

## INDUSTRIAL VIBRATION SENSOR SELECTION: PIEZOVELOCITY TRANSDUCERS (PVT™)

*PiezoVelocity Transducers (PVT) have distinct advantages over traditional velocity pickups and piezoelectric accelerometers in many industrial monitoring applications. Onboard velocity integration overcomes low frequency cable pickup and the input noise of data acquisition equipment. In addition, the inherent high frequency attenuation of the velocity output greatly reduces overload distortion.*

### I. Introduction to PiezoVelocity Transducers

Accurate and reliable vibration sensors are critical for successful machinery monitoring programs. PiezoVelocity Transducers (PVT™) outperform general purpose accelerometers and electrodynamic velocity pickups on slow speed equipment. In the 90 to 3600 cpm range, PVT internal integration provides greater signal fidelity than standard accelerometers. Solid state PiezoVelocity Transducers are more reliable and measure broader frequencies than electrodynamic pickups. PVTs are the best investment for many permanent sensor installations in paper mills, steel mills, and power generation facilities.

The PVT is essentially a piezoelectric accelerometer with an on-board velocity converter. The transducer employs a piezoceramic sensing element and dense seismic mass to produce a charge output proportional to acceleration. The high impedance charge signal is converted within the sensor to a low impedance voltage output and integrated to velocity. Section views of compression and shear mode PVTs are shown in Figures 1a and 1b; the integration amplifier and circuit diagram are shown in Figures 2a and 2b.

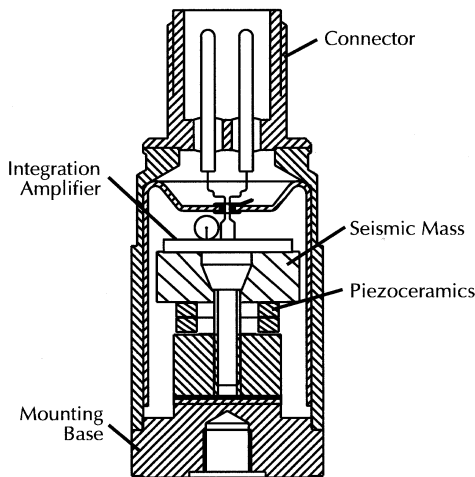


Figure 1a. Compression Mode PiezoVelocity Transducer

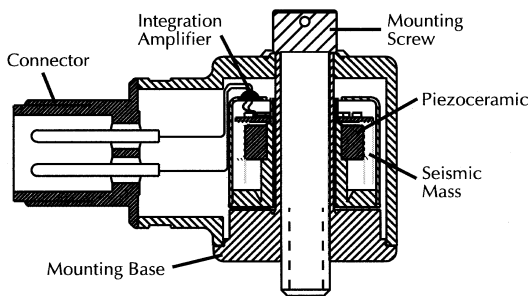


Figure 1b. Shear Mode PiezoVelocity Transducer

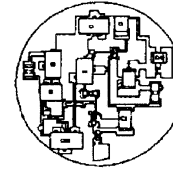


Figure 2a. Hybrid Integration Amplifier

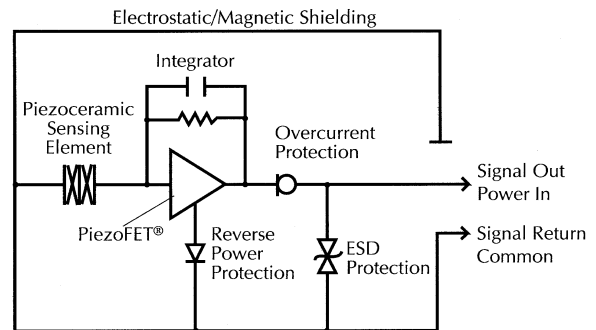


Figure 2b. Circuit Diagram for a PiezoVelocity Transducer

Recent advances in hybrid circuit technology allow increasingly sophisticated circuits such as integrators, signal conditioners, and protection systems to be designed into piezoelectric sensors. Electronic miniaturization has led to the development of multifunction sensors with simultaneous acceleration, velocity, and temperature outputs. Double integrated piezoceramic displacement sensors are also available. Although many output configurations are available for specific applications, 100 mV/ips PVTs are the best value for most industrial applications.

