UNDERSTANDING ACCELEROMETER VIBRATION SENSORS – PIEZOELECTRIC VS MEMS

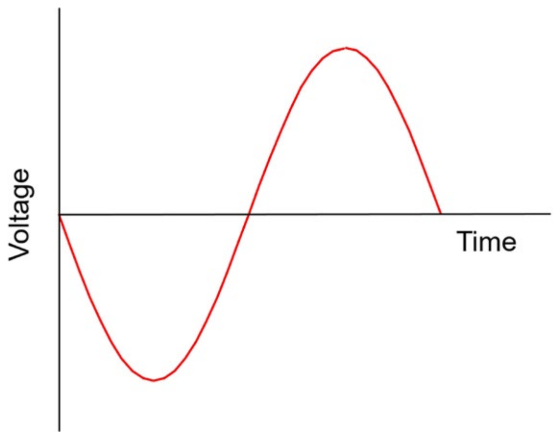
MACHINE HEALTH MONITORING SERIES PART 2 OF 3: UNDERSTANDING VIBRATION MONITORING

WHITE PAPER

In this second part of a white paper series (read Part 1 here) that explores vibration sensing in the context of machine health monitoring, learn about accelerometers, their dynamic nature, a few key specifications and an overview of how they work. Then, a comparison of the two major accelerometer sensing technologies, piezoelectric and MEMS, and the most important factors to consider when selecting a sensing technology is provided.

Accelerometer vibration sensors are the first link in the measurement chain of a vibration condition monitoring system. A predictive maintenance program based on vibration will not meet expectations if an accelerometer is incorrectly specified or installed. The plant operator should have some understanding of the machine being instrumented and what types of faults need to be detected. It is these fault-detection requirements that should drive the accelerometer specifications. Understanding accelerometers and their characteristics are critical to successfully implementing a predictive maintenance program.

Figure 1



Dynamic, time-based voltage waveform. Accelerometers output a dynamic voltage signal in response to vibration acceleration acting on the sensor.

ACCELEROMETERS ARE A DYNAMIC SENSOR

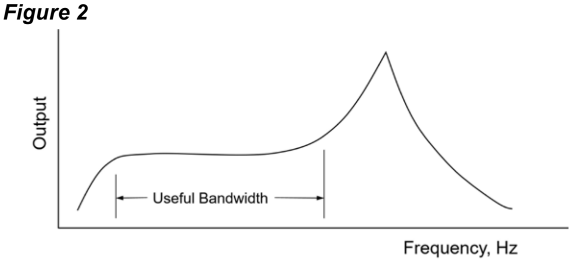
Accelerometers output a dynamic voltage signal in response to vibration acceleration acting on the sensor. For example, if one were to connect the output to an oscilloscope and then rapidly vibrate the accelerometer, the oscilloscope would display a dynamic, time-based voltage waveform. The waveform might be a simple sine wave, or, more likely, a complex waveform. This contrasts with more commonly known devices such as pressure sensors, where the output is a “processed” signal. Typical processed output signal formats are 4-20 mA and 0-5 Vdc.

These dynamic waveforms are critical to understanding accelerometers and their use in condition monitoring applications to detect and diagnose machine faults as they are replications of machine vibrations. The waveforms contain rich frequency spectral content that can be analyzed with a tool such as the Fast Fourier Transform (FFT), which allows the diagnosis of machine faults.

FREQUENCY RESPONSE

Closely related to the dynamic nature of an accelerometer's output is the concept of the accelerometer's frequency response. The frequency response is a way for the sensor manufacturer to specify the accelerometer's useable bandwidth. An accelerometer will have only a limited ability to sense a range of vibration frequencies. Beyond those limits, the sensor's ability to sense vibration will degrade and be less accurate. Knowing this bandwidth helps users select the most appropriate accelerometer to meet the needs of their condition monitoring requirements. A wider bandwidth allows the user to diagnose a larger range of machine faults, for example, while a narrower bandwidth device may be less expensive but adequately meet the needs of the condition monitoring program.

Figure 2



Graphical representation of frequency response. Frequency response is a way for the sensor manufacturer to specify the accelerometer's useable bandwidth.

Frequency response is a specification of the accelerometer's output over a range of frequencies and can be expressed graphically. The output in this case is the sensor's "sensitivity", where sensitivity is defined as the ratio of voltage output (in mV units) to input acceleration (in g units). Sensitivity is expressed in units of mV/g. In a practical sense, this plot could be generated by testing the accelerometer on a calibrated shaker, where the acceleration amplitude and frequency can be accurately controlled. Points on the plot are generated by moving from one frequency point to another until the desired frequency range is covered.

