Phase Measurements: Theory & Application

This paper is intended to help the reader develop an understanding of the concept of phase as it applies to vibration and signal analysis. Simple examples are presented to demonstrate the basics of phase relationships; then machinery diagnostics and troubleshooting examples are presented. The idea of a complex spectrum is discussed, and various methods for display of complex spectra are illustrated. Finally the paper illustrates simple mode shape and operating deflection shape determination using vibration spectrum measurements with phase.

Why Consider Phase?

Often when conducting routine vibration testing of machinery, the overall signal strength (a broad-band reading) is measured as a first step. Actual machinery diagnostics however, requires narrow-band signature analysis to identify specific peaks in vibration spectra. In the same way that narrow-band signature analysis reveals another layer of information, phase information can provide even more clues when diagnosing machinery and structural problems.

What is phase?

A simple example is a pair of pendulums. When they are set so that they swing in unison, they are said to be "in phase" as shown in Figure 1A, and if they are set to swing in opposition, they are "out of phase" as shown in Figure 1B.

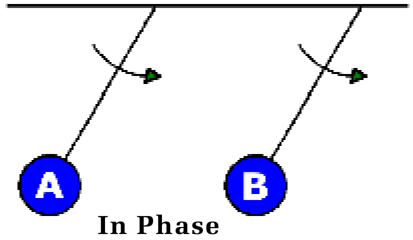


Figure 1A. Two pendulums swinging in phase.

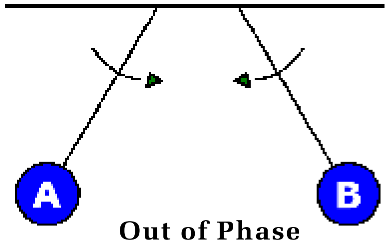


Figure 1B. Two pendulums swinging out of phase.

Of course there are infinite conditions that exist between in phase and out of phase. These conditions are described using angles such as "90 degrees phase difference" for example. If you consider the left side stop position as zero phase point, then the pendulum is at 180 degrees phase when at the extreme right, and continues on to 360 degrees as it proceeds back to the left hand extreme.

Literature Number PM-AN136

Here are some examples:

