An Introduction to MEMS Vibration Monitoring

By Mark Looney

Introduction

Inertial MEMS sensors play a significant role in the massive expansion of today's personal electronic devices. Their small size, low power, ease of integration, high level of functionality, and superb performance encourage and enable innovation in gadgets such as smartphones, gaming controllers, activity trackers, and digital picture frames. In addition, inertial MEMS sensors have substantially improved reliability and reduced cost in automotive safety systems, allowing them to be deployed in most automobiles.

The continuous advancement in functional integration and performance has also helped MEMS accelerometers and gyroscopes find their way into many different industrial systems. Some of these applications offer lower-cost alternatives to present products and services, while others are integrating inertial sensing for the very first time. Vibration monitoring is emerging as an application that has both types of users. Traditional instruments that monitor machine health for maintenance and safety often use piezoelectric technology. High-speed automation equipment monitors vibration to trigger feedback control of lubrication, speed, or belt tension—or to shut down equipment for quick attention from maintenance staff.

Although piezoelectric devices have a mature user base, MEMS accelerometers offer easy integration and reduced cost to an emerging group of new users. In addition, their advanced functional integration allows devices such as the ADIS16229 digital MEMS vibration sensor with embedded RF transceiver to provide a complete solution including signal processing and communications. This type of programmable device can wake itself up periodically, capture time-domain vibration data, perform a fast Fourier transform (FFT) on the data record, apply user-configurable spectral analysis on the FFT result, offer simple pass/fail results over an efficient wireless transmission, provide access to data and results, and then go back to sleep. New adopters of vibration sensing are finding that quick deployment and the reasonable cost of ownership are good reasons to evaluate fully integrated MEMS devices.

Vibration Monitoring Applications

When using vibration to observe machine health, the objective is to correlate observable vibration with typical wear-out mechanisms, such as bearings, gears, chains, belts, brushes, shafts, coils, and valves. In a typical machine, at least one these mechanisms requires regular maintenance. Figure 1 shows three examples of the vibration vs. time relationship for a normal wear-out mechanism. Although it takes time and experience to develop this type of relationship, a well-correlated vibration signature can be a cost-saving alternative to regular maintenance that follows short cycle times. Using actual observations, such as vibration, provides an opportunity to take quick action when warning conditions are detected (red curve), while avoiding premature maintenance on machines that have more life remaining (blue and green curves).

Figure 1 also shows two alarm settings (warning, critical) and three stages of the machine's maintenance cycle (early, middle, end). The warning level defines the maximum vibration during normal operation, where the observed vibration contains no indication of potential hazard for the machine or support staff. When in the normal range, some instruments can support infrequent vibration measurements. The critical level indicates that the asset is at risk of severe damage, creating unsafe conditions for support staff or the environment. Obviously, machine operators want to avoid operation at this level, and typically take the machine off line. When the vibration is above the warning level, but below the critical level, the machine can still perform its task, but it should be observed more frequently and may likely require additional maintenance.

Sometimes, these three zones of operation (normal, warning, critical) can correlate to the three stages of a machine's maintenance cycle: early life, midlife, and end-of-life, in which case they may influence the vibration monitoring strategy. For example, during early life, an instrument might only require daily, weekly, or monthly observation of key vibration attributes. As it moves into midlife, this might change to hourly observation, and as it approaches end-of-life, vibration monitoring might occur even more often, especially in cases where people or the asset are at risk. At this stage, machines that monitor vibration using portable equipment will accumulate recurring costs that might become prohibitive when compared to the cost of maintenance. While major assets can justify special attention, many other instruments cannot bear the recurring cost. To complement manual measurements, embedded MEMS-based sensors provide a more cost-effective approach for equipment that requires real-time vibration data.

