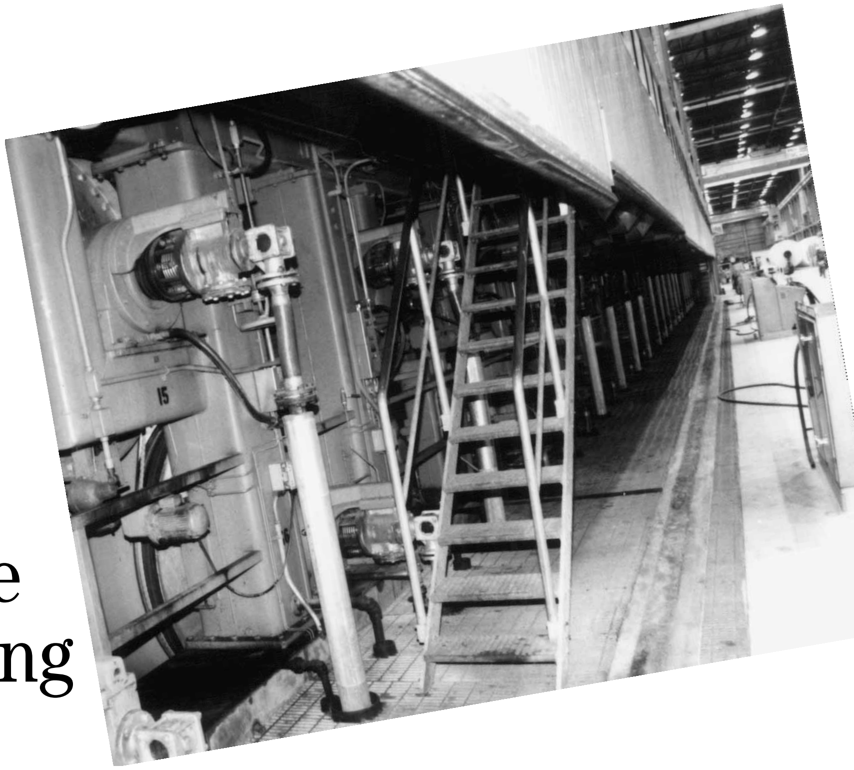
REALTIME
Update

Hewlett-Packard Winter 1995

A Newsletter for Noise, Vibration and Electromechanical Test Professionals



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.

Also in this issue:

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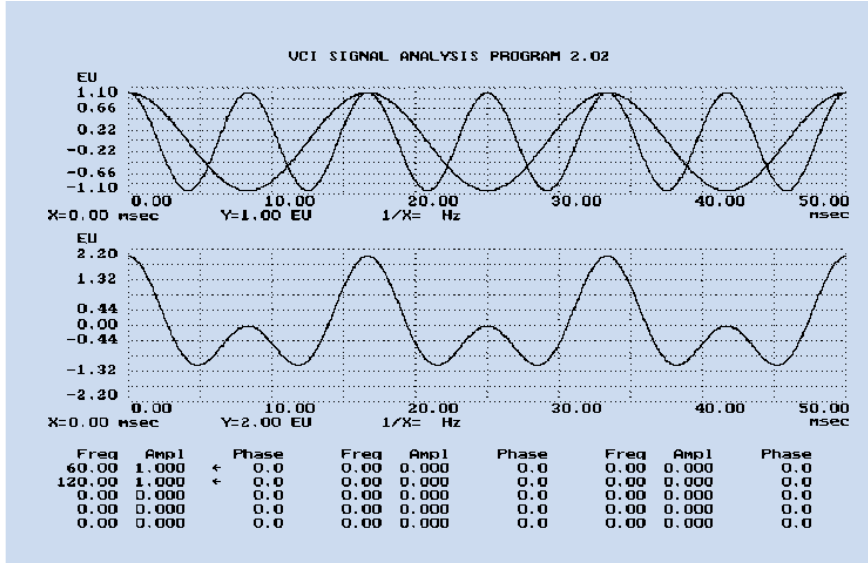

Figure 1
A single frequency with an in-phase harmonic produces the combined waveform shown in the lower trace.

