MEASUREMENT OF FREQUENCY DEPENDENT SENSITIVITY AND PHASE CHARACTERISTICS OF EDDY CURRENT DISPLACEMENT TRANSDUCERS

Dr. B.T. Murphy
Mr. G. Rambado
Dr. J.K. Scharrer
Rocketdyne Division
Rockwell International
Canoga Park, CA

ABSTRACT

Tests were conducted to measure the sensitivity and phase characteristics of proximity transducer systems from two manufacturers (designated probe A and probe B) as a function of frequency. An electromagnetic shaker was used to generate vibrational motion ranging from 100 to 5000 Hz at various displacement levels. Both sinusoidal and banded white noise signal sources were supplied to the shaker. The shaker head motions were measured by the displacement transducer and also by an accelerometer to provide a reference. The sensitivity and phase spectra were measured with a MASSCOMP data acquisition and analysis system. The data were corrected for gain and phase error introduced by various signal conditioning systems used in the test setup. The corrected data represent sensitivity and phase error inherent to the proximity transducer system. Data for probe A will be presented in detail, and data for probe B will be discussed only in terms of how it differs from probe A.

INTRODUCTION

Accurate rotordynamic analysis of high performance turbomachinery requires accurate inputs for bearing and seal stiffness and damping coefficients (and inertia, when required). For full accuracy, computer codes used to generate these coefficients must be anchored to experimental data. Ultimately, the confidence level in the results of a rotordynamic analysis are highly dependent on the confidence in the bearing and seal stiffness and damping coefficients. Various aspects of the measurement of these coefficients has been discussed elsewhere (see Reference 1 for a review). Among the requirements for conducting such experiments is the accurate measurement of the amplitude and phase of bearing or seal dynamic deflection. Non-contacting eddy current displacement probes are often the choice for making the deflection measurement directly on a rotating shaft. In the past such probes have only been calibrated statically against a stationary target. It was thus deemed necessary to measure how the gain and phase characteristics of an eddy current probe are affected by the dynamic movement of the target. This was done by measuring the gain difference and phase delay of two eddy current probes with respect to a carefully calibrated reference accelerometer. The moving target in our tests was a metal plate mounted on the head of an electric shaker.

TEST SETUP

A schematic of the test setup is shown in Figure 1. An electromagnetic shaker was driven by both sinusoidal and banded white noise signal sources. A proximity transducer system, which includes a probe with an integral cable, an extension cable, and a proximitor, was used to measure the absolute displacement of the shaker head. Also, an accelerometer (ENDEVCO 2242), mounted on the shaker head, was used to measure the shaker head motion. The low level accelerometer signal was increased by an external voltage amplifier and recorded on channel 1 of the MASSCOMP. The proximitor (oscillator/demodulator) signal sensitivity was increased by a B&K 2607 amplifier and recorded on channel 2 of the MASSCOMP. Gain settings of the various components were adjusted as required during the test.

DATA ANALYSIS

The MASSCOMP data acquisition and analysis system was used to generate sensitivity and phase measurements from the sinusoidal and white noise data in the 100 to 5000 Hz frequency range. Both sinusoidal and white noise data were collected for comparison purposes. Spectral averaging (50 averages) was used to improve the statistical accuracy of the data. The accelerometer signal was integrated twice in the frequency domain to generate the transfer function of channel 2 to channel 1. Approximate sensitivity factors of 2.2148 mV/g and 175000 mV/in were used for the acceleration and displacement transducers, respectively, during the test. Static calibration data of probe A and harmonic calibration data for the accelerometer were later used to correct and refine the temporary sensitivity factors. The accelerometer was calibrated against an ENDEVCO 2270 accelerometer which itself was calibrated by the National Bureau of Standards (NBS). The NBS calibration is for amplitude only and its absolute accuracy is quoted as ∀ 1% from 100 Hz to 2000 Hz, and ∀2% from 2000 Hz to 10000 Hz. This calibration provides precise sensitivity factors at a series of discrete frequencies throughout the test frequency range. Although a phase calibration was not performed by the NBS (∀1 degree when it is), the very high resonant frequencies of the accelerometers used here suggest that their phase error is negligible in the test frequency range. For proximeter probes in general, a static calibration is typically the only calibration that is performed. Figure 2 shows that in this particular test setup the static sensitivity was a nonlinear function of air gap. In every test the gap voltage was recorded so that a refinement could be made to the constant 175,000 mv/inch used during data collection.