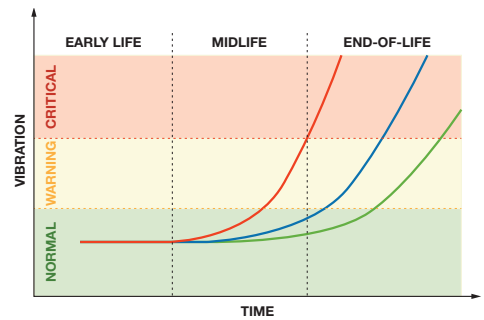

Figure 1. Example vibration vs. time.

Nature of Vibration

Vibration is a repetitive mechanical motion. A number of attributes are important for developing a vibration-sensing instrument. First, an oscillating motion often has both linear and rotational components. Most vibration-sensing relationships tend to focus on the magnitude of the oscillation, not on absolute position tracking, so linear sensors such as MEMS accelerometers are sufficient for capturing motion information. When the motion is mostly linear, understanding the direction can be important, especially when using single-axis sensors. Conversely, a 3-axis sensor can offer more mounting flexibility, as the orthogonal orientation enables pickup on one or more axes regardless of the vibration direction.

Since vibration is periodic, spectral analysis offers a convenient way to characterize the vibration profile (the relationship between vibration magnitude and frequency). The profile shown in Figure 2 has both broadband and narrow-band components, with primary vibration at ~1350 Hz, four harmonics, and some low-level wideband content. Every piece of moving equipment will have its own vibration profile, with the narrow-band response often representing the natural frequencies of the equipment.

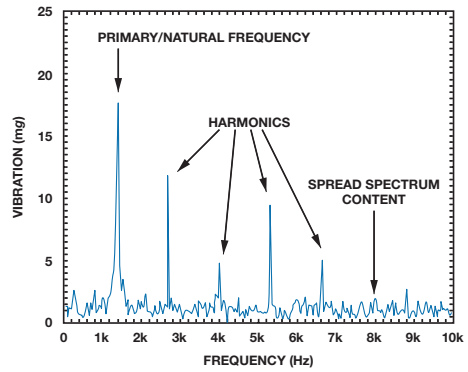

Figure 2. Example vibration profile, natural frequency ~1350 Hz.

Signal Processing

The sensor selection and signal-processing architecture depends on the application's objectives. As an example, the signal chain shown in Figure 3 continuously monitors a specific frequency band, providing warning and critical lights on a nearby control panel. The manufacturer's insight into the mechanical design aids with the band-pass filter design, specifically with the start frequency, stop frequency, and pass-band roll-off rates. Rotation speed, natural frequencies of the mechanical structure, and fault-specific vibration behaviors can all influence the band-pass filter. While this type of approach is simple, vibration monitoring requirements can change as historical data from a particular machine becomes available. Changes in monitoring requirements can lead to changes in the filter structure, which can present a recurring engineering cost. Developers can trade complexity for flexibility by digitizing the sensor response, implementing key signal processing functions such as filter, rms computation, and level detectors, and leveraging auxiliary I/O outputs to control indicator lights or provide a numerical output.

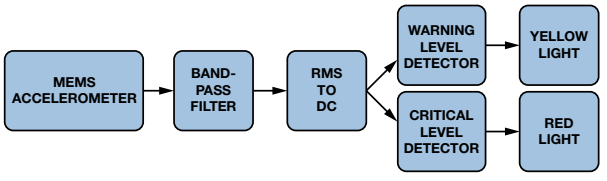

Figure 3. Time-domain vibration signal chain example.

Figure 4 shows a signal chain for the ADIS16228, which uses a digital triaxial vibration sensor with FFT analysis and storage to monitor the spectral content of equipment vibration.

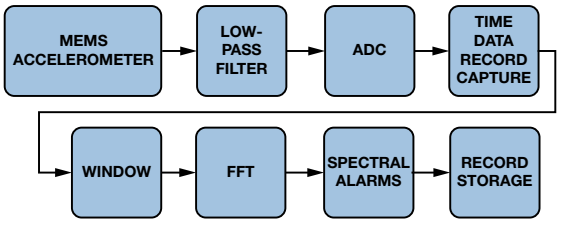

Figure 4. ADIS16228 signal chain for spectral vibration analysis.