Commonly, the frequency response specification is stated as an amplitude tolerance over a frequency range, such as:

±10% from 1 Hz to 9 kHz

±3 dB from 0.5 Hz to 14 kHz

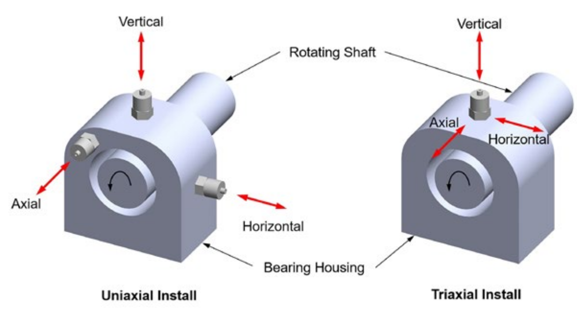
This means that if one were to test this accelerometer on a shaker, its output would fall within a ±10% tolerance band over a frequency range from 1 Hz to 9 kHz, and within a ±3 dB tolerance band (approximately ±30%) from 0.5 Hz to 14 kHz. Note that in both these cases, the tolerance band is relative to a defined reference value.

ACCELEROMETERS ARE DIRECTIONAL

Accelerometers are not sensitive in all directions at once, in contrast to a pressure sensor, for example. Accelerometers are sensitive only in a defined directional axis and the manufacturer strives to make sure the sensor is insensitive in all other directions. The reason for this directional sensitivity is so the user can make sense of the data from the sensor and have confidence the data is from the defined direction only. Since the data being analyzed can only come from the direction (or directions) that the sensor is designed for, conclusions can be made about the vibration from the machine and what that might indicate about its health.

Accelerometers can be either single axis (uniaxial) or 3-axis (triaxial). To detect as wide a range of machine faults as possible, a rotating machine should be instrumented for vibration at the bearing locations in three directions: vertical, horizontal and axial. This can be done with either three uniaxial accelerometers or – more cost-effectively - a single triaxial accelerometer. The tradeoff for using a triaxial accelerometer is that the horizontal and axial direction vibrations at the sensors may not be as representative as being truly monitored in those locations by uniaxial accelerometers.

Figure 3



Accelerometers are sensitive only in a defined directional axis and the manufacturer strives to make sure the sensor is insensitive in all other directions. Using a single triaxial accelerometer to provide simultaneous measurements in three directions is more cost effective than using three uniaxial devices.

Along with direction, accelerometers have polarity. This means, depending on the direction of the input acceleration, the accelerometer may output a positive going voltage signal, or a negative going signal. This convention will be defined by the sensor's manufacturer. This is key for the user to make sense of the data. To diagnose some machine faults, the analyst needs to know specifically which direction (up or down, for example) the acceleration is coming from.

HOW ACCELEROMETERS WORK

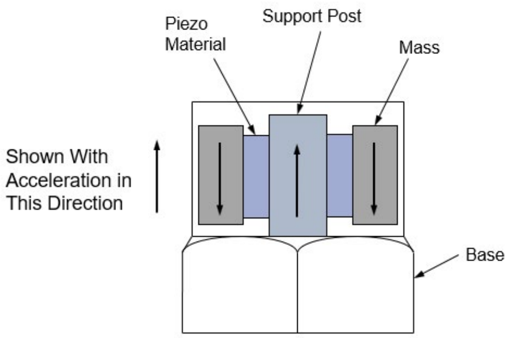
There are two sensing technologies used in accelerometers for vibration monitoring: piezoelectric-based and MEMS-based. Understanding how each works will give some insight to the advantages and disadvantages of each.

Piezoelectric

Piezoelectric sensing technology is the most mature of the two technologies, with its origins going back nearly a century. Ruggedized, industrial piezoelectric "shear-mode" type accelerometers have become a standard in condition monitoring applications. They are robust, cost effective and have excellent performance characteristics.

In the most common sensing configuration found in the market today, an annular ring of piezoelectric material is mounted on a post set on the mounting base of the accelerometer. A "seismic" mass is then compressed around the ring of piezoelectric material. As the accelerometer's base is accelerated upward, for example, the seismic mass resists that motion momentarily, due to its inertia. This creates a "shear" force through the piezoelectric material. Due to its piezoelectric nature, the material will output an electrical signal (actually an electric charge) in response to that force. As the accelerometer's base is then accelerated downward, this action is reversed, and the piezoelectric material outputs a signal in response, but in the opposite polarity (negative going instead of positive going, for example). Since the electrical signal is very high impedance, an impedance-converting electronic circuit, mounted inside the sensor's casing, is used to condition the signal before being output downstream.

Figure 4



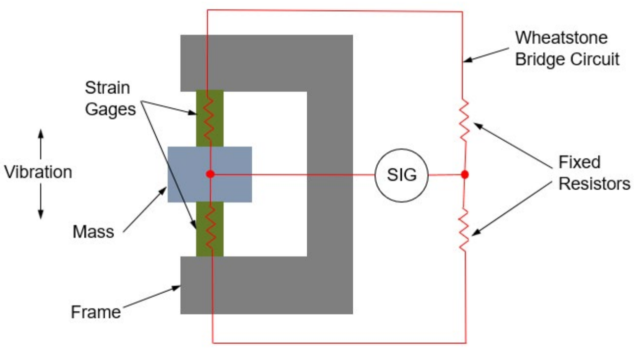
Ruggedized, industrial piezoelectric "shear-mode" type accelerometers have become a standard in condition monitoring applications as they are robust, cost effective and have excellent performance characteristics.