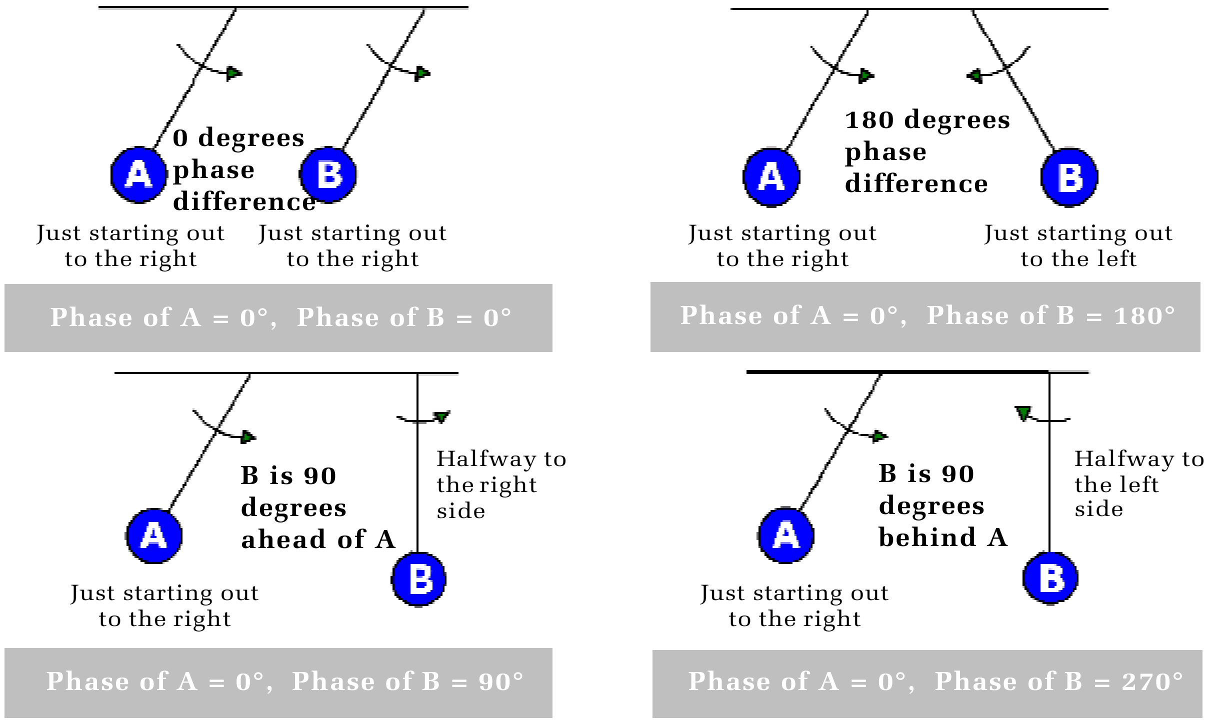


Figure 2. Various phase relationships illustrated.

Frequency

If the pendulums are swinging at the same frequency, then their phase difference will always be the same. If not, their phase difference will be changing with time. Normally when talking about phase, we confine ourselves to one single frequency and if the motion or vibration is in a steady state, then the phase won't change with time.

Real world applications

Jumping from our simple pendulum to the real world, phase difference between two points on a machine reveal useful information. For example, if a machine with an overhung rotor is vibrating excessively at its rotational rate, the vibration could have several different causes, i.e. imbalance, wobble, or misalignment. Observing the phase at two points on opposite sides of the coupling can help differentiate the actual problem. Imbalance and/or wobble will result in "in phase" rotational rate vibration at the two measurement points (Figure 3B) and misalignment will cause out of phase vibration (Figure 3A).

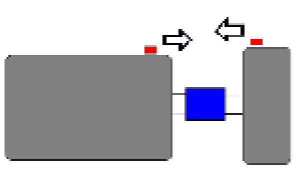


Figure 3A
Angular Misalignment causes out of phase axial movement at the rotational rate.

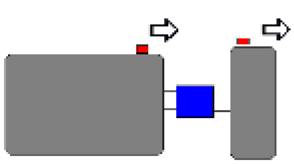


Figure 3B
Imbalance of an overhung rotor causes vertical and lateral movement that is in phase at the rotational rate.

Use of phase for balancing

When doing dynamic balancing, the vibration of a rotating machine is recorded along with a tachometer signal (sometimes referred to as a key-phasor). The tach signal works like pendulum A in the illustrations shown in Figure 2, it serves as a zero point or datum.

During the balancing process, the rotational rate vibration is recorded and its phase difference relative to the tachometer signal is noted. Then by adding trial weights at known angles relative to the marking used to generates the tach signal, and recording the resulting magnitude and phase shift in the rotational rate vibration, a computer program indicates where a balance weight should be placed to minimize imbalance vibration.

Complex spectra

Narrow band vibration analysis involves close inspection of vibration spectra. The usual representation of these spectra are "auto power spectra" which puts everything in 2 dimensions. The vertical dimension is the amplitude of vibration (i.e. mils, ips, VdB, G, mm/s… etc.), and the horizontal dimension is frequency (0 to 200 Hz for example). The frequency range is divided into frequency bins or lines of resolution. Typically you will see 400, 800 or 1600 lines of resolution and for every line, there is a discrete amplitude. Behind the scenes however, there are phases associated with every line. These phases are removed when the "auto power" operation is done, but the information is retained in a "complex" spectrum. The complex spectrum has a third dimension, phase. For every discrete frequency, there are 2 pieces of information, phase and amplitude.