### II. Historical Developments

Early analysts relied on velocity sensors and velocity based vibration severity charts. Today, a vast majority of machinery vibration information is recorded and quantified in terms of velocity. Most vibration measurements in the process industries are analyzed in terms of inches per second (ips) in the United States, or mm/sec in the SI system. Velocity readings are generally recommended for measurements in the 100 to 30,000 cpm (1.7 to 500 Hz) frequency band<sup>1</sup>.

Electrodynamic pickups were some of the earliest vibration sensors. In the 1930's Westinghouse built vibration transducers using speaker voice coils<sup>2</sup>. The voice coil produces a voltage proportional to velocity when driven by mechanical vibrations. This technology developed into the modern electrodynamic velocity sensor and has been used successfully for many years. Today, most measurements are made with accelerometers, and then converted into velocity within the data collection instrumentation.

Until the 1970's, vibration analysis equipment was best suited to measure velocity. Before the invention of FFT analyzers, analysts used broadband (volt) meters or narrow band analyzers. Broadband meters have no frequency resolution and narrow band analyzers were prohibitively slow unless wide bandwidths were chosen. Velocity, which increases in direct proportion to machine speed, allows the destructive vibration energy to be evaluated independent of frequency. Consequently, early machinery vibration severity charts were written in terms of velocity.

Diagnostic experience has lessened the value of generic severity charts; most machines are too complex to be characterized by simple pass/fail criteria. Many measurements, including roller bearing and gear analysis, emphasize frequency and event, rather than amplitude.

**III. Electrodynamic Velocity Pickups**

Electrodynamic velocity pickups consist of a permanent magnet surrounding a floating inductive coil. The coil is coupled to the sensor housing through a spring. The magnet is rigidly attached to the sensor housing and follows the vibratory motion of the mounting structure (Figure 3). Configurations where the magnet floats and the coil is attached to the structure are also used<sup>3</sup>.

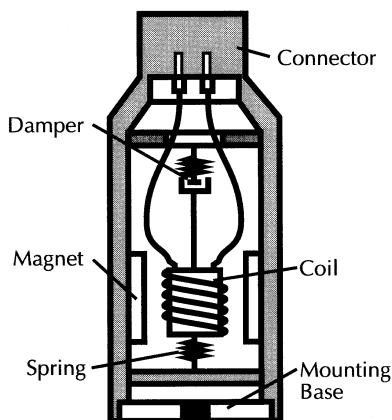


Figure 3. Basic Constuction of Electrodynamic Velocity Pick-up

**Electrodynamic Pickups: Farady's Law of Induction**

As the coil moves inside the magnet, an electromagnetic force is developed according to Faraday's Law of Induction. The changing magnetic flux ( $\Phi$ ) is proportional to the field strength of the magnet, length of coil wire, and relative velocity between the magnet and coil. The voltage produced is given by:

$$\begin{aligned} \epsilon &= -d\Phi/dt = -Bl dx/dt \text{ (MKS)} \\ &= -0.155Blv \text{ (English)} \end{aligned}$$

Where the electromotive force  $\epsilon$  is in volts, the magnetic field strength  $B$  in Gauss, the coil length inches, and velocity ips. The sensitivity of an electrodynamic pickup in Volts per ips is:

$$Sv \text{ (V/ips)} = -0.155Bl$$

Over the calibrated frequency range, the inertial mass of the coil (or magnet) resists the motion of the housing and remains suspended in free space. The relative motion of the magnet induces a voltage in the coil proportional to velocity.

In contrast to piezoelectric devices, electrodynamic pickups are used above the natural frequency of the transducer. Depending on the magnet mass and coupling spring stiffness, most industrial pickups resonate from

480 to 840 cpm (8 to 14 Hz) . Critical damping is achieved electrically or with oil to flatten the low frequency response. Below the natural frequency, the sensor output is attenuated by the inverse square of the frequency.

**Electrodynamic Pickups: Advantages and Limitations**

Electrodynamic pickups are self generating and can be coupled to data collection equipment without auxiliary electronics. This allows them to be used on gas turbines and other high temperature machinery. They are easily mounted directly to the machine surface, but are sensitive to mounting orientation and cross axis resonances.

Electrodynamic velocity pickups generate a very powerful output signal, but introduce phase errors at low frequency and are susceptible to electromagnetic fields. They also contain moving parts that are subject to wear and possible failure. Although modern designs minimize traditional deficiencies, solid-state piezoelectric devices are far more advanced.

The electrodynamic frequency response is very limited compared to PVTs. The typical 600 cpm (10 Hz) cutoff frequency is above the running speed of many paper machines and other industrial equipment. Conversely, typical PVTs cutoff at 90 cpm (1.5 Hz). Comparison response characteristics are given below (Figures 4a and 4b).

