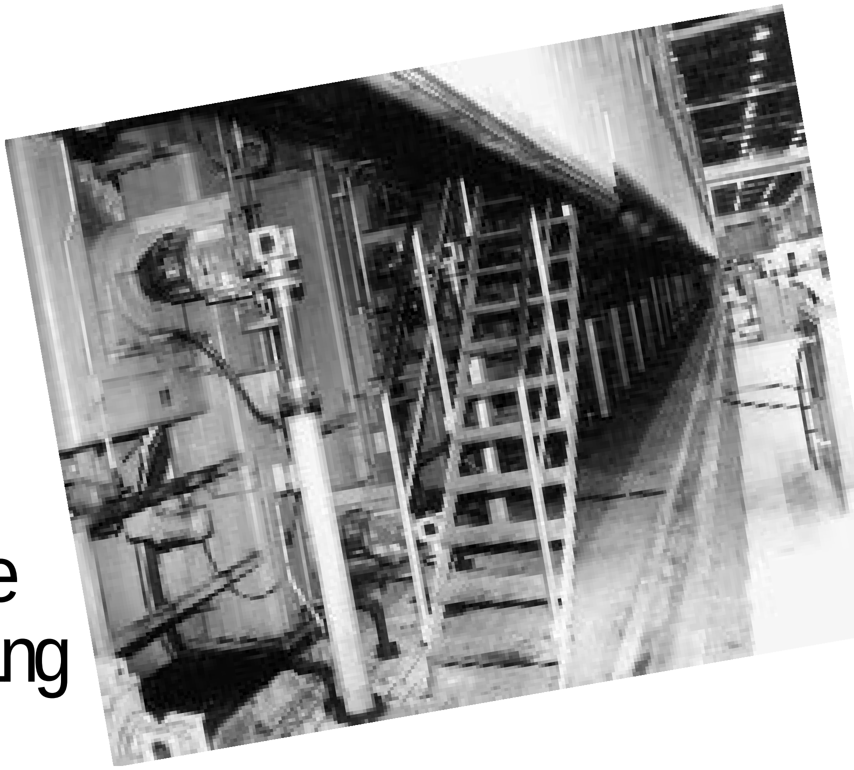
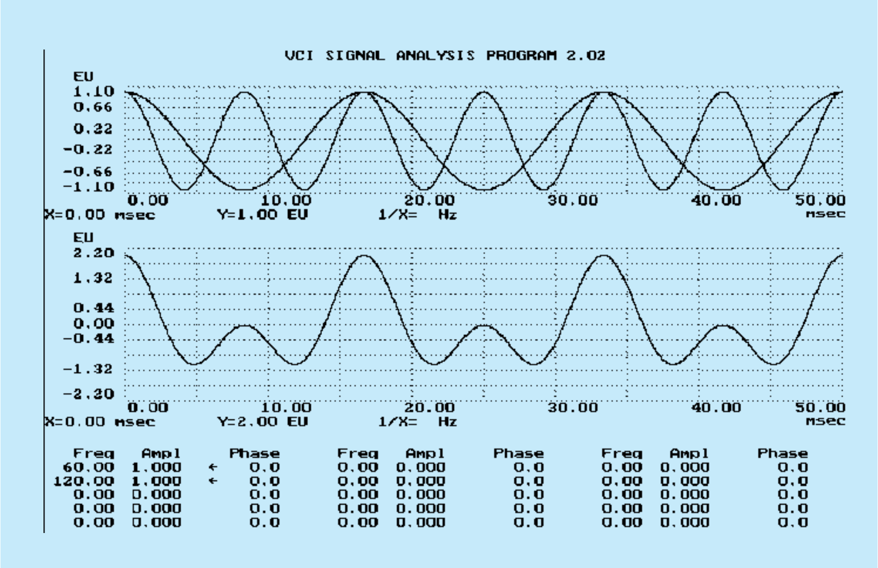


# Is Phase Missing from Your Diagnostic Toolbox?

*by James I. Taylor, Vibration Consultants, Inc.*

We all know that dynamic signal analyzers provide some great frequency-domain tools for diagnosing rotating machinery problems. However, in a rush to FFT ourselves into the frequency domain, it's too easy to overlook a powerful time-domain tool. Phase can be a real lifesaver when you're trying to pull apart the harmonically rich vibration spectra that rotating machinery generate. By combining insights from both domains, you'll increase your chances of reaching the right diagnostic conclusions.