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.

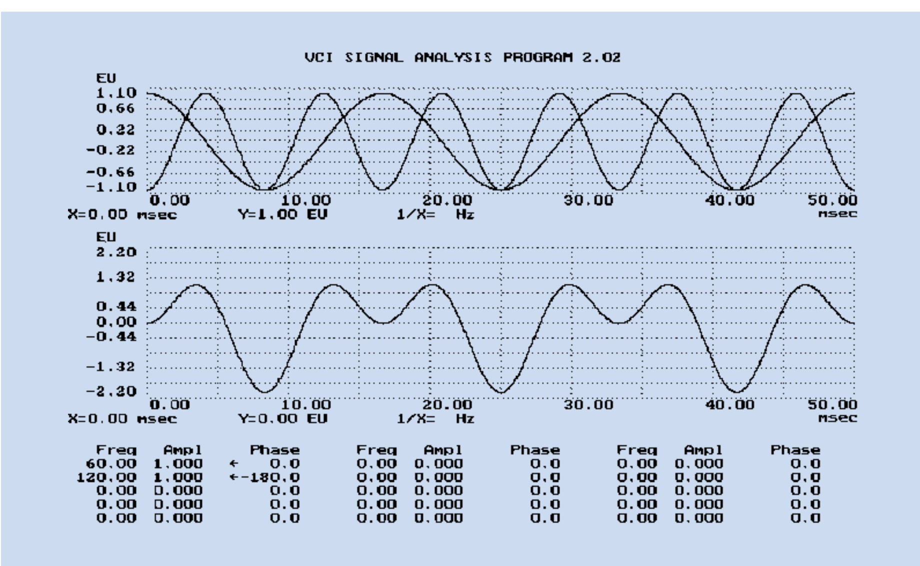

Figure 2
This combined waveform (lower trace), the result of combining a single frequency with a harmonic that is 180° out of phase, will produce the same frequency domain display as the waveform from figure 1 — even though the signals are obviously quite different in the time domain.

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.

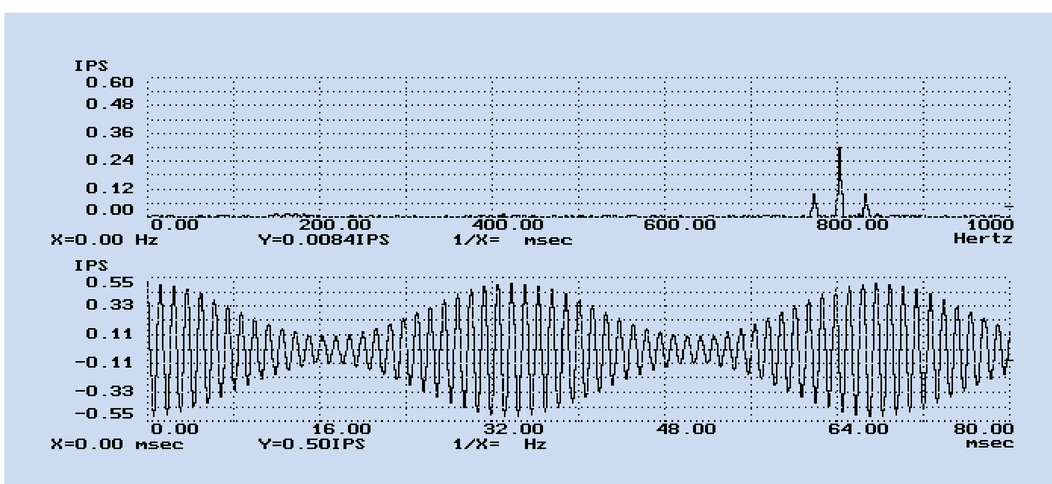

Figure 3
A gearmesh frequency of 799.2 Hz with a modulating gear speed of 29.6 Hz produces this double sideband amplitude modulation. The upper trace shows the frequency spectrum; the lower trace shows the time domain.