Core Sensor

The core sensor for either approach can be a MEMS accelerometer. The most important attributes for selecting a core sensor will be the number of axes, package/assembly requirements, electrical interface (analog/digital), frequency response (bandwidth), measurement range, noise, and linearity. While many triaxial MEMS accelerometers support direct connection with most embedded processors, capturing the best available level of performance might require single- or dual-axis solutions that have analog outputs. For example, the ADXL001 high-performance wideband *i*MEMS® accelerometer leverages its 22-kHz resonance to provide one of the widest available bandwidths, but it is only available as a single-axis, analog-output device. Analog outputs can enable a quick interface in systems that have an available analog-to-digital channel, but the present trend of development seems to favor those sensors that have digital interfaces.

The core sensor's frequency response and measurement range determine the maximum vibration frequency and amplitude that it can support before saturating the output. Saturation degrades the spectral response, creating spurious content that can cause false alarms, even when the saturation frequency does not interfere with a frequency of interest. The measurement range and frequency response are related by

$$A_{p\text{-}p} = D_{p\text{-}p} \times \omega^2$$

where D is the physical displacement, ω is the vibration frequency, and A is the acceleration.

While the frequency response and measurement range place upper boundaries on the sensor's response, its noise and linearity place limits on the resolution. The noise will establish the lower limit of the vibration that will cause a response in the output, while the linearity will determine how much false harmonic content is generated by a vibration signal.

Analog Filter

The analog filter limits the signal content to one Nyquist zone, which represents one half of the sample rate in the example system. Even when the filter cut-off frequency is within the Nyquist zone, it is impossible to have infinite rejection of higher-frequency components, which can still fold back into the pass band. For a system monitoring only the first Nyquist zone, this fold-back behavior can create false failures and distort the view of the vibration content at a particular frequency.

Windowing

Time-coherent sampling is often not practical in vibration-sensing applications, as nonzero sample values at the start and end of the time record result in large spectral leakage, which can degrade the FFT resolution. Applying a window function before calculating the FFT can help manage the spectral leakage. The best window function is dependent on the actual signal, but in general, the trade-offs include process loss, spectral leakage, lobe location, and lobe levels.

Fast Fourier Transform (FFT)

The FFT is an efficient algorithm for analyzing discrete time data. The process transforms a time record into a discrete spectral record, where each sample represents a discrete frequency segment of the Nyquist zone. The total number of output samples is equal to the number of samples in the original time record, which in most cases represents a number in the binomial series (1, 2, 4, 8 …). Spectral data has both magnitude and phase information, which can be represented in either rectangular or polar form. When in rectangular form, one half of the FFT bins contain magnitude information, while the other half contains phase information. When in polar form, one half of the FFT bins contain the real result, while the other half contains the imaginary result.

In some cases, both magnitude and phase information are helpful, but the magnitude/frequency relationship often contains enough information for detecting key changes. For devices that offer only magnitude results, the number of FFT bins is equal to one half of the samples in the original time-domain record. The FFT bin width equals the sample rate divided by the total number of records. In a way, each FFT bin is like an individual band-pass filter in the time domain. Figure 5 provides an example of an actual MEMS vibration sensor, which samples at 20480 samples per second (SPS) and starts with 512-point records. In this case, the sensor only provides the magnitude information, so the total number of bins is 256 and the bin width is equal to 40 Hz (20480/512).

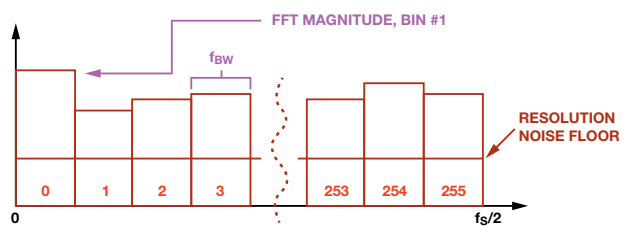

Figure 5. ADIS16228 FFT output.