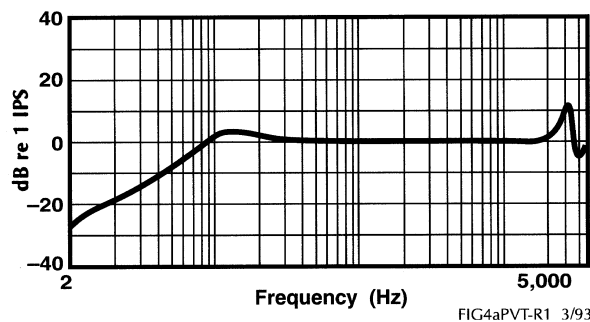


Figure 4a. Electrodynamic Velocity Pickup

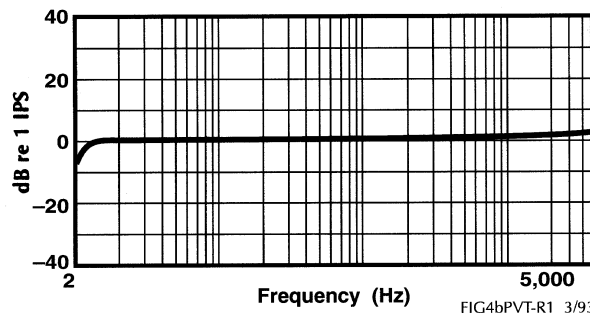


Figure 4b. PiezoVelocity Transducer Response

High frequency usage is limited by the contact resonance of the mount. Depending on the sensor housing and mounting surface stiffness, the contact resonance varies between 120,000 and 180,000 cpm (2000 to 3000 Hz). The calibrated bandwidth is usually limited to 60,000 cpm (1000 Hz) . In contrast, piezoceramic PVTs measure well beyond 300,000 cpm (5000 Hz). Many bearing and gear defects exhibit fault frequencies far above the range of electrodynamic pickups.

**IV. Piezoelectric Accelerometers**

Industrial accelerometers consist of a piezoceramic material sandwiched beneath a seismic mass. The seismic mass and piezoceramic create a simple mass/spring system with a very high natural frequency. Accelerometers and PVTs use Tungsten masses and Lead-Zirconate Titanate piezoceramics to maximize sensitivity at low frequency.

In the region below resonance, the mass applies a force to the piezoceramic proportional to the vibratory acceleration of the structure. The piezoceramic, in response to the applied force, generates a proportional electric charge on its surface; the charge output is then conditioned as necessary.

Accelerometers are extremely versatile and widely used for industrial machinery monitoring. Typical industrial accelerometers measure micro-g vibration levels from below 60 cpm to greater than 900,000 cpm (1 to 15,000 Hz). However, the PVT provides a stronger output on slow to moderate speed machinery.

In low frequency applications, standard 100 mV/g accelerometers are limited by electronic amplifier and monitor noise. Over the frequency range of 90 to 3600 cpm (1.5 to 60 Hz), the PVT has a significantly greater signal-to-noise ratio than a typical accelerometer. In most cases, PVTs can directly replace the piezoelectric accelerometer; accepting the same mounting, connectors, cabling, powering and monitoring equipment.

Below 90 cpm, PVTs are limited by the cutoff frequency of the integration circuit. Relative to acceleration, the output of the PVT increases with decreasing frequency. The cutoff is required to limit gain and keep the amplifier in its linear range. On very slow speed equipment, 500 mV/g low frequency accelerometers are generally used.

**V. PiezoVelocity Transducers**

Consider, for discussion, a dual output acceleration/velocity sensor. Both channels share the same piezoceramic sensing element, and therefore have equivalent outputs before signal conditioning. Applying a broadband vibration, the crossover frequency is the point where the voltage output of the velocity and acceleration sensors are equal. Using English system conversions, this occurs at  $386/2\pi$  or 61.4 Hz. Figure 5 shows the crossover frequency and response comparison between a 100 mV/g accelerometer and 100 mV/ips PVT relative to an acceleration reference standard.