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.

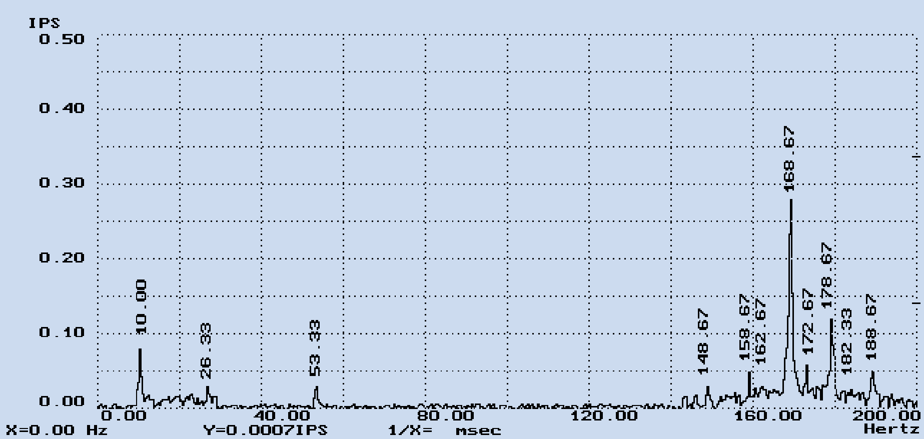

Figure 4
This frequency spectrum from a gear in the paper dryer shows a gearmesh frequency of 168.7 Hz. The upper sidebands are significantly higher than the lower sidebands, indicating an in-phase condition attributable to gear eccentricities.

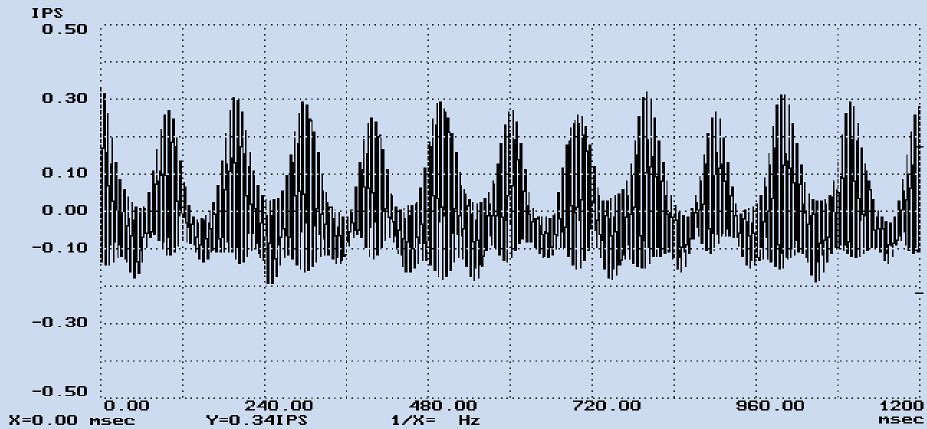

Figure 5
The time signal from the dryer gear shows the truncation on the negative half of the signal that we would expect to see in an in-phase condition.

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. ■

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For more information on VCI's machinery diagnostics software (three VCI packages were used to produce the plots shown in this article), please call VCI at (813) 839-2826 or fax to (813) 837-5306.