MEMS

MEMS (Micro-Electro-Mechanical System) sensing technology is relatively new, although the origins of the technology go back to the 1960s. MEMS sensors have proliferated in recent years with the advent of the Internet of Things (IoT) and wireless sensors. MEMS-based accelerometers have only recently made inroads into condition monitoring due to improved ruggedness and increased bandwidth.

MEMS technology leverages manufacturing techniques learned from integrated circuit production. The same silicon wafers used to make ICs are used to make tiny mechanical structures that respond to forces due to acceleration. These structures are either designed to be a "capacitive" or "ohmic" device. If ohmic, for example, a silicon structure would be built that involved at least two strain gages as part of a Wheatstone Bridge. As the structure is exposed to vibration acceleration, the seismic mass alternately compresses and stretches the strain gages, alternately unbalancing the bridge. A voltage signal directly proportional to the vibration is then created across the bridge. An impedance-converting electronic circuit is not needed.

Figure 5



MEMS-based accelerometers have only recently made inroads into condition monitoring, due to improved ruggedness and an increase in bandwidth. MEMS technology leverages manufacturing techniques learned from integrated circuit production.

FACTORS TO CONSIDER WHEN COMPARING PIEZOELECTRIC VS. MEMS ACCELEROMETER TECHNOLOGY

Piezoelectric-based sensors and MEMS-based sensors each have their own unique characteristics and are not intended to be interchangeable in every application. Whether a user utilizes one technology over another should be based on the requirements of their predictive maintenance program. The overriding requirement should be the range of machine condition faults that can be detected. However, other important criteria also come in to play, such as power limitations, temperature extremes, available installation space, and, of course, economic considerations. All these factors will help guide the plant operator to use one technology over the other.

The bandwidth of the accelerometer is the single most important factor determining its ability to detect early stage bearing faults (so-called stage 1 or stage 2 faults). Wider accelerometer bandwidths may allow the earliest potential bearing-fault detection. Piezoelectric-based sensors have the advantage here. However, if such early detection is not required, MEMS-based technology has more than adequate bandwidth to detect later stage (stage 3) bearing failures. In fact, if a user is only interested in narrow band machine faults such as unbalance and misalignment, MEMS-based technology is the ideal choice.

Figure 7

Characteristic	Piezoelectric	MEMS
Bandwidth	15 kHz	8 kHz
Power Requirement	2 mA	200 µA
Output	Analog	Digital
Noise	10 µg/√Hz	200 µg/√Hz
Temperature Maximum	Up to 120°C	Up to 105°C
Cost	$$	$

This table summarizes the six most important characteristics to consider when comparing Piezoelectric vs. MEMS accelerometer technology.

MEMS technology has the additional benefit of low power requirements, making it a good fit for battery-powered wireless IIoT (Industrial Internet of Things) applications. Additional digital circuitry can be added on to the silicon chip, right alongside the accelerometer sensing structure, making the sensor output digital. No additional digitization circuitry needs to be added later.

Piezoelectric-based technology is better suited for higher temperature extremes. MEMS technology is rarely rated beyond 105°C. Piezoelectric technology, however, is commonly rated to 120°C, and sometimes to 150°C for special cases.

Piezoelectric-based technology has the advantage of a lower noise floor, generally specified on the order of 10 µg/√Hz. MEMS-based technology generally has a noise floor on the order of 200 µg/√Hz. This higher noise floor can make early bearing fault detection more challenging since the vibration spectral component amplitudes of early bearing faults can be quite low.

When implementing vibration condition monitoring as part of a predictive maintenance program, it is important that the accelerometer vibration sensors be selected to meet the requirements of the program. Goals of the predictive maintenance program need to be defined and should drive the specifications of the sensors. The critical specifications of accelerometers need to be understood so that the proper selection can be made. Frequency response of the accelerometer is the most critical specification, as a wider bandwidth will allow a wider range of machine faults to be diagnosed.

Whether to use a piezoelectric-based accelerometer or a MEMS-based design will also depend on the goals of the predictive maintenance program. Understanding the advantages and disadvantages of each technology will guide the user to selecting the appropriate sensor for their condition monitoring requirements. Neither technology has an advantage over the other in all cases, as there are appropriate applications for each.

Coming Up in Part 3

With knowledge of vibration and vibration sensors in-hand, how can machine faults be detected? The simple narrow band case of machine rotor unbalance will be explored. In the more complex, wide band case, rolling element bearing faults will also be explored. In both cases, it will be illustrated how machine learning and artificial intelligence can be implemented to automate the task of detecting machine faults.