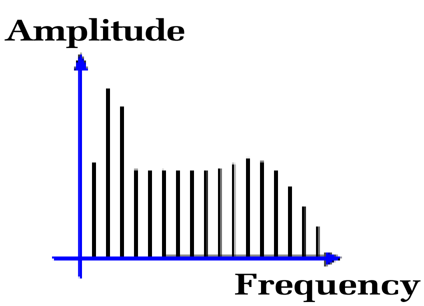


Figure 4A
Auto Power Spectrum has only amplitude for each frequency.

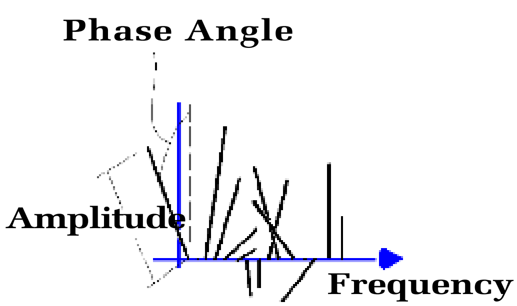


Figure 4B
Complex valued spectrum has both amplitude and a phase angle for each frequency.

Magnitude and Phase Plots

The diagram shown in Figure 4B illustrates the difficulty in displaying complex spectra. Generally complex spectra are depicted by two 2D graphs, one showing just the magnitudes and the other showing just the phases for each frequency bin. This kind of depiction is referred to as a Bode plot. Alternatively, if one were to look down the horizontal axis of Figure 4B (directly at the arrowhead) and connect all the end points of the vectors with a line, you would get a Nyquist plot.

Here are some examples of 2D graphs depicting the components of complex spectrum:

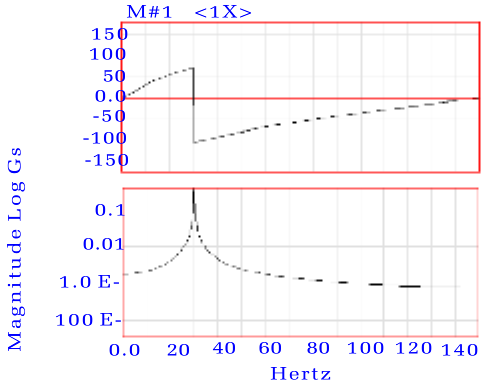


Figure 5A Bode plot of a pure 30 hertz sine wave with 70 degrees phase at 30 Hz.

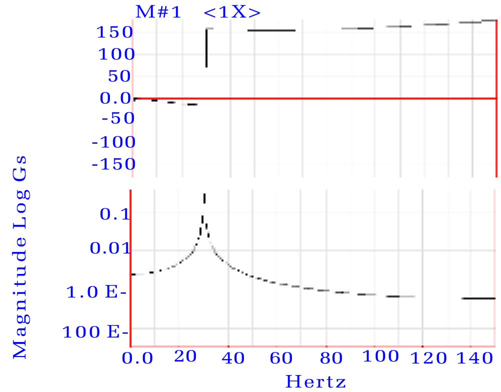


Figure 5B Bode plot of same pure 30 hertz sine wave, but with a 90 degree phase shift compared to Figure 5A.

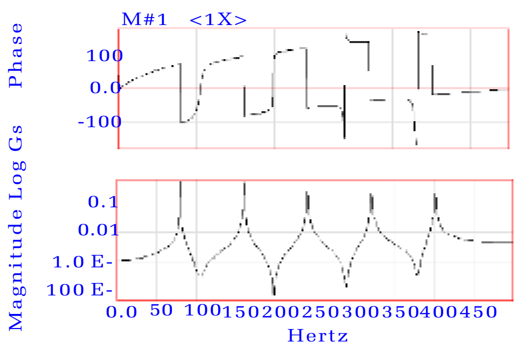


Figure 5C
Bode plot depiction of complex spectrum with 5 different individual frequency components.