New Software Expedites MRIT Measurements

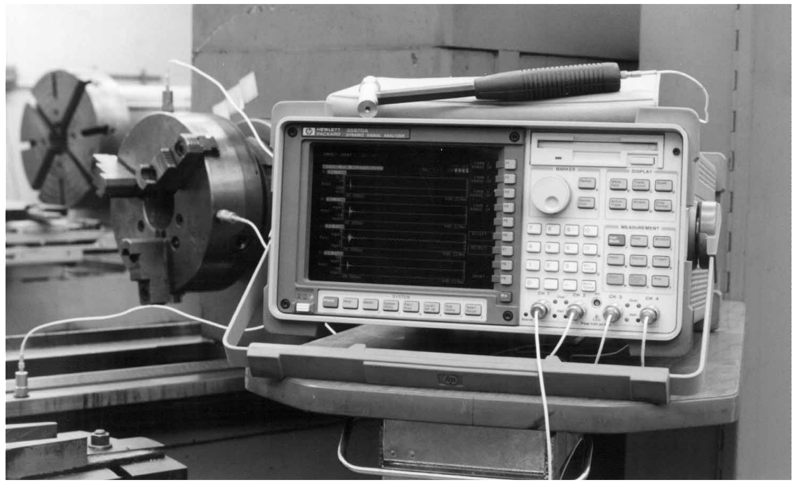


Figure 1
Four input channels and the ability to run application software make the HP 35670A a good choice for MRIT tests.

Multiple-reference impact testing (MRIT) is a great way to collect data in many modal analysis applications. It combines the simplicity of impact testing with the benefits of multiple-reference measurements. (For more information on the MRIT technique, please see page 8.)

A new software package developed by The Modal Shop and distributed by HP now makes MRIT even easier and faster by automating the data collection process for you. The Model 3200 MRIT Acquisition Software is written in HP Instrument BASIC and runs inside the portable HP 35670A dynamic signal analyzer.

With its four input channels and built-in programmability, the HP 35670A is a perfect platform for MRIT measurements (see figure 1). The MRIT software optimizes this versatile analyzer for MRIT by reducing test time and effort. The software both controls the analyzer and provides additional features that manage the test process, automate repetitive tasks, and improve test results.

Take full advantage of MRIT
With the Model 3200 software, you'll enjoy the benefits of the MRIT technique in a fast, practical way:

- *Reduce data collection time.* Without some form of automation, MRIT can be a repetitive, labor-intensive task. By taking over the data and test management chores, the software cuts test times by as much as 50%.
- *Get up to speed quickly.* The software transforms the analyzer's softkey-driven user interface into a dedicated modal data collector.
- *Get complete results.* The multiple-reference implementation of impact testing lets you resolve closely spaced—even repeated—roots and spatially uncoupled modes.
- *Reduce data collection errors.* The nature of MRIT testing means you'll make a lot of measurements in the field, in less-than-ideal conditions and with limited access to test structures. You need to focus on the job at hand and not on running your equipment. The Model 3200 software helps you stay focused by simplifying the entire procedure.

Make data collection fast and simple
This software boosts your efficiency and effectiveness during every step of the measurement procedure:

Test Setup. The software starts by initializing the analyzer for impact testing and organizing the relevant user-defined parameters. It lets you define pretrigger delay and force and exponential windows independent of time record lengths, so you don't have to reenter these values if you change the time record.

Pretest Measurements. A suite of pretest measurements shorten your test set-up time. For instance, an automatic check of the roll-off of the input spectrum (see figure 2) helps you select the right impact hammer