Spectral calibrations of the displacement signal conditioning system (B&K amplifier), the acceleration signal conditioning system (external amplifier), and the MASSCOMP input channels were also generated at the various gain settings. Banded white noise was supplied to the external amplifier, the B&K amplifier, and the MASSCOMP to generate gain and phase spectra of these measurement systems. These calibrations define the gain and phase error associated with each of these systems in the test frequency range. These data are not reproduced here for lack of space.

The various measurement systems were used at 1:1 and 10:1 gain settings during the test. Gain and phase correction factors were measured for the displacement signal conditioning system at both the 1:1 and 10:1 gain settings. The acceleration signal conditioning system 10:1 gain correction is already accounted for in the accelerometer sensitivity calibrations. Spectral calibrations of the acceleration signal conditioning system 1:1 gain were not acquired, and are therefore not considered. The acceleration signal conditioning system phase error (10:1) and the MASSCOMP gain (1:1) and phase error (1:1) were found to be negligible. Correcting for the gain and phase error introduced by the various signal conditioning subsystems and for the transducer sensitivities isolates the sensitivity and phase difference between the accelerometer and proximity transducer system. Results are presented as the ratio of the probe A measured displacement to the accelerometer measured displacement. Positive phase angle values mean the probe A signal leads the accelerometer signal in time.

RESULTS AND DISCUSSION - PROBE A

Sinusoidal Data: Sensitivity and phase versus frequency plots of the raw and corrected sinusoidal data are shown in Figures 3 and 4. Sinusoidal frequencies were chosen to coincide exactly with a line in the FFT spectrum to eliminate spectral leakage. Data at 102.52 Hz was collected at several displacement levels. Two of the data points were taken at only .0176 grms. This low acceleration level results in a low accelerometer output signal, which is reflected by the low coherence value of 0.8. Both the sensitivity and phase measurements of these data deviate from the general trend. These points are included for information only and may be disregarded when assessing the data. Probe A is observed to exhibit a dynamic range of greater than 150 db as it was found to accurately measure displacement as small as 1 microinch. This statement is based on a measurement recorded at 1000.98 Hz and 0.1 grms (coherence = 0.997). It took a displacement this small for the coherence to drop below 0.999.

The net sensitivity error is noticeably reduced by the gain and sensitivity corrections. Phase error introduced by probe A is observed to increase in a linear fashion throughout the frequency range.

White Noise Data: Gain and phase versus frequency plots of the raw and corrected white noise data are shown in Figures 5 and 6. These data were obtained from sensitivity and phase spectra recorded using band limited white noise input to the shaker across the following bands: 30-1000 Hz, 500-2500 Hz, and 2500-10000 Hz. The overlapping data at 500 Hz, 750 Hz, 1000 Hz and 2500 Hz are observed to be dependent on the band input used. The data recorded at the different bands are indicated in Figure 5. These discrepancies may be due to non-linearities in the measurement system. These data exhibit the same general trends as the sinusoidal data.

A comparison of the corrected sinusoidal and white noise data is shown in Figures 7 and 8. Disregarding the low coherence sinusoidal data at 102.52 Hz and disregarding the white noise data discrepancy at 2500 Hz (again with a low coherence), the corrected plots show good agreement between the sinusoidal and white noise data. The sensitivity error due to probe A is found to be limited to ∀5% up to 5000 Hz with respect to the static calibration constant. A lagging phase error is introduced by probe A, which is seen to increase linearly with frequency, reaching a maximum value of -16 degrees at 5000 Hz.

RESULTS AND DISCUSSION - PROBE B

The static calibration data for probe B is shown in Figure 9. The curve is seen to be more linear than for probe A. The possible implications of this will be discussed below.