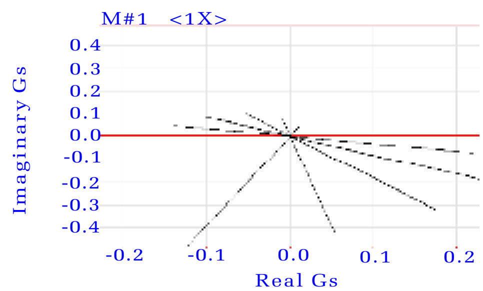
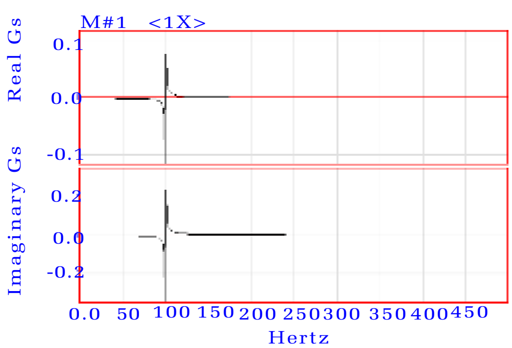


Figure 5D
Nyquist plot of complex spectrum shown in Figure 5C.

Real and Imaginary

Note that the Nyquist plot shown in Figure 5D is labeled not with phase or magnitude, but real and imaginary. Refer to Figure 4B and note that if the view were not from an angle, but directly from the side we would see something similar to what is shown in Figure 4A, but only the vertical components of each line would be visible. Conversely if we look at it from the top down, we would also see a 2 dimensional projection of just the horizontal component of each line. These vertical and horizontal views are technically termed the real and imaginary parts respectively. We can view the real and imaginary parts of any complex spectrum. Figures 6A, B, and C compare the real and imaginary plots with the bode plot and the autospectrum which lacks phase information. Figure 6D is the Nyquist plot of the same signal.



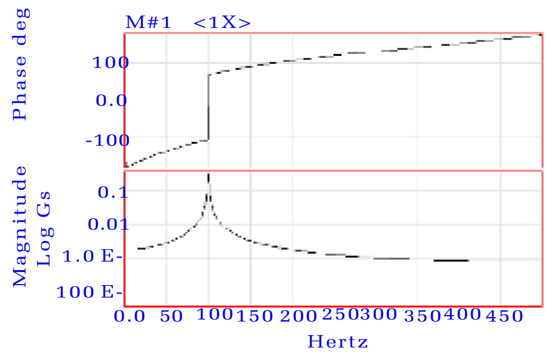
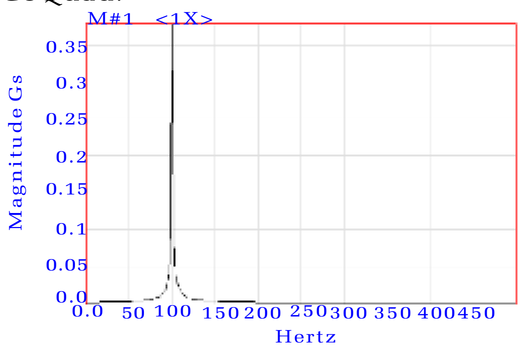


Figure 6A Real and imaginary portions of a 100 hz signal, this format is sometimes referred to as CoQuad.

Figure 6B Bode plot of the same signal. Note that the amplitude scale for the bode plot is logarithmic.



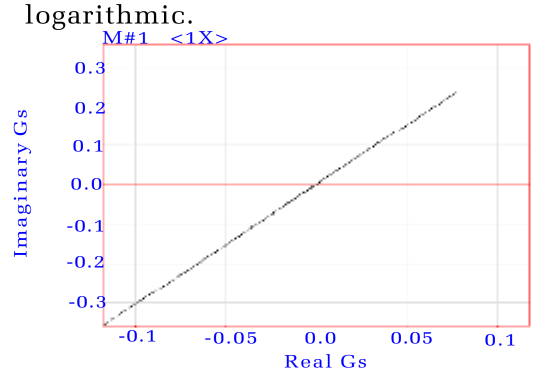
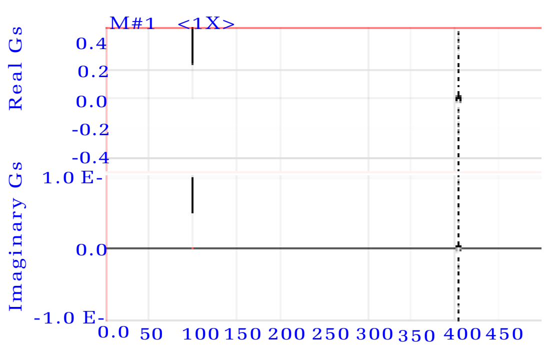