The bin width is important because it establishes the frequency resolution as the frequency shift from one bin to an adjacent bin, and because it determines the total noise the bin will contain. The total noise (rms) is equal to the product of the noise density (~240 μg/√Hz) and the square root of the bin width (√40 Hz), or ~1.5 mg rms. For low-frequency applications, where noise tends to have the most influence on resolving vibration, a decimation filter prior to the FFT process can help improve the frequency and magnitude resolution without requiring a change in the ADC's sample frequency. Decimating the 20480 SPS sample rate by a factor of 256 enhances the frequency resolution by a factor of 256 while reducing the noise by a factor of 16.

Spectral Alarms

One of the key advantages of using an FFT is that it enables simple application of spectral alarms. Figure 6 provides an example that includes five independent spectral alarms that monitor the natural frequency in the machine (#1), its harmonics (#2, #3, and #4), and the wideband content (#5). The warning and critical levels correspond to the levels in the machine-health vibration vs. time profile. The start and stop frequencies complete the process variable definition represented by this relationship. When using an embedded processor, the spectral alarm definition variables (start/stop frequencies, warning/critical alarm levels) can be in configurable register locations that use digital codes for configuration. Using the same scale factors and bin numbering scheme can greatly simplify this process.

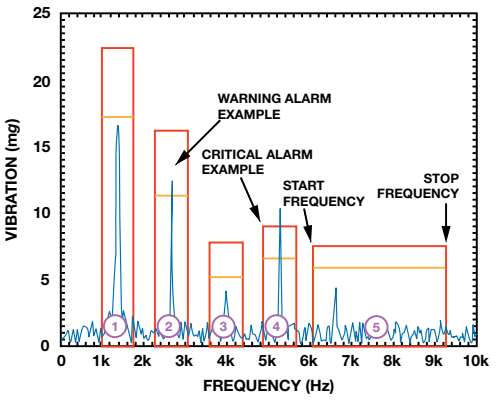

Figure 6. Example FFT with spectral alarms.

Record Management

One of the key functions associated with process variable relationships is record management. Storing FFT records from different stages of each machine's lifetime enables analysis of a variety of behaviors that may lead to a wear-out curve that contributes to maintenance and safety planning. In addition to compiling historical vibration data, some will find value in capturing condition data associated with parameters such as power supply, temperature, date, time, sample rate, alarm settings, and filtering.

Interface

The interface depends on the existing infrastructure in a particular plant. In some cases, industrial cable-ready communication standards such as Ethernet or RS-485 are readily available, so the interface between a smart sensor and the communication system might be an embedded processor. In other cases, that same embedded processor might be used to interface the smart sensor with an existing wireless protocol, such as Wi-Fi, ZigBee, or a system-specific standard. Some smart sensors, such as the ADIS16000 wireless gateway node for remote sensors and the ADIS16229, come with a ready-to-deploy wireless interface that is available through common embedded interfaces such as SPI or I^2C.

Conclusion

Inertial MEMS technology is ushering in a new era of vibration monitoring and is enabling a wider user base for this type of instrumentation. Performance, packaging, and familiarity may contribute to continued use of piezoelectric technology, but vibration monitoring is clearly growing and evolving. Through functional integration and ease of adoption, MEMS devices are gaining increasing attention in new vibration monitoring applications. Convenience, through advanced signal processing at the point of sensing, reduces the monitoring burden to a simple state (normal, warning, critical) for most situations. In addition, remote data access through convenient communication channels is creating new applications for vibration monitoring instruments. Future advances in key performance metrics (noise, bandwidth, and dynamic range) and the high level of functional integration will help this trend to continue in the near future.

References

Circuit Note CN0303. *MEMS-Based Vibration Analyzer with Frequency Response Compensation.*

Scannell, Bob. MS-2507. *Enabling Continuous and Reliable Process Monitoring with Wireless Vibration Sensors.*

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