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120.00   1.000   ←    0.0      0.00   0.000      0.0      0.00   0.000      0.0
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  0.00   0.000        0.0      0.00   0.000      0.0      0.00   0.000      0.0
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**Figure 1**
A single frequency with an in-phase harmonic produces the combined waveform shown in the lower trace.

It helps to remember three key points:

- A frequency component identifies the basic problem.
- The amplitudes of this component and its harmonics indicate the severity of the problem.
- Phase relationships help you distinguish between looseness and eccentricity.

In other words, while a vibration spectrum can reveal much about what's going on inside a machine, the frequency domain does not yield all the answers. The time domain is the only place we can identify peak and peak-to-peak amplitudes of each cycle, phase relationships between signals, and the presence of such distinctive characteristics as truncated waveforms, pulses, and modulation.

One of the trickiest issues in machinery diagnostics is the fact that two very different waveforms can yield similar spectra since their phase relationships are ignored when viewed in the frequency domain. That's why careful examination of phase relationships between fundamentals and their harmonics in the time domain can prevent a misdiagnosis of a rotating machinery problem. And such a misdiagnosis can be very expensive when you factor in lost production, labor charges, and the unnecessary costs of reworking or replacing machine parts that may not have been defective in the first place.

## Are you getting the whole story?

Rotating machinery problems that generate discrete, sinusoidal frequency components are usually the easiest to diagnose. For example, a pure imbalance problem in a rotating device generates a single frequency component at the rotor speed with little or no harmonic content. Similarly, gearmesh components are typically sinusoidal and appear at a frequency equal to the number of gear teeth multiplied by the speed of the gear.

Most rotating machinery problems, however, generate harmonically rich waveforms. The number of harmonics and their relative amplitude is often proportional to the severity of the problem.

Rotor looseness (which grows worse as bearings become worn) is a good example. A loose rotor that isn't restrained by belts or other devices will generate harmonics of the rotor speed. The number and amplitude of these harmonics increases as the bearing clearance increases.

Other problems generate harmonically rich waveforms with modulation. These require careful study in both frequency and time domains. Typical problems in this category include bearing defects, some forms of looseness, and many types of gear problems, including eccentricity and mesh troubles.

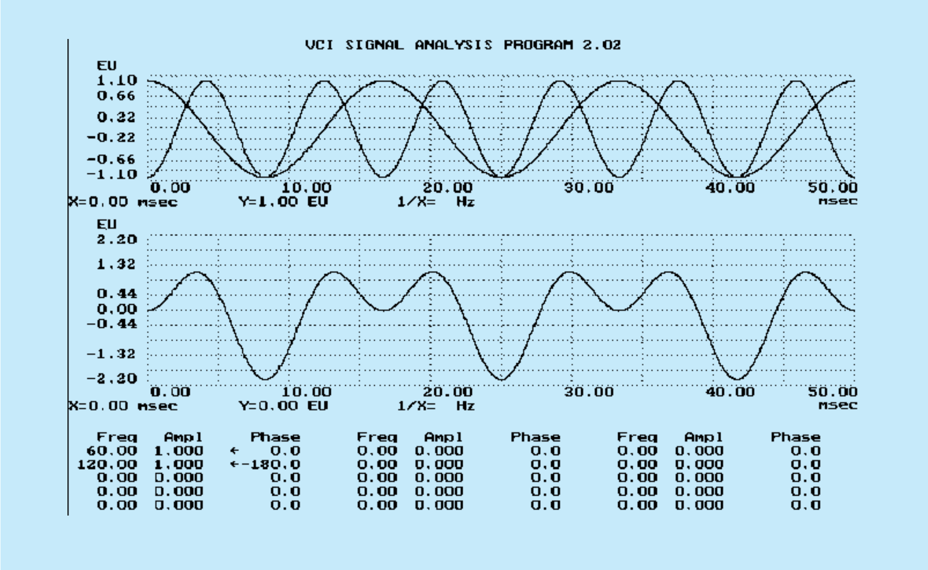

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**Figure 2**
This combined waveform (lower trace), the result of combining a single frequency with a harmonic that is 180° out of phase, will produce the same frequency domain display as the waveform from figure 1 — even though the signals are obviously quite different in the time domain.

