

Application Note

ADE Technologies Standard for AEM Testing

In the analysis of rotating machinery such as spindles and hard-disk-drive (HDD) motors, it is considered essential to quantify both the nonperiodic and periodic components of the runout signal. The nonperiodic motion is usually referred to as asynchronous error motion (AEM) or nonrepeatable runout (NRRO). The periodic component, typically called synchronous error motion (SEM) or repeatable runout (RRO), consists of all parts of the signal that occur at N times the rotational rate, where N is a positive integer. The nonperiodic signal consists of everything else. These measurements are so well known that both IDEMA (the trade association for the data storage industry) and ANSI (American National Standards Institute) have specifications (T17-91 and B89.3.4.M, respectively) describing how to perform the measurements.

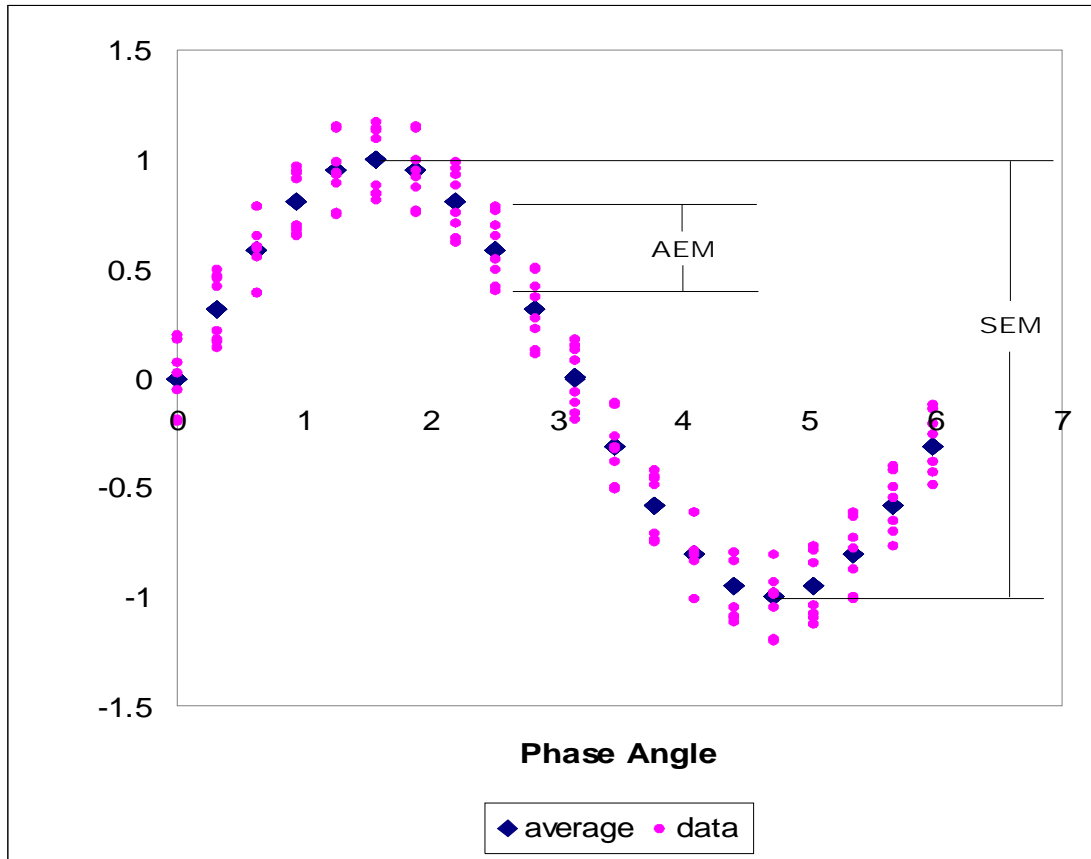
To illustrate the causes of AEM and SEM, consider the radial runout of a ball-bearing spindle. The runout signal will contain certain components that are periodic with respect to the spindle's rotation rate. These signals would include a component at the rotation rate caused by imperfect centering, as well as frequency components at integral numbers of the rotation rate caused by imperfect circularity. Nonperiodic components will also be present. The rate at which the balls in the ball bearing precess around the shaft commonly causes an asynchronous signal as do noncircularity of the balls and vibrations of the spindle.

IDEMA spec T17-91 teaches that data are collected by synchronously sampling the radial or axial position of the rotating part at a rate many times its rotational rate, over some number of revolutions. Because the sampling is synchronous with the rotational rate, the samples repetitively occur at fixed spots on the sampled part. So, if the part were sampled N times per revolution, there would be N spots at equal angular spacing around the part that are sampled once per revolution.

The specification also teaches a calculation method. The peak-to-peak variation in the reading obtained at each spot over the sampled revolutions represents the asynchronous runout at that spot. The average of all readings at each spot represents the synchronous position at that spot. The peak-to-peak value of all synchronous positions is used to calculate the synchronous error motion. The largest of the asynchronous error motions as measured at each spot, is often considered to be the asynchronous error motion of the unit under test.

The graph below illustrates these calculations. The curve represents several revolutions of a spindle sampled 20 times per revolution with each revolution plotted on top of the other. The synchronous signal is the average of the readings at each sampled point. The AEM at each sampled point is the peak-to-peak value of the readings taken at that point, and the SEM is the peak-to-peak value of the synchronous signal.

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This method of synchronous data sampling has several disadvantages. First, different angular rotation rates, or different numbers of samples per revolution require different sample rates. This requirement increases the complexity of the equipment used to make the samples, which therefore has an adverse affect on its price. In addition, it also increases the complexity of digitally filtering the sampled data.

