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.

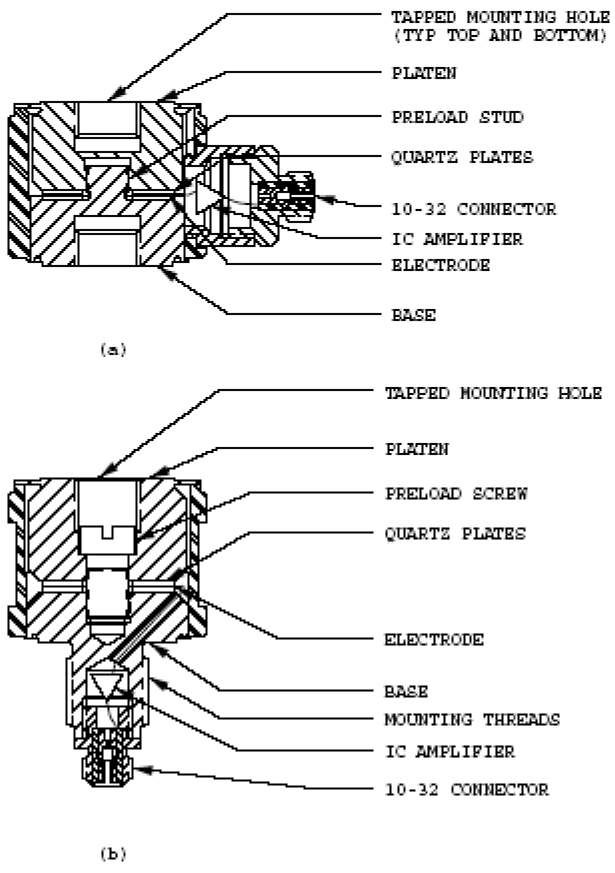

Figure 1: LIVM Force Sensors

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 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).

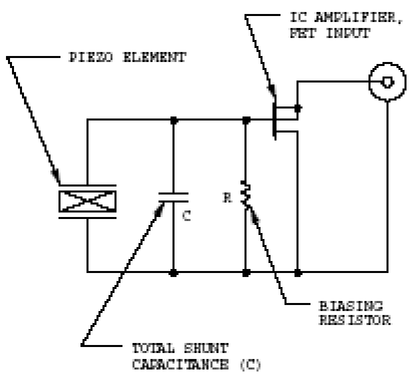

Figure 2: Schematic of LIVM Force Sensor

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 x 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.

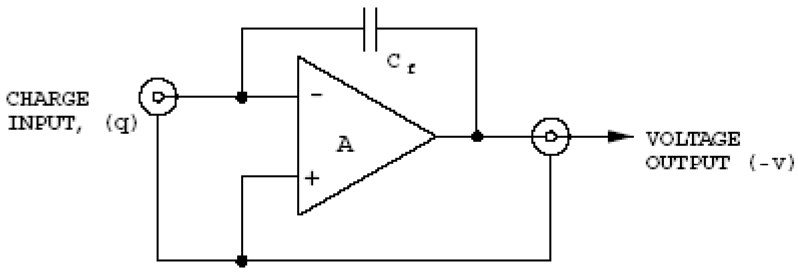

Figure 3: Charge Amplifier, Simplified Schematic

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-tometal impacts and high frequency vibrations.

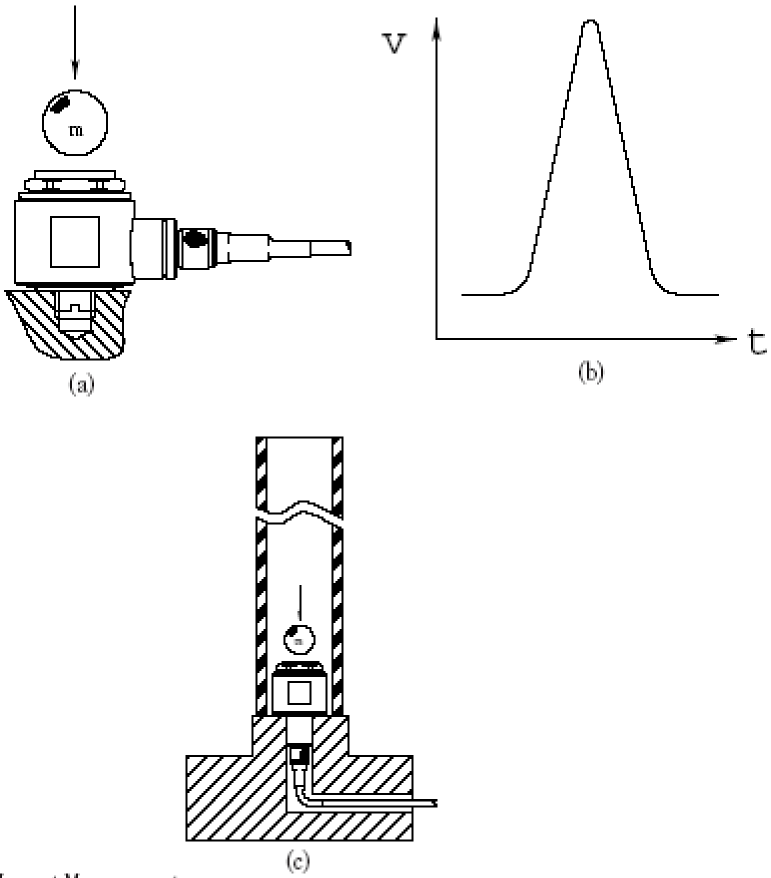

Figure 4: Impact Measurement

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.

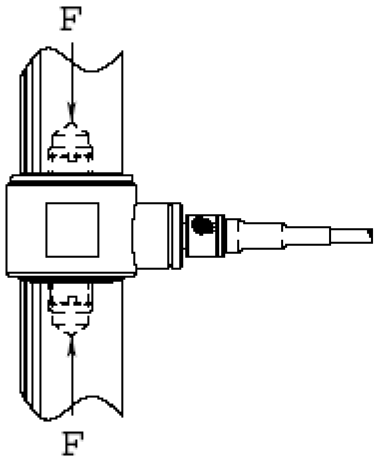

Figure 5: Dynamic Force Measurement

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.

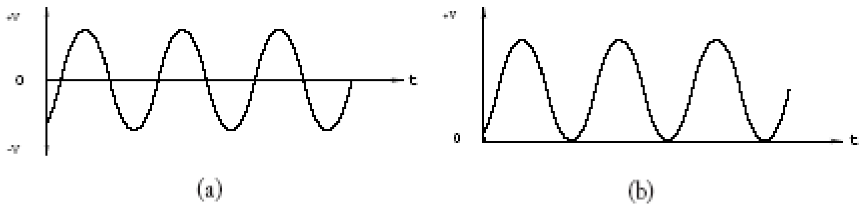

Figure 6: Dynamic Output Waveforms

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.