Complicating the matter is the bothersome fact that identical frequencies can be generated by more than one equipment problem. For example, imbalance, a bent shaft, and looseness can generate a fundamental. Loose machine bolts and a bent shaft can also generate a second harmonic of the rotor speed. A loose rotor can generate a fundamental and several harmonics. A second harmonic of the gearmesh frequency may be caused by too little or too much backlash – or gears that oscillate. Multiple harmonics of gearmesh frequency and modulation may be caused by loose or eccentric gears. In other words, you can't always assume the frequency spectrum is telling you everything you need to know.

Gearmesh problems can be particularly elusive because a gearmesh anomaly may be different for each pair of meshing teeth. Since the same two teeth will not mesh again until one cycle of the hunting tooth frequency is completed, each memory period of gearmesh frequency could be different. This requires enough time data to ensure that the relatively long hunting tooth period is presented for required diagnosis. You'll also need variable lines of resolution, true zoom, and synchronous time-domain averaging for diagnosing gear problems.

## Exploring phase relationships

*(Please note that throughout this article, we're discussing phase relationships between the various components in a vibration signal, not phase relative to an input trigger or phase between two input channels. These phase issues are important, of course, but they're not relevant here.)*

As mentioned earlier, similar (or perhaps even identical) frequency spectra can be generated from two signals that the time domain shows to be quite different. The top trace in figure 1 shows the time record of a fundamental and its second harmonic. The signals are in-phase and of equal amplitude. The bottom trace shows the same two signals mixed together. Mixing in-phase components produces a composite waveform with truncation at the bottom. The top half of the signal reflects the sum of the two signals.

Now consider figure 2. The top trace shows the same fundamental and its second harmonic, but this time, the harmonic is 180° out-of-phase. The bottom trace shows the two signals mixed. The composite waveform has truncation at the top. The bottom half of the signal reflects the sum of the two signals.

Comparing the two figures, you can see how hard it would be to identify the true nature of a machine's behavior when the frequency domain hides such vital information.

Maximum truncation occurs at either 0° or 180°, as we see in figures 1 and 2. Truncation does not occur when the fundamental and harmonic are 90° or 270° out-of-phase. If the phase relationship is between 90° and 270°, some top truncation occurs, but it is not as great as when the signals are 180° out-of-phase. Conversely, some bottom truncation occurs if the phase relationship is between 270° and 90°, but the truncation is not as great as when the signals are completely in phase.

## Gear modulation

Given a perfect set of meshing gears, we'd expect to see only a low-level component at the gearmesh frequency. Each cycle would be sinusoidal, with consistent amplitude. When an imperfection shows up, however, two things begin to happen. First, we see a larger amplitude of the gearmesh frequency. Second, we notice modulation that occurs at a rate equal to the speed of the offending gear or at multiples of the gear speed (for example, at once, twice, or three times the gear speed). In this case, the gearmesh frequency is the carrier and the gear speed is the modulator.

If the modulator is sinusoidal, we'll end up with simple double-sideband (DSB) amplitude modulation. Consider this example. A 27-tooth gear is in mesh with a 61-tooth gear. The speed of the 27-tooth gear is 29.6 Hz. The gearmesh frequency would be 27 x 29.6 Hz, or 799.2 Hz. Figure 3 shows what DSB modulation looks like in both the time and frequency domains. The frequency domain reveals a carrier at 799.2 Hz and two sidebands 29.6 Hz from the carrier. The time domain reveals that both sidebands are in-phase with the carrier.