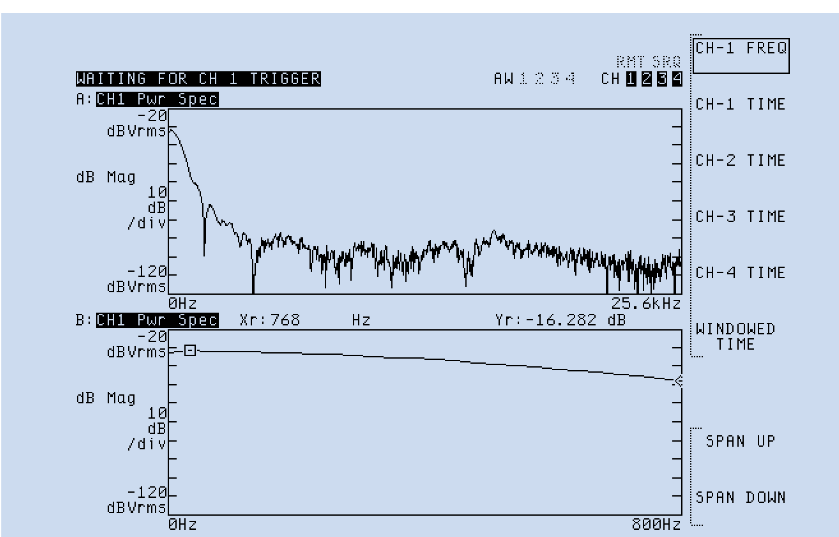
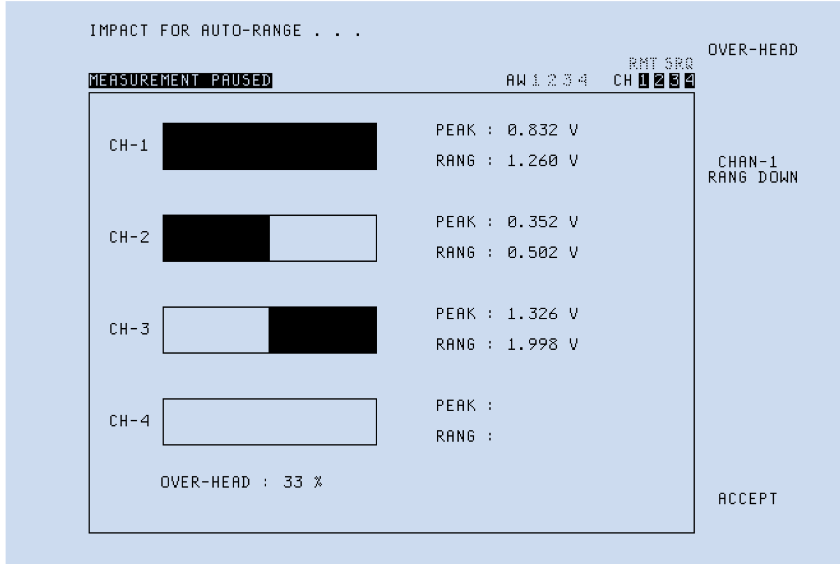


Figure 2
Showing input roll-off to help you select the right hammer and tip is just one of the ways the MRIT software facilitates test set up.

Figure 3
With this quick status indicator, you'll find it easy to optimize input range settings.



and tip for the desired frequency range. You can also use the digital-scope mode and windowed time record preview to check out your measurement setup before starting full-scale data collection.

Autoranging. Optimizing the dynamic range of the input channels is a crucial concern with impact testing, and the MRIT acquisition software helps you get it right every time. It adapts autoranging to the properties of the impact transient time signals and provides a graphical autorange display that shows you ranging conditions even when you're not close to the analyzer (see figure 3).

Measuring and Displaying FRFs. The program also measures FRFs, with overload rejection and optional average preview. You can quickly review the measured FRFs in any of the common FRF display formats.

Managing Test Data. The MRIT program saves the FRFs to SDF files on disk with a single keystroke, and it automatically generates and updates filenames. The software also compiles a list of measured impact locations by writing a test log on the nonvolatile RAM disk. To help you keep track of where you are in a test, you can view the test log on-screen as well.

After a test, it's easy to import the data set into such popular analysis packages as SMS STAR, LMS CADA-PC or Vibrant ME'Scope for modal parameter estimation. Team the HP 35670A with The Modal Shop's MRIT software and a notebook PC for a powerful and portable modal diagnostic system.