Sinusoidal and white noise tests were conducted in the same fashion as for probe A. Corrected sensitivity and phase versus frequency plots of the sinusoidal and white noise data are shown in Figures 10 and 11. Probe B is observed to exhibit more sensitivity and phase error throughout the test frequency range. The sensitivity and phase error reach maximum values of 35% and 150 degrees, respectively, at 5000 Hz. Unlike probe A, however, the sensitivity as well as the phase error introduced by probe B are observed to increase linearly up to 5000 Hz.

Also unlike probe A, the overlapping data in the white noise bands are in good agreement. Whereas probe A sensitivities indicated by the two white noise bands differed by about 4% in the 500 to 1000

Hz range, the bands for probe B differed by only about 1%. Also, the sinusoidal data matches the white noise data more closely than it did for probe A. This is believed to be due to probe B having shown better amplitude linearity in the static calibration data. This should be verifiable with additional tests. Additionally, another probe A with a static calibration curve as straight as probe B could likely be found and tested.

PROBLEMS

There are two problems with the data presented which could be due to errors in the measurement approach. One problem, mentioned earlier for probe A, is the discrepancy in the corrected sensitivity for overlapping white noise bands and also for sine wave versus random. It is suspected that transducer amplitude nonlinearity may be the cause, and results for probe B support this, but this has not been verified. Operator error(s) somewhere in the acquisition/analysis process may also have caused this. Note that operator error can create sensitivity error more readily than phase error, and the discrepancies here are much more pronounced in the sensitivity data.

The other problem is in the sensitivity versus frequency data. It was expected that probe sensitivity would decrease with frequency. In an overall sense it does decrease. However, the corrected sensitivity data should approach one at zero frequency (i.e., the static cal). Figure 7 shows that probe A definitely misses the mark on the high side by about 2%. Probe B also misses the mark although low by about 2%. There presently is no explanation for this other than possibly poor signal quality from the accelerometer at the low end of the frequency range, or transducer nonlinearity. However, the sinusoidal data at 200 Hz had a coherence of 0.999, and the largest sinusoidal amplitude was only 1.3 mils. Another aspect of the probe A sensitivity curve which was unexpected is the observed leveling off at high frequency (see Figure 7). Sensitivity was expected to decrease continually in the fashion displayed by probe B.

RECOMMENDATIONS

In retrospect, some important improvements could be made in the test method. These improvements would enhance accuracy, hopefully resolve existing discrepancies, and reveal other significant characteristics about eddy current displacement transducers. They include:

1. Testing more proximity transducer systems for unit-to-unit variations.
2. Acquire spectral calibrations of all measurement subsystems at all gain settings, and check with both white noise and sinusoidal waveforms.
3. Acquire measurements of overall spectral noise floors.
4. Inspect sinusoidal waveforms as a visual check of coherence.
5. Convert sinusoidal time data directly to a plot of millivolts versus mils.
6. Investigate affect on probe sensitivity of aiming probe at small target (i.e., centered versus off-centered aiming at the shaker head target).
7. Perform checks on amplitude linearity vs. frequency at different white noise grms levels.
8. Account more completely for the accelerometer calibration procedure, or use the NBS accelerometer directly, and also measure accelerometer amplitude linearity.
9. Make sure MASSCOMP interchannel crosstalk doesn't influence the coherence estimates.
10. Resolve discrepancy between static and low frequency dynamic data.
11. Have the NBS phase calibrate the accelerometer.