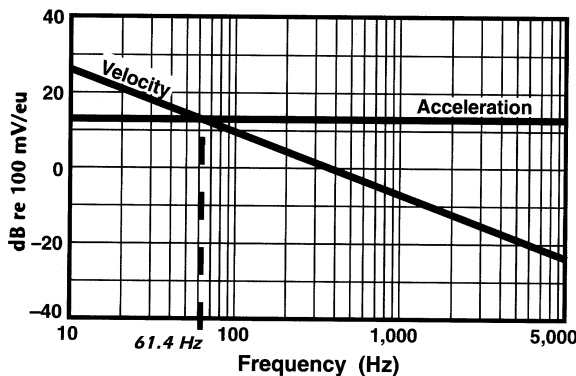


Figure 5. Crossover Frequency and Response Comparison between an Accelerometer and a PVT

The internal integrator shapes the piezoceramic output into velocity by sloping the frequency response negative 6 dB per octave (-20 dB per decade). Above the crossover frequency, the amplitude of the velocity signal is attenuated and decreases by one half as the frequency is doubled. Below crossover, the signal doubles every time the frequency is halved.

For example: A velocity measurement at 4 Hz (approximately 1/16 of 61.4) will have a voltage output 24 dB (16 times) greater than the accelerometer. Conversely, the velocity output at 6140 Hz (two decades above 61.4 Hz) is, in terms of voltage, 40 dB (100 times) less than the accelerometer.

**PVT Low Frequency Amplification**

In many slow speed applications, the accelerometer is externally integrated to velocity inside the monitor. Along with vibration information, the integration circuit amplifies low frequency electronic noise from the sensor and the monitor. Figure 6 shows electronic amplifier noise plots for a 100 mV/g general purpose accelerometer and a 100 mV/ips PVT. The electronic noise from the accelerometer is considerably higher than the PVT. This integration noise produces a response commonly referred to as "ski slope".<sup>4</sup>

In terms of acceleration, low frequency vibration energy is very low in amplitude. The increased low frequency sensitivity of a PVT can dramatically improve data integrity by amplifying the vibration signal before it reaches the monitor. A low frequency 500 mV/g accelerometer may exhibit a lower noise floor compared to an equivalent PVT, however, in the 90 to 720 cpm bandwidth, the PVT has a higher output voltage. The higher output voltage further reduces the noise contribution of the monitor and increases the Figure 6.

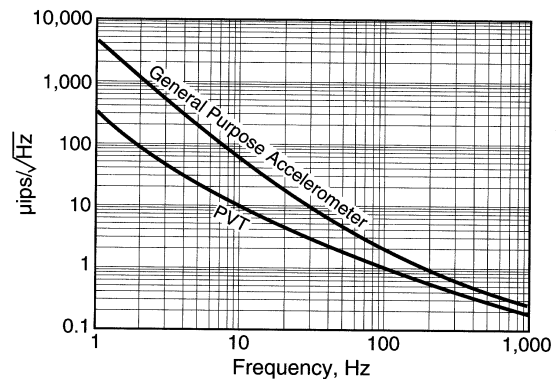


Figure 6. Noise Response Comparison Between a 100 mV/g General Purpose Accelerometer and a 100 mV/ips PiezoVelocity Transducer Normalized in Terms of Velocity

The spectral plots in Figure 7 contrast the outputs of a PVT and an accelerometer. These readings, taken on a cooling tower fan, show "ski slope" integration noise affecting the accelerometer measurement. The fan running speed is 118.56 cpm.

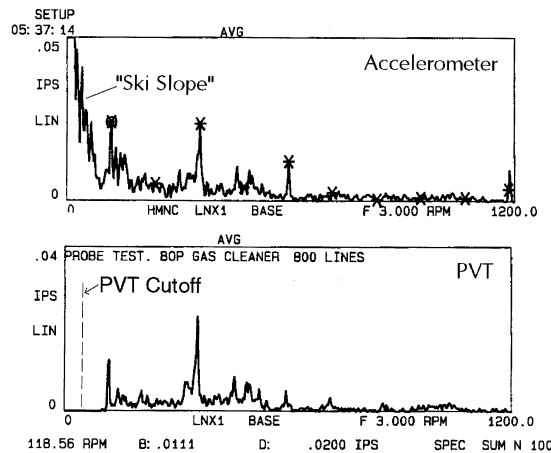


Figure 7. Spectral Plot Comparison Between an Accelerometer and a PiezoVelocity Transducer

### High Frequency Mechanical Noise Attenuation

In some applications, very high amplitude signals are present far above the frequencies of interest. Because accelerometers are inherently sensitive to high frequency vibrations, mechanical noise can excite machine structures and overload the internal amplifier<sup>5</sup>. Amplifier overload will produce intermodulation distortion and severely interfere with low frequency measurements. High frequency noise sources include worn steam seals, air leaks, pump cavitation, and impacts from reciprocating machinery. Intermodulation distortion due to nondiscrete noise (i.e. steam "hiss") is sometimes called "washover" distortion.