Get results in a hurry

Here's a quick example of how much time you can save using the MRIT software and an HP 35670A. For a test of a one-meter box beam that involved 148 impact locations and three references, an HP 3567A PC spectrum analyzer (with a 486/33 PC) took about seven hours to complete the test. The HP 35670A and the MRIT program did the job in about four hours—a 40% reduction. When you have limited access to the test article, or you're working in unsafe or unpleasant conditions, you'll definitely appreciate the speed and convenience of the MRIT approach. ■

For more information on The Modal Shop's MRIT Acquisition Software for the HP 35670A dynamic signal analyzer, check 3 on the Reply Card. For more information on the HP 35670A, check 4 on the Reply Card.

Realtime Basics:

An Easier Way to Get Multiple-Reference Measurements

by Bill Fladung, University of Cincinnati

Modal analysis measurements made with multiple references provide the key benefit of helping you resolve repeated or closely spaced modes. You may be familiar with the multiple-input, multiple-ouput (MIMO) technique, in which the test structure is instrumented with many response transducers and excited by two or more stimulus sources (usually electrodynamic shakers). These stimulus locations serve as the references for the data set and allow your modal analysis software to uncover modes hiding on top of each other.

For all its power, MIMO is not the ideal technique for all modal test situations. To begin with, instrumenting a structure with all those response transducers can be an expensive, time-consuming adventure. Then you have to find a way to measure all those channels simultaneously, which leads you to multichannel analysis systems.

When you need the level of performance it offers, MIMO is the only way to go. However, for troubleshooting and field testing, MIMO can be more power than you need and more complexity than you can handle. For these situations, many structural engineers are turning to multiple-reference impact testing (MRIT). In contrast to MIMO, which can involve dozens or hundreds of response channels driven by two or more stimuli, MRIT uses just a few response channels driven by one roving stimulus (usually an impact hammer).

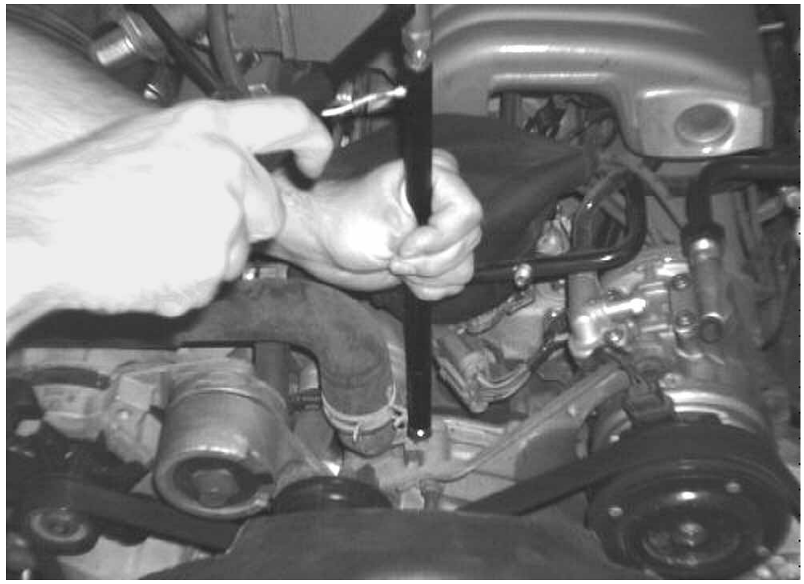


Figure 1
An instrumented punch lets you reach places you can't reach with a hammer.

Taking advantage of reciprocity

In a MIMO test, the two or more stimulus inputs serve as the reference measurement points. In an MRIT test, you use the response measurements as the references because they are common to the entire set of measurements. And thanks to the principle of reciprocity, the impact locations become the degrees of freedom of the mode shapes. Reciprocity, as you'll recall, is one of the fundamental assumptions made in modal analysis. We assume that an FRF for an output at point *P* and an input at point *Q* is equivalent to the FRF for an output at point *Q* and an input at point *P*. It's reciprocity that lets you use a few outputs with numerous inputs, the reverse of the typical MIMO setup.