Figure 6C Standard autospectrum display of 100 hz signal.

Figure 6D Nyquist plot of the same signal.

These examples, while smooth and clear are not representative of the way real signals look. The sudden shift in phase (see top of Figure 6B) before and after 100 Hz is due to something known as leakage. Leakage occurs when a signal has a frequency that is between 2 frequency bins of the spectrum. The following plots (see Figures 7A and 7B) are examples where the signal frequency is centered on a particular spectrum bin. Note that in the Bode plot, the phase jumps around randomly after about 110 hertz because the only bins with any real information are around 100 hertz. All other bins have small values corresponding to the computational error, built into the Fast Fourier Transform (FFT) process, which yields meaningless phase values.



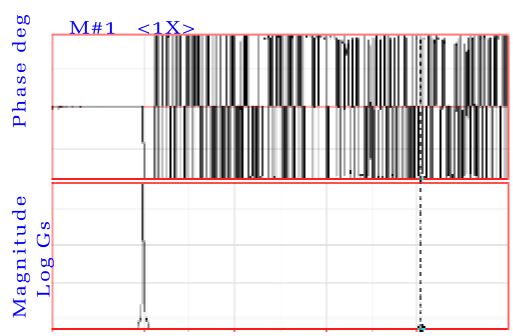


Figure 7A CoQuad display of complex spectrum with minimal leakage
Figure 7B Bode plot of the same signal.

Checking for phase at a particular frequency
Normally, for routine vibration analysis, phase information is needed for one or two particular frequencies of interest, such as the rotational rate or some system resonance frequency or the frequency of a particular external excitation source. Most spectrum analyzers provide cursors that display the magnitude and phase at any particular frequency, additionally some data collection devices will record and report the phase at a particular frequency, without necessarily saving the complex spectrum.

Deflection and mode shapes:
Determining the magnitude and phase at a fundamental frequency for several points on a structure can provide enough information to calculate the stresses and strains in the structure. Knowing the stresses can assist in determining root causes of structural fatigue and failure.

For example, consider the simple bracket undergoing forced oscillations shown in Figure 8A. Without the phase information, it is difficult to differentiate between the many possible mode shapes. However, as illustrated in Figures 8B and 8C, phase information permits the determination of deflection shapes which in turn permits calculation of stresses and strains, and root cause failure analysis.

Figure 8A
Structural bracket undergoing forced vibration. Vertical displacement auto power spectra are shown, but no phase information.

Figure 8B
Operating deflection shape predicted if simultaneously recorded complex spectra show that the phases measured at points A and B differ by 180 degrees at 10 Hz.

Figure 8C
Operating deflection shape predicted if simultaneously recorded complex spectra show that the phases measured at points A and B differ by 0 degrees at 10 Hz.

Summary and Recommended Reading
This paper illustrates and discusses the concept of phase, outlining several applications of phase measurements for solving practical vibration problems typical of rotating machinery and structures. It is however, simply a brief overview of the subject. More information on the subject of machinery and structural vibration analysis can be found in the DLI Publication “Introduction to Machine Vibration” by Glenn White, and Gulf Publishing Company’s “Machinery Failure Analysis and Troubleshooting” by Heinz Bloch and Fred Geitner. More information on complex signal processing is available in numerous applied mathematics, physics, and control systems texts.

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