

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.

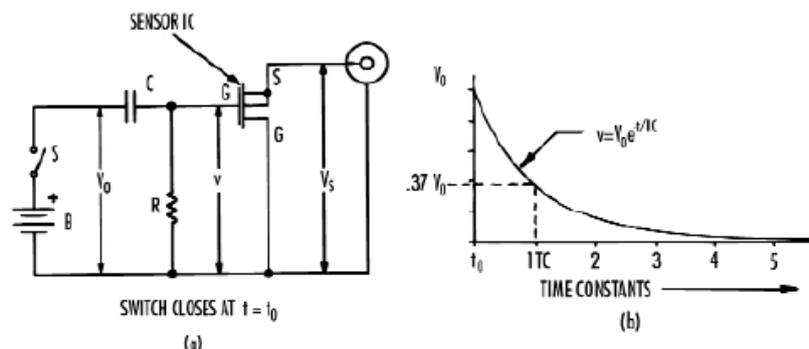


Figure 1: Discharge Time Constant (TC) Output vs. Time

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 (V0) is impressed across the input terminals at time t0. 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 t0, voltage (v) instantly assumes value V0, then immediately begins to discharge (or decay) exponentially with time. The decay function is described by the following equation:

	$v = V_0 e^{-t/RC}$	(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. $RC = TC \text{ (Ohms)} \times \text{(Farads)} = \text{(Seconds)}$ (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:

$$v = V_0 e^{-1} = V_0 / e = .37V_0 \tag{Eq. 3}$$

This result states that at time t=TC (one time constant) the signal has discharged to .37V0, or put in another way, has lost .63 (63%) if its initial value V0. 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:

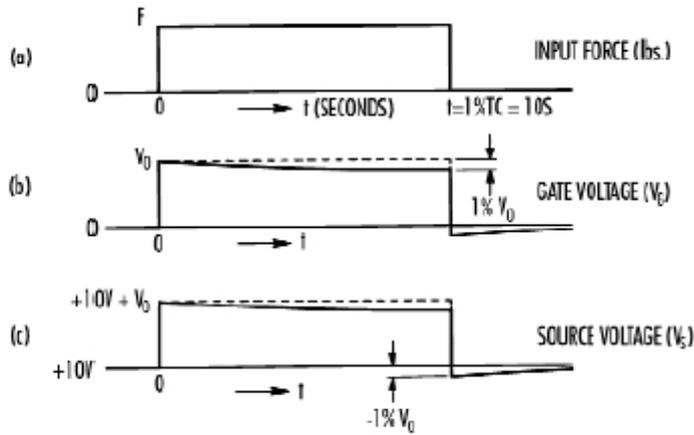


Figure 2: Approaching Static Response

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. Figure 2b shows the corresponding gate voltage v . At time t_0 , this voltage instantly assumes value V_0 (sensor sensitivity \times 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 \times 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

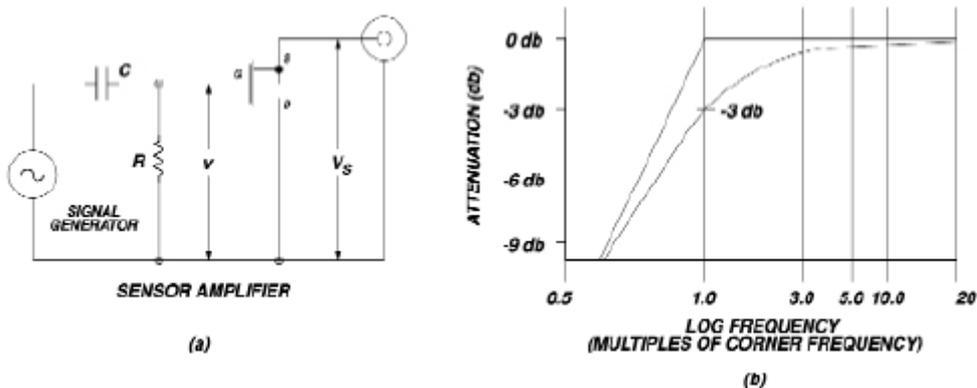


Figure 3: Low Frequency Response Characteristics

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.

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

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

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

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. 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.

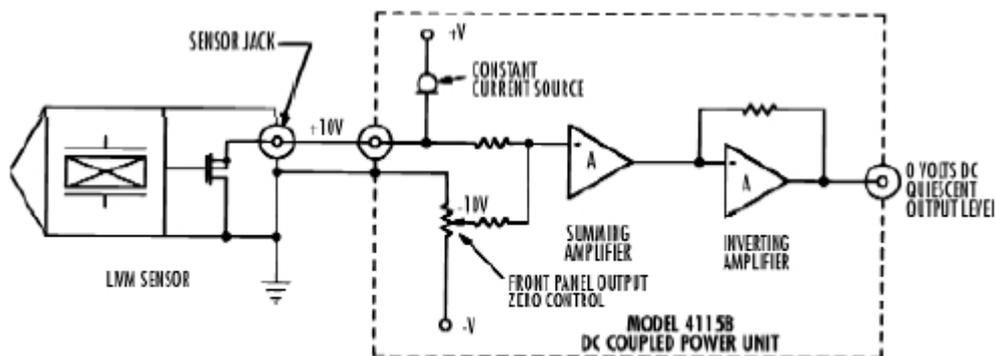


Figure 5: Functional Schematic, Model 4115B

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.