule, the frequency response of a recessed diaphragm system will be useable to about 1/3 of the passage natural frequency. The fastest rise time that can be expected to be transmitted by the passage is roughly 1/3 of the period of this frequency. These are general guide rules only and are not hard and fast rules. Remember that the chart values, (Figure 10), must be corrected for variations in media and temperature.

Recess (Inches)	Passage Natural Frequency	Approximate Fastest Rise Time
.001	3.3 mHz	.1 mSec
.002	1.6 mHz	.2 mSec
.003	1.1 mHz	.3 mSec
.005	660 kHz	.5 mSec
.010	330 kHz	1 mSec
.050	66 kHz	5 mSec
.100	33 kHz	10 mSec
.200	16.6 kHz	20 mSec
.500	6.6 kHz	50 mSec
1.00	3.3 kHz	.1 mSec
2.00	1.66 kHz	.2 mSec

Figure 10: Cavity length vs. resonant frequency and rise time

Mounting Adapters

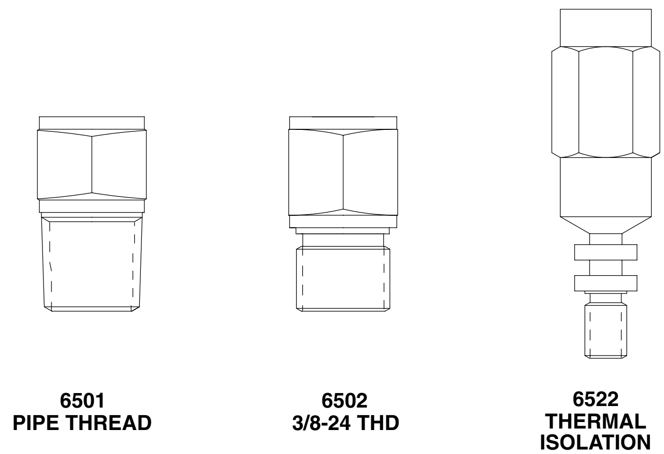


Figure 11: Various mounting adapters

Several mounting adapters are available which can simplify sensor installation. The critical internal seal seats in these adapters are precision machined to preclude leakage and the larger external threads provided by some of these adapters require less precision machining and skill in mounting. Mounting adapters can be used to adapt the installation to pipe threads or larger machine threads, to isolate the sensor diaphragm from high flash temperature (Model 6522) or from ground loop interference (Model 6520). Custom mounting adapters can be designed and fabricated to suit most applications. Contact the factory for help in solving your special installation problem.

load to slugs by dividing LbF by 32.3. Metric units may be used as long as all values are converted.

Sensor Range vs. Sensitivity and Discharge TC

For a basic LIVM force sensor configuration the maximum force range is dictated by mechanical limitations such as the maximum allowable stress the designer wishes to place on the crystals and other members in the design. Each variation of a particular model will produce a convenient 5 Volt signal for full scale. The following is an explanation of how this is done. Refer to the electrostatic equation below:

$$V=\frac{Q}{C} \qquad \text{(Eq. 2)}$$

Where: V = Voltage across piezoelectric crystals, Volts
Q = Electrostatic charge generated by crystals, Coulombs
C = Total capacitance across crystal element, Farads

Equation 2 defines the voltage sensitivity of the sensor in terms of generated electrostatic charge and shunt capacitance. The equation states that the voltage (V) produced by the crystal element equals the electrostatic charge (Q) generated by the stress due to the input force, divided by the total shunt capacitance (C) of the crystal element plus any other capacitance across the element. (refer to Figure 2).

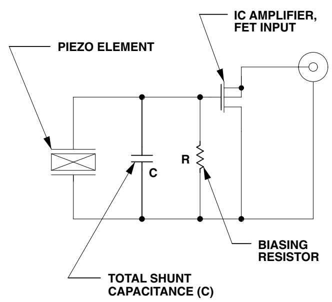


Figure 2: Schematic of LIVM Force Sensor

In accordance with Equation 2, to obtain 5 Volts full scale we must select a capacitor with the proper value and place it across the crystal element so that when full scale charge is distributed over the total shunt capacity the output voltage will be 5 Volts. For lesser ranges we can (by reducing this capacitance value accordingly) obtain 5 Volts for various lower force levels, the limit being the sensitivity obtained with no capacitor across the crystal element. In this manner we can create a family of force sensors with fixed full scale ranges from a maximum of 5,000 LbF (1mV/LbF) to a minimum of 10 LbF (500 mV/LbF) using the same basic mechanical configuration.