Another problem is the generation of the trigger signals used to take the synchronous samples. It is most advantageous to have the signals generated by the rotating part itself such as could be accomplished by using a rotary encoder connected to the rotating part. However, it is often impossible to use this technique, and instead, the trigger signals are commonly generated by an electronic circuit.

Such circuits are fed a once-per-revolution pulse, and from this, generate N pulses per revolution by means of some frequency multiplication technique such as a phase-locked loop (PLL) frequency multiplier. PLLs, by necessity, have a loop filter that, in this case, samples the phase once per revolution. Due to the phase shift of the filter, the loop always lags as it tries to follow any r.p.m change in the motor. PLLs can also have phase jitter. The PLL circuitry combined with the necessity of variable-rate sampling increase the complexity, inaccuracy, and price of the system.

A more subtle, but even larger problem with the synchronous sampling method is that it can cause the system to sample at higher or lower than optimal rates—the former can both degrade the signal-to-noise ratio of the system while increasing system cost and complexity, and the latter can cause frequency aliasing* of signals. This problem is best explained by an example from the disk-drive-motor industry.

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Consider a 7200 r.p.m. (120 r.p.s) HDD motor. Its main synchronous runout signal occurs at 120 Hz, but in the interest of capturing the harmonics of the signal, a bandwidth of 1.2 kHz (10 X 120) would seem reasonable. The principal AEM component of interest typically appears at about 50% to 60% of the r.p.s., but other frequencies of interest including vibration can have spectral components at several times the r.p.s.. Hear again, a minimum bandwidth of 1 kHz or so seems appropriate. It is not surprising then to note that the HDD industry often uses a bandwidth of 2 kHz to 5 kHz when analyzing such motors.

Suppose we were to sample the signal from this motor at 32 times per revolution; the sample rate would be 3.84 kHz. We know from the Nyquist sampling theorem* that signals 0.5 times or higher than the sample rate will alias. Therefore, in our example, signals higher than 1.92 kHz will alias down to lower frequencies creating false outputs. Given that our filter is commonly set at 2 to 5 kHz, and given that may not be a steep, many-pole filter, aliasing is likely.

Conversely, let's now imagine that we want to sample our motor signal at 512 times per revolution. In this case our sample rate will be 61.44 kHz, which is much higher than it needs to be. In fact, sampling at more than about 5 times the required bandwidth is of little value—remember that the aforementioned low-pass filter that is set at 2 to 5 kHz severely attenuates all frequencies above its pass band. In addition, oversampling, in this case, leads to a distinctly undesirable side effect—excess noise and price.

The excess noise arises from the need to use high-speed A/D converters. For example, commonly available 16-bit data acquisition cards that can sample up to 200 kHz to 350 kHz typically have single-conversion noise of 2 to 4 counts. Typical noise levels for 16-bit data-acquisition cards that can sample at 1 MHz are commonly 7 to 14 counts. In addition, cost rises steeply with data-acquisition speed. The requirement for such high sample rates can be readily seen by considering a high-speed HDD motor spinning at an r.p.m. of 14,000, sampled at 1024 sectors per revolution, and inspected by three gaging channels. In this case, the sample rate is $14,000/60 * 1024 * 3 = 717 \text{ k samples/second}$.

ADE has solved these problems by using a patented asynchronous sampling technique. In this method, the motor signal is sampled at a fixed rate. A single high-frequency clock both measures the time at which the once-per-rev trigger pulses occur and also triggers the A/D card. Therefore, the phase angle of every data point is accurately known, and with appropriate signal processing, the AEM and SEM components of the signal are readily calculated. This technique eliminates the phase lag associated with the PLL approach because the phase information is precisely updated every revolution.

Because of the fixed sample rate, it now becomes simple to implement a high-quality zero-phase digital filter, which we have done. Unlike previous schemes, the frequency of the analog filter is now set so it can function as a good anti-aliasing filter, and the digital filter is used to set the desired system bandwidth. The fact that the digital filter has zero phase shift means its waveform fidelity is excellent, and the fact that the filter is placed after the A/D converter in the signal chain means that it has the ability to filter not only the analog system noise but also A/D noise.

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The ADE system uses an additional noise-lowering technique: because the typical total runout signal encountered when measuring motors or spindles is quite a bit less than the total range of the capacitance gage used to measure it, a prescaling circuit, upon calculation of the ratio of the runout range to the gage range, can pre-amplify signals before they are presented to the A/D converter. This technique can greatly improve the effective resolution of the converter. For example, if one can prescale by four times, the effective converter resolution is increased by 2 bits.

**According to the Nyquist sampling theorem, one must sample any signal at a rate greater than twice its maximum frequency component to avoid aliasing. The Nyquist frequency is one half the sampling frequency, and any signals with frequency components above the Nyquist frequency will alias between DC and the Nyquist frequency. The alias frequency is the absolute value of the difference between the frequency of the input signal and the closest integer multiple of the sampling rate. For example, let's say that the sampling frequency is 1 kHz and the signal has frequencies at 400, 800, and 1700 Hz. The signal at 400 Hz will be sampled correctly, but the signal at 800 Hz will alias to $1 \text{ kHz} - 800 \text{ Hz} = 200 \text{ Hz}$, and the signal at 1700 Hz will alias to $1 \text{ kHz} * 2 - 1700 \text{ Hz} = 300 \text{ Hz}$.*

Interestingly enough, Harry Nyquist's 1928 paper, "Certain Topics in Telegraph Transmission Theory", published while he worked for Bell Labs, established the sampling theory long before the advent of modern digital electronics.