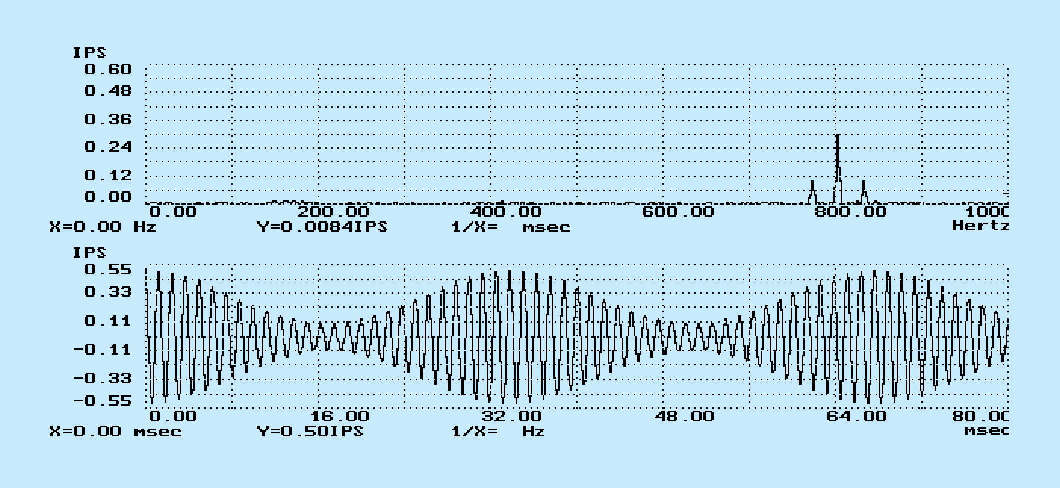

**Figure 3**
A gearmesh frequency of 799.2 Hz with a modulating gear speed of 29.6 Hz produces this double sideband amplitude modulation. The upper trace shows the frequency spectrum; the lower trace shows the time domain.

Although the above example is hypothetical (real gear signatures are rarely so clearly defined) it does demonstrate some important points. If you've studied radio electronics, you might remember that the amplitude of a sideband is determined by the percent modulation (using the appropriate math, we can calculate the modulation percentage in either frequency or time domains). Since there are two sidebands and they are in-phase with the carrier, their amplitudes add. This produces a modulation percentage twice that of what we would see with just a single sideband.

Overmodulation (which occurs when the amplitude of the modulator is greater than the carrier) causes phase reversal, distorts the modulator, and generates additional sidebands. This poses a whole new set of diagnostic challenges. In the frequency domain, it produces sidebands that may appear higher than the carrier, and these additional sidebands may be unrelated to the rotating machinery problem you're trying to solve. To find out whether these sidebands are in fact caused by overmodulation, you need to view the signal in the time domain.

By pondering gear modulation for a moment, you can see why using demodulation measurements can hamper a diagnosis. When you demodulate, you lose the carrier signal and can no longer distinguish between a gear-speed frequency component and a gearmesh frequency modulated by gear speed — and the two are caused by distinctly different mechanical processes. Consequently, my recommendation is to avoid both demodulators and envelope detectors for vibration analysis measurements.

## Using phase to distinguish eccentricity and looseness

Single-sideband (SSB) modulation is similar to the modulation produced by certain gear problems. SSB modulation produces either an upper single sideband (USSB) or a lower single sideband (LSSB). If the phase is negative at the summing point, the LSSB is produced. If the phase is positive at the summing point, the USSB is produced.

Pure SSB modulation in rotating machinery, while theoretically possible, is extremely unlikely due to phase shifts, distortion, overmodulation, and noise generated by the typical rotating machine. What we tend to see instead is a less-pure type of SSB modulation known as vestigial sideband (VSB) modulation. With VSB modulation, there are upper and lower sidebands, but one is significantly higher than the other.

It is this differential that helps us identify eccentricity and looseness problems. An eccentric gear is normally in-phase with the gearmesh frequency (remember that the gearmesh frequency is the carrier and the gear speed is the modulator). This produces VSB modulation with a greater upper sideband amplitude due to the predominance of in-phase components.

In contrast, loose gears are normally out of phase with gearmesh frequency (though they may be unstable and thus sometimes appear in-phase). A loose gear, therefore, tends to produce VSB modulation with a more pronounced lower sideband.

## Phase diagnostics in action

Consider the case of a paper machine. The background noise was quite high. The gear problem on the paper dryer was discovered during a routine vibration survey.