12. Use a better low frequency accelerometer or velocity transducer to verify convergence to the static calibration.

CONCLUSIONS

Tests were conducted to measure the sensitivity and phase characteristics of proximity transducer systems from two manufacturers as functions of frequency from 100 Hz to 5000 Hz. As expected, both systems were found to have sensitivity and phase characteristics which deviate from the static sensitivity at increasing frequency. Probe A transducer sensitivity was found to be within ∀5% of the statically measured sensitivity for frequencies up to 5000 Hz. The probe B sensitivity decreased linearly to 65% of the static value at 5000 Hz. Both transducers were found to exhibit a wide dynamic range capable of accurately measuring relative displacements on the order of one microinch at 1000 Hz. This suggests that measurement uncertainties associated with using an eddy current probe to make dynamic measurements would best be quoted as a constant percentage of full scale readout (i.e., like a piezoelectric accelerometer). The appropriate percentage uncertainty value should be determined by statistical analysis of static calibration data. A significant phase delay was measured for the both proximity transducer systems. The phase delays are typical of a time delay effect as they are observed to increase linearly reaching a maximum of 16 and 150 degrees of lag at 5000 Hz for probe A and probe B, respectively. These equate to time delays of 8.9 and 84 microseconds. These observations are supported by both the sinusoidal and white noise data. Several important anomolies were present in the data which may be due to transducer amplitude nonlinearity, although this has not yet been verified.

REFERENCES

1. Murphy, B.T., Scharrer, J.K., and Sutton, R.F., "The Rocketdyne Multifunction Tester- Part I: Test Method," Proceedings of the Sixth Workshop on Rotordynamic Instability Problems in High-Performance Turbomachinery, Texas A&M University, May 21-23, 1992.

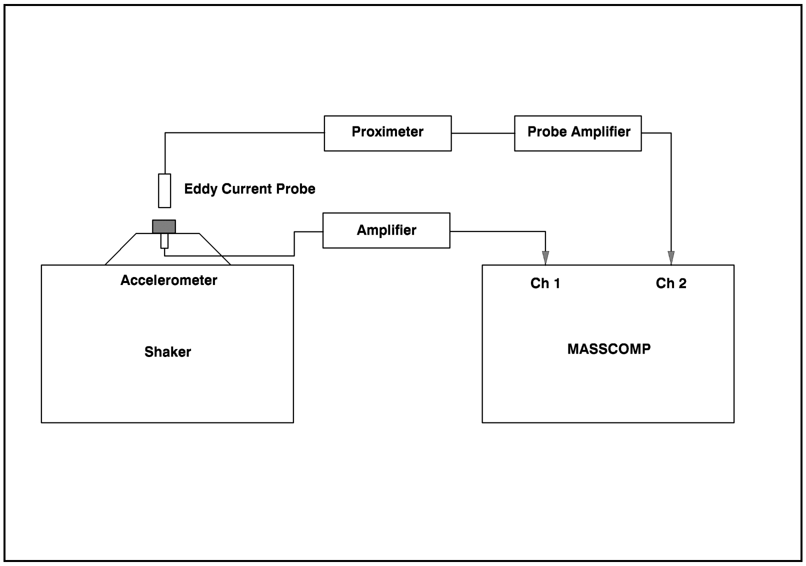

Figure 1. Test Setup.

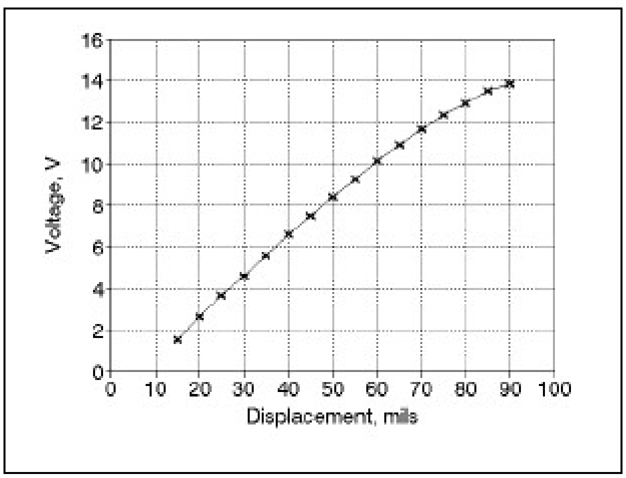

Figure 2. Probe A Static Calibration Curve.