When an external integrator converts the signal to velocity, the distortion products are amplified along with the low frequency vibration data. These distortion products sometimes appear as a magnified "ski slope" and can easily mask real vibration data. False signals can exceed alarm conditions and trigger shutdown of healthy machinery. Internal integration attenuates these signals before they can corrupt and obscure low frequency data.

### High Frequency Electromagnetic Noise

High frequency electromagnetic noise can also interfere with a low frequency measurements. Accelerometer cables, installation routes, and termination enclosures may introduce false signals if they are not protected from electromagnetic radiation and transient sources. Electromagnetic noise sources include radio transmissions, radar equipment, and electrostatic discharges.

Accelerometer amplifiers can operate as AM radio detectors and convert radio signals to audio frequencies. Cables, depending upon length and location, will act as antennae and receive the radio transmissions. Once received, the amplifier can rectify the interference and insert low frequency artifacts into the band of interest. The low frequency amplification and high frequency filtering of the PVT eliminates these problems.

## VI. PVT Machinery Applications

Measurement errors caused by low frequency distortion are particularly acute in industrial applications such as paper machine monitoring. In these applications, low amplitude, low frequency signals are monitored in an environment surrounded by competing vibration sources and electromagnetic interference. PVTs are less susceptible to high frequency sources, electrical and mechanical, and therefore eliminate many errors. In addition, velocity amplification inside of the sensor reduces the relative amplitude of any signals picked up by the cable before they enter the receiving system. Distortion products that may occur are small in comparison with the amplified velocity signal.

### Paper Machine Roller Bearings

PVTs have distinct advantages in paper machine applications where low frequency noise reduction is a primary objective. Paper machine running speed faults are typically measured in the 100 to 1200 cpm band. PVTs prevent external integration noise from hiding looseness, misalignment and imbalance information. They also attenuate noise from steam seal leaks and electrostatic discharge.

In the bearing fault frequency bands below 120,000 cpm, PVTs compete with general purpose accelerometers and are far superior to electrodynamic pickups. Mount the PVT radially at the load zone of the bearing for greater sensitivity to high order fault harmonics.

PVTs are not recommended for use with HFD type measurements. Although the PVT will detect high frequency impact noise, accelerometers will provide earlier warning of bearing faults. Very slow speed rollers turning less than 100 cpm, should be monitored with 500 mV/g low frequency accelerometers.

### Cooling Towers

PVTs perform well in cooling tower applications. Many cooling tower fans operate in the 100 to 700 cpm region. The PVT provides strong velocity data on fan speed, blade pass, looseness, and alignment. Mount the PVT horizontally on the pinion of the gear box to increase sensitivity to gear mesh harmonics.

If fan speeds are less than 100 cpm, 500 mV/g low frequency accelerometers should be used. 100 mV/g accelerometers are generally used to monitor the motor end of the cooling tower.

### Vertical Pumps

Vertical pumps typically operate between 300 and 1800 cpm. PVTs provide earlier detection of imbalance and blade pass problems than standard accelerometers. The PVT eliminates mechanical overload from high frequency cavitation noise.

If monitoring HFD for incipient bearing faults or cavitation problems, 100 mV/g accelerometers are preferred. Use proximity probes to monitor relative movement of the pump shaft.

## VII. Conclusions

Piezoelectric velocity sensors exhibit many advantages over traditional electromagnetic pickups and accelerometers. Rugged, lightweight construction, and interchangeability with piezoelectric accelerometers, eases installation and increases reliability. PVTs provide unmatched signal fidelity over the frequency range of many industrial machinery applications. In addition, the unique response characteristics filter unwanted electromagnetic and mechanical noise.

PVTs are available in a variety of packages, including triaxial, handprobe, and bolt through configurations. The sensitivity and frequency response can be factory adjusted to customer specification. Amplifiers include such features as miswiring and electrostatic discharge protection circuitry. Intrinsically safe models with Factory Mutual, CSA, and EECS certification are also available. ■

## VIII. Reference

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5. Schloss, Fred, "Accelerometer Overload", *Sound and Vibration*, January 1989, p.12.

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TN18PVT-R2 9/93