It is also necessary to place a resistor across the crystal to bias the MOSFET amplifier at its proper operating point (refer again to Figure 2). State of the art and leakage considerations limit this resistor value to approximately 1 Terraohm (1×10^{-12} Ohm). This means that the lower range sensors which have smaller value ranging capacitors will also have shorter discharge time constants because of the lower RC product. This makes the lower range units slightly more difficult to calibrate and raises the lower corner frequency accordingly. The article "Low Frequency Response and Quasi-Static Behavior of LIVM Sensors" will further define this topic.

CHARGE MODE FORCE SENSORS

Dytran charge mode force sensors generate electrostatic charge signals analogous to dynamic force inputs. Unlike LIVM sensors, charge mode sensors contain no internal electronics. The output from the piezoelectric crystals is routed directly to the coaxial connector. A coaxial cable is then used to connect the sensor to an external charge amplifier which converts the electrostatic charge generated by the crystals to a low impedance voltage signal.

Why Charge Mode?

1. Containing no internal electronics, charge mode force sensors can be used well above the +250°F limit for most LIVM sensors. In-line LIVM charge amplifier (Models 4751 and 4705) convert charge mode sensors to LIVM operation.

2. When used with electrostatic charge amplifiers such as the Dytran Model 4165, the system discharge time constant can be very long. Static calibration methods can be used and system low frequency response approaches DC.

3. The range switching capabilities of the Model 4165 amplifier make sensitivity adjustment very simple in contrast to the fixed sensitivity of LIVM sensors.

4. Reset buttons on laboratory charge amplifiers allow instant resetting (or discharging) of charge mode sensors, returning the system output to zero (ground reference) level at any time. This is an advantage in many applications, since waiting 5 time constants for LIVM sensors to fully discharge to ground level can be time consuming for the longer TC units.

5. Standardizing system sensitivity to precise round numbers in mV/LbF is easy to accomplish by dialing the sensor sensitivity in to the front panel adjustment pot on the 4165. The fixed sensitivity of most LIVM systems precludes such standardization.

Construction and Operating Principles

Construction of charge mode force sensors is similar to the LIVM types except that the charge mode sensors do not contain a built-in IC amplifier (refer to Figure 1). Charge mode sensors utilize the same thin piezoelectric crystals as LIVM sensors with one major difference: the crystals in charge mode sensors are oriented to produce a negative-going charge output in response to compressive forces on the sensor. This is because most electrostatic charge amplifiers are signal-inverting instruments. In such a system, output voltage from the charge amplifier will be in phase (positive-going) with applied compressive forces. Tension on the force sensor will produce negative-going output voltages from the measurement system.

The charge amplifier is essentially an infinite gain inverting amplifier with capacitive feedback (see Figure 3). The electrostatic charge generated by stress on the crystals (due to input force) is effectively "nulled out" at the input (summing junction) of the charge amplifier by a charge "fed back" across the feedback capacitor.

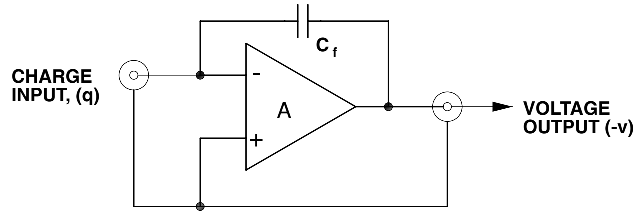


Figure 3: Charge Amplifier, Simplified Schematic

The voltage necessary to generate the nulling charge is then a measure of the input charge and thus the input force. This voltage will vary with the choice of feedback capacitor (selected by the front panel range switch on the Model 4165) in accordance with the electrostatic equation V=Q/C. The system sensitivity is set by simply selecting various values of feedback capacitor.
Many charge amplifiers also contain standardization features to allow the setting of system sensitivities to exact round numbers such as 100 mV/LbF, 1.00 mV/LbF, etc., making it very convenient to set up measurement criteria.

Applications

Because of their high stiffness and strength (they are almost as rigid as a comparably proportioned piece of solid steel), piezoelectric force sensors may be inserted directly into machines as part of the structure by removing a section and installing the sensor. By virtue of this high rigidity, these sensors have very high natural frequencies with fast rise time capabilities making them ideal for measuring very quick transient forces such as those generated by metal-to-metal impacts and high frequency vibrations.