MRIT produces a multiple-reference FRF data set that is similar to a MIMO data set but doesn't require a multiple-input FRF estimator since there is only one input to the system. You can process MRIT data sets with any multiple-reference parameter estimation software.

Equipment for MRIT testing

Handheld impact hammers are convenient for MRIT because they're easy to move from point to point as you rove across the structure. An instrumented punch is a good alternative when you don't have enough space to land a hammer impact (see figure 1).

The most common type of response transducers for MRIT are accelerometers, but you can use proximity probes for tests on rotating machinery (while in operation) or microphones for acoustic modal tests on very small objects.

The hardware-software combination described on page 7 is an example of an ideal solution for collecting MRIT measurements. The four-channel HP 35670A dynamic signal analyzer provides high-quality measurement functions, and The Modal Shop's Model 3200 MRIT Acquisition Software runs inside the HP 35670A to automate the data collection process.

MIMO or MRIT?

Because it requires minimal setup time and test equipment and is adaptable to many testing conditions, MRIT is becoming a popular method for troubleshooting and field testing applications. It's also a good alternative to MIMO testing for certain situations, such as small, lightweight objects or very large structures. In addition, you can use MRIT as a preliminary procedure for a large-scale MIMO modal investigation to identify modes of interest or to determine exciter locations.

On the other hand, the nature of impact testing does give MRIT some limitations that you need to consider when choosing a test method. First, delivering consistently usuable impacts with a hammer does require some skill and experience. Second, you may not be able to excite an entire structure sufficiently using an impact stimulus. And third, a structure's basic geometry may keep you from impacting at desired locations. This could preventing you from determining the mode shape coefficients corresponding to the degrees of freedom that you can't measure.

For the jobs it was designed to handle, however, MRIT is a effective tool that delivers results with less time and trouble. ■

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Realtime Answers

Q. How can I choose the right microphone for SPL acoustic measurements?

Microphones are used for a variety of sound pressure level (SPL) tests ranging from simple amplitude to complex multichannel sound power measurements. To make a repeatable, accurate and standards-compliant measurement, you'll need an instrumentation microphone. These units use air-dielectric capacitors (diaphragms) that are polarized with a large voltage, typically 200 Vdc.

Instrumentation microphones come in a huge variety of types, sizes, sensitivities and frequency ranges, but selecting the right one boils down to just three questions: the kind of sound field you'll be in, the amplitude levels you expect to encounter and the required frequency range. Here's a closer look at each question.

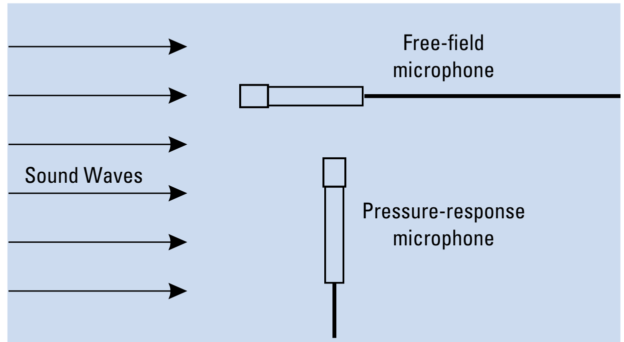
1. What kind of sound field will you be in?
Sound fields fall into two general categories: free and reverberant. In a free field, the sound typically emanates from a point source, and all sound wave fronts travel radially outward from this point. Examples of free fields include aircraft noise high over an open field and conditions inside an anechoic chamber. A reverberant field, in contrast, is much more complex, with many reflections or sound sources. The interior of a car is a good example.

Microphones are made specifically for each type of field. Free-field measurements usually involve clearly defined sound sources. Free-field microphones are designed to be pointed directly at this type of sound source. This creates some special problems for the measurement, however. Because the microphone blocks the sound path, sound waves can build up on the microphone diaphragm, especially at higher frequencies. Consequently, the design of free-field microphones compensates for these potential inaccuracies. In addition, free-field microphones are very directional; they work in other directions but are accurate only in the correct orientation.