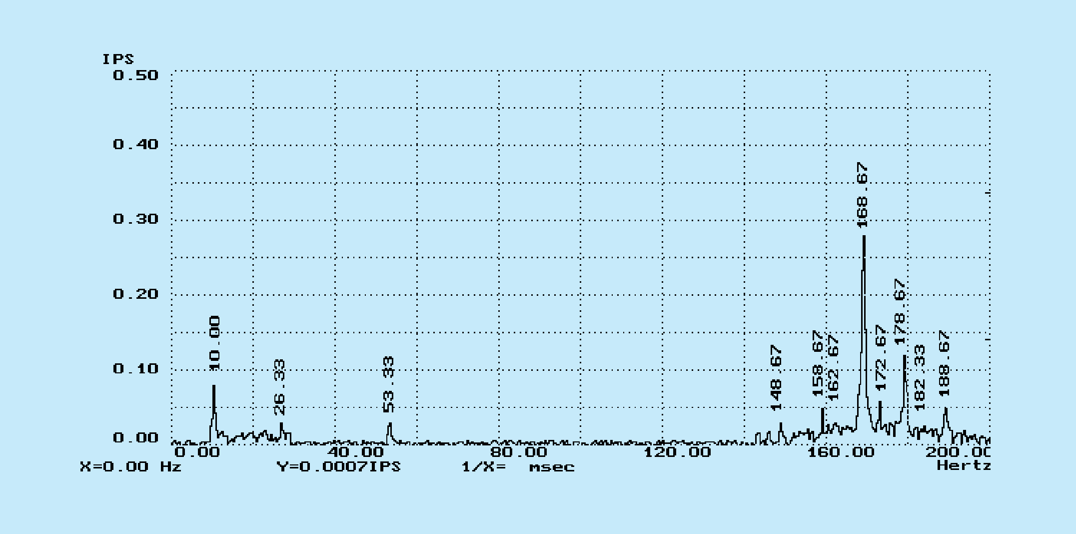

**Figure 4**
This frequency spectrum from a gear in the paper dryer shows a gearmesh frequency of 168.7 Hz. The upper sidebands are significantly higher than the lower sidebands, indicating an in-phase condition attributable to gear eccentricities.

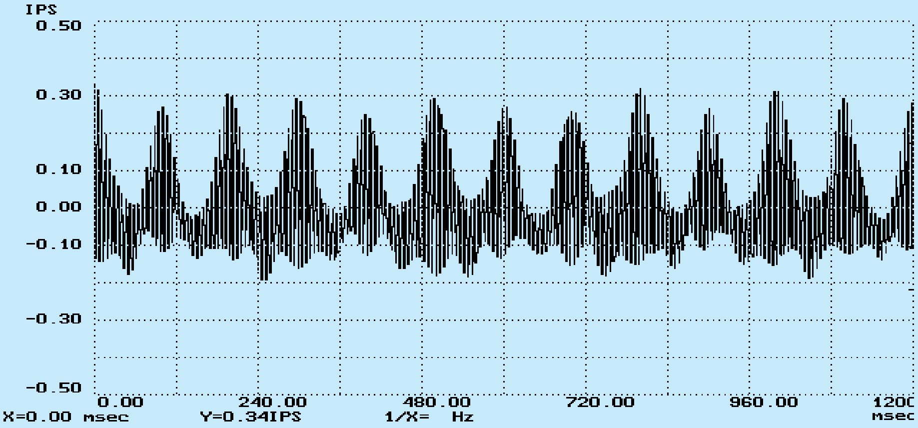

**Figure 5**
The time signal from the dryer gear shows the truncation on the negative half of the signal that we would expect to see in an in-phase condition.

The gear has 84 teeth and turns at roughly 2 Hz, for a gearmesh frequency of about 168 Hz. Figure 4 shows the vibration spectrum. First of all, note the prominent 10 Hz component. This is five times the 2 Hz gear speed and indicates an event occurring at five times gear speed.

The largest component is the gearmesh frequency at 168.7 Hz. There are two upper sidebands at 178.7 and 188.7 Hz and two lower sidebands at 158.7 and 148.7 Hz. The spacing of the sidebands indicates high spots (5 x 2 Hz) on the gear.

Since the amplitude of the lower sidebands is significantly smaller than the upper sidebands, we can suspect an in-phase condition. We know that gear eccentricities tend to produce in-phase components, whereas looseness tends to generate out-of-phase components. To be certain, we need to examine the vibration signal in the time domain.

Figure 5 shows the time record. Note the truncation on the negative half of the signal. This verifies an in-phase condition. As the teeth at and near the spokes go into mesh, the amplitude increases. The amplitude decreases as these teeth go out of mesh.

The suspected problem was eccentricity in a large gear with five spokes. Gears of this type often have high places in line with the spokes. Typically, the gear is within tolerance when manufactured but expands unequally when it is pressed or shrink-fitted to the shaft. (In fact, some machine designers avoid spoked gears for this very reason.)

Aside from illustrating a generic concern with spoked gears, this case highlights the insights that phase and the time domain in general can provide. The tougher your problems get, the more sense it makes to use every possible tool in your diagnostic toolbox. ■