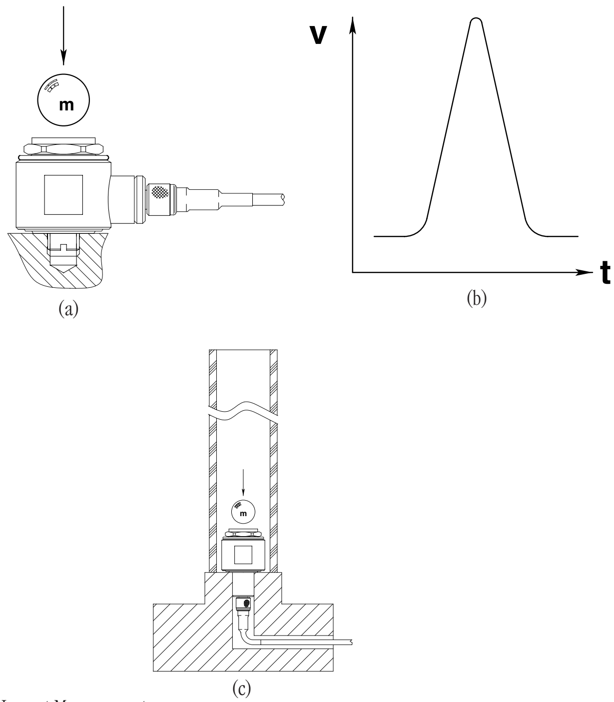


Figure 4: Impact Measurement

Figure 4 illustrates two typical LIVM force sensors configured to measure impact forces. In Figure 4a, a radial connector force sensor (series 1051V or 1061V) is fastened to a rigid mounting surface and a test object is impacted against the cap of the sensor. The output waveform from the sensor is illustrated by Figure 4b. Figure 4c illustrates the use of an axial connector force sensor (series 1050V or 1060V). This type of sensor is recommended where radial space is limited, as in the drop tube application shown in Figure 4c. The output signal would again look like Figure 4b.

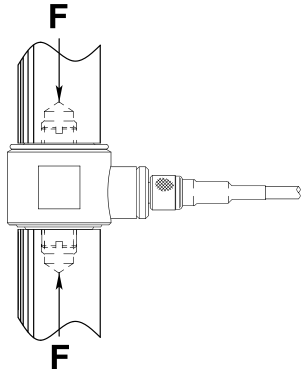


Figure 5: Dynamic Force Measurement

The force sensor in Figure 5 has been mounted in series with a pushrod in a machine to measure the dynamic forces axial to the rod, i.e., in the direction of the main axis of the rod. Any static forces in the rod due to a preload (tension or compression), or the weight of the rod itself, will initially result in an output signal from the sensor. This signal will disappear within 5 TC's and only the dynamic component will remain. Refer to the article "Low Frequency Response and Quasi-Static Behavior of LIVM Sensors" in this series for more information on this topic. Figure 6a is the output signal from the sensor in response to a vibratory force within the rod and Figure 6b illustrates the output signal resulting from only compression forces moving through the rod.

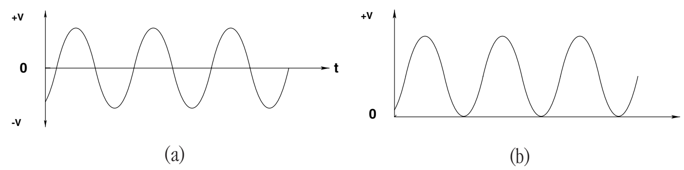


Figure 6: Dynamic Output Waveforms

The uses of piezoelectric force sensors are limited only by the imagination of the user. The examples given here illustrate only a few of the potential applications of these sensors.

Figure 2b shows the corresponding gate voltage v. At time t_0, this voltage instantly assumes value V_0 (sensor sensitivity X force F). After time t_0 + 10 sec., voltage v has decayed in accordance with Equation 1, losing 1% of its initial value. At time t_0 + 10, the input force F is abruptly removed. Voltage V instantly drops to a point 1% below the original baseline (again responding with voltage change V_0), then begins to charge toward the baseline in accordance with Equation 1.

Figure 2c shows the corresponding output voltage measured at the output of the sensor (at the source terminal of the IC). Notice that the voltage waveform is similar in form, but elevated upward by the sensor bias voltage (approximately +10 Volts DC).

If we were attempting to calibrate this sensor by static means we would have .01 x 1000 or 10 seconds to take the reading of the output voltage after the application of the input step for a reading with 1% accuracy. A means of transient signal capture such as a digital storage oscilloscope facilitates such calibrations.

Low Frequency Response

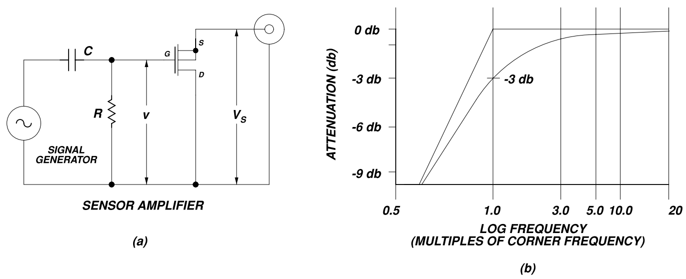


Figure 3: Low Frequency Response Characteristics

The RC circuit shown in Figure 1a is also a first order high-pass filter illustrated in Figure 3a above. We now switch to the frequency domain to describe the effect of TC on low frequency response.