In a reverberant field, the sound wave fronts are mixed together. It's difficult to isolate the sound source but there are definite pressure variations caused by the sound. The best choice is a pressure microphone. These units don't compensate for the buildup of sound pressure on the diaphragm and thus produce the best answer when held sideways to the sound field. In contrast to free-field microphones, pressure microphones are generally insensitive to direction. They work with sound from many directions and are less accurate if you aim them directly at a point source.

In a pinch, you can use a pressure microphone in the free field by orienting it sideways to the sound source. However, you shouldn't use a free-field microphone in a pressure field, especially when the frequencies of interest are 5 kHz or greater.

Free-field Measurements



2. How loud will the sounds be?
A sound field is typically measured in dB SPL, a unit that expresses how loud a sound seems to the human ear. SPL is a logarithmic unit and is referenced to the threshold of human hearing at 20 µPa. The equation for dB SPL is:

$$\text{dB SPL} = 20 \log (Pa_m/20E\text{-}6\ Pa)$$

where Pa_m = measured pressure in Pascals.

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With a little experience, you can estimate SPL values. Some reference examples: a quiet meadow is around 20 dB, an office is 60 dB, band music is roughly 100 dB, and aircraft take-off is up at 125 dB. With an estimated SPL value, you can then solve for Pa_m, the measured pressure in Pascals.

$$(20E\text{-}6)(10^{SPL/20}) = Pa_m.$$

Microphone sensitivities are typically specified in dB relative to 1 volt per Pascal. The HP ACOJ-7047, for instance, is rated at -29 dB re: 1V/Pa.

The microphone sensitivities and the SPL values both reference Pascals. Consequently, you can take a given SPL value and a specified microphone sensitivity and compute the resulting voltage output levels. As an example, a microphone with sensitivity n dB:

$$n\ dB = 20 \log [(x\ V/Pa)/(1V/Pa)]$$

would have an output voltage of:

$$[10^{n/20}] = x\ V/Pa.$$

Example problem: How many mV would you get from the HP ACOJ-7047 (-29 dB re: 1V/Pa) in a 65 dB SPL field?

Step 1
Using $[10^{n/20}] = x\ V/Pa$, where n = microphone sensitivity:
$[10^{-29/20}] = 35.48\ mV/Pascal.$
Step 2
Using $(20E\text{-}6)(10^{SPL/20}) = Pa_m$.
$(20E\text{-}6)(10^{65/20}) = 0.0356\ Pa_m$.
Step 3
(35.48 mV/Pa)(0.0356 Pa) = 1.26 mV

In this example, we combined a fairly typical sound field with a high-output microphone and ended up with a signal of only 1.26 mV. This low voltage is typical of the output levels of most instrumentation microphones. It's a good idea to run through the equations to see if the microphone you are looking at is sensitive enough to meet your needs. You may need to choose a higher-sensitivity model or add amplification to your measurement path. (Note that microphone sensitivity increases with larger diaphragm diameters. That's why 1/4-inch microphones tend to be less sensitive than 1-inch models.)

3. What frequency range do you need?
Frequency and sensitivity are often interrelated. The 1-inch diameter microphone may be more sensitive, but the increased diaphragm size makes it less responsive to high frequencies. Similarly, the small diaphragm of the 1/4-inch microphone can be very sensitive to high frequencies but less sensitive to low ones. Evaluate the frequency range needed for your measurement and then explore the sensitivity needed. You'll often find that the higher-output microphones have a lower frequency range.

Summary
In order to make a "sound" measurement, be sure to understand both the sound field and the expected signals. Anticipate the frequency range and transducer output levels you need and match the microphone to both the analyzer and the measurement environment. Studying the manufacturers' data sheets and working through computations for your measurements before buying will help you get the right equipment and use it successfully. ■