Figure 3b is a Bode plot or graph of the low frequency response of an LIVM sensor. A very significant point on the graph is the corner frequency f_c. At this frequency the output from the sensor has decreased by 3db or approximately 30% from its reference sensitivity (the sensitivity that would be obtained at about 1 decade (10X) above the corner frequency). The slope or rolloff rate of the sensor is always -6dB/octave, standard for a first order high pass filter. In the Bode plot, this slope line crosses the reference axis at f_c. The phase shift at f_c is 45°.

Corner frequency f_c is set by the TC. To find f_c for your sensor, first consult the calibration certificate or data sheet supplied to obtain the TC, then solve for the corner frequency as follows.

$$\text{Corner Freq.} = f_c = \frac{.16}{\text{TC (sec)}} = \text{Hz} \qquad \text{(Eq. 4)}$$

Another important frequency is where the output is down by 5% from the reference sensitivity. This point is approximately 3x the corner frequency or:

$$\text{-5\% Freq.} = f_{-5\%} = 3 \text{ X } f_c(\text{Hz}) \qquad \text{(Eq. 5)}$$

Figure 4 is a chart of attenuation and phase shift vs. frequency for a high pass, 1st order filter. The values for these two parameters can be determined at multiples of the corner frequency with this chart.

Multiple of Corner Frequency f_c	Attenuation Factor	Attenuation (dB)	Phase Shift (degrees)
$.1f_c$	.10	-20	-84.3
$.5f_c$	.45	-6.9	-63.3
$1.0f_c$	.707	-3.0	-45.0
$2.0f_c$	.89	-1.0	-26.4
$3.0f_c$	.95	-.5	-18.3
$4.0f_c$	.97	-.3	-14.0
$5.0f_c$	.98	-.2	-11.3
$10.0f_c$	.99	-.04	-5.7

Figure 4: Attenuation & Phase Shift vs. Multiples of Corner Frequency

High Frequency Response

The relationship between TC and high frequency response and/or rise time is often misunderstood so some clarification may be in order. Sensor and power unit coupling TC's have absolutely no effect on these two characteristics.

High frequency response and rise time for any sensor are controlled by mechanical design characteristics and may also be affected by system factors such as drive current, cable length, mounting techniques, passage resonances, mass loading, etc. These topics are covered in other sections of this catalog.

The LIVM Power Unit as it Effects Low Frequency Response and Quasi-Static Capability

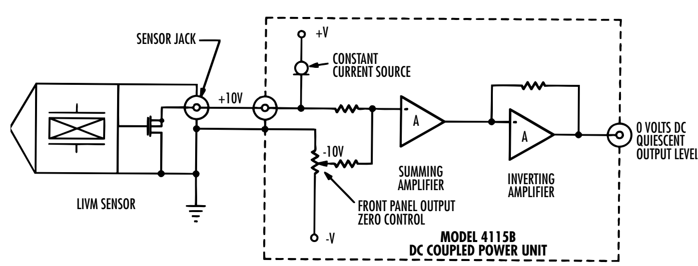
At the beginning of this section you were told to ignore the effect of power unit on low frequency response for the time being. You cannot ignore it completely however, because the AC coupled power unit is often the limiting factor in low frequency and quasi-static system capability rather than the sensor itself. All AC (capacitively) coupled power units are high pass filters which can impair the low frequency response and quasi-static behavior of your system. (Refer to the section "System Low Frequency Response" in the article "Introduction to LIVM Accelerometers" for a more complete treatment of the effect of power unit on LF & Q-S response.)

The DC Coupled Power Unit

One way to take full advantage of the long TC built into your sensor is to use the Model 4115B DC coupled power unit. This unit uses a summing op-amp circuit rather than a capacitor to direct couple the sensor to the readout.

Figure 5: Functional Schematic, Model 4115B

A user-variable negative DC voltage is applied to the summing junction of the amplifier to exactly null the DC bias voltage from the sensor allowing precise zeroing of the output signal. This versatile power unit is especially useful for calibration of pressure and force sensors by static means. The 4115B also has



an "AC" coupling mode for use with sensors in thermally unstable environments or for strictly dynamic use. Consult the summary product data sheet on Model 4115B for specifications and features.

Transient Thermal Effects

When using LIVM sensors with very long time constants (greater than several minutes) with DC coupled power units such as the 4115B, varying temperatures can affect crystal preload structure, generating slowly changing output voltages, which may appear as annoying baseline shift in the output signal. In situations like this, it is important to insulate the sensor against transient (sudden) thermal inputs. Dytran can provide insulating jackets (or boots) for many sensors to minimize this problem. Consult the factory for details.