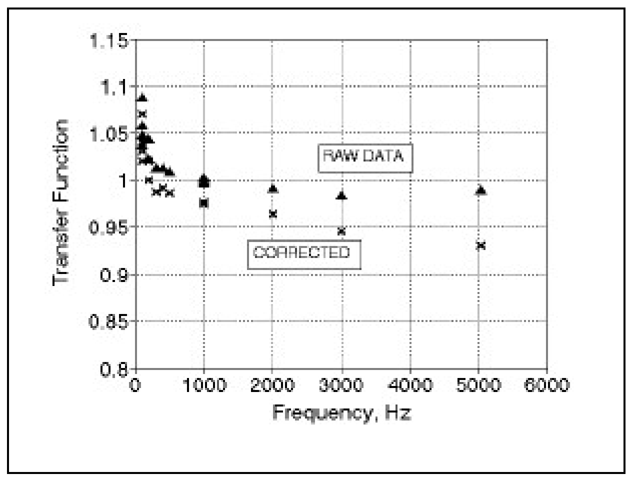

Figure 3. Probe A Sine Wave Gain Data, Raw and Corrected.

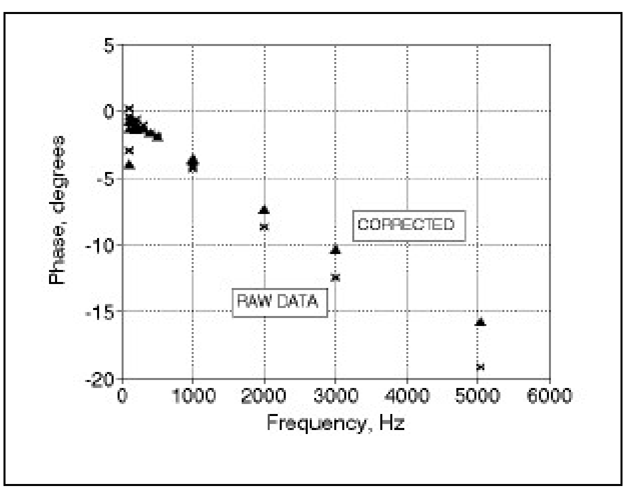

Figure 4. Probe A Sine Wave Phase Data, Raw and Corrected.

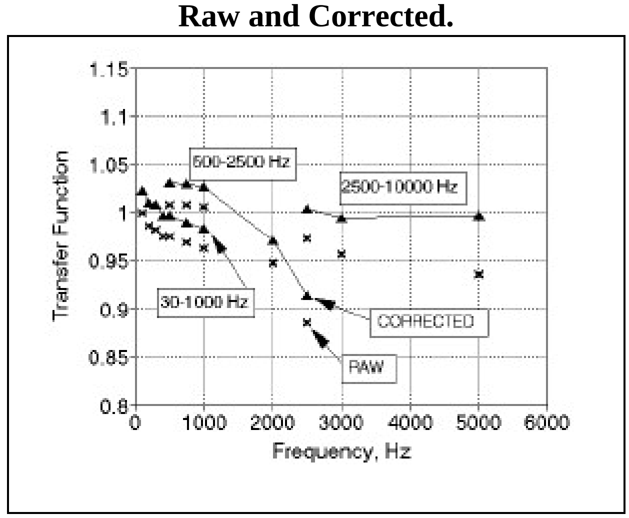

Figure 5. Probe A White Noise Gain Data, Raw and Corrected.

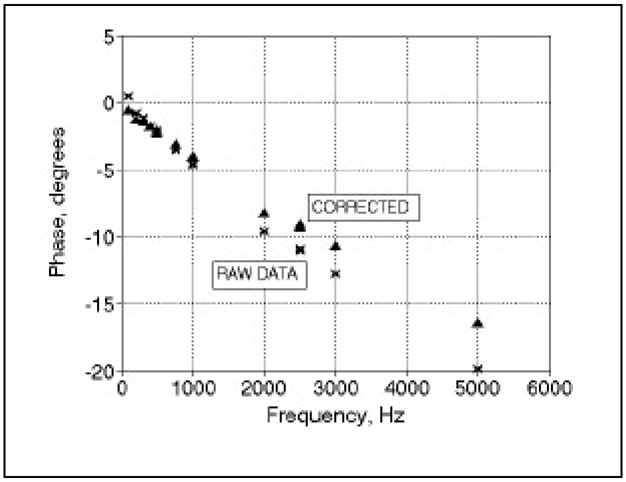

Figure 6. Probe A White Noise Phase Data, Raw and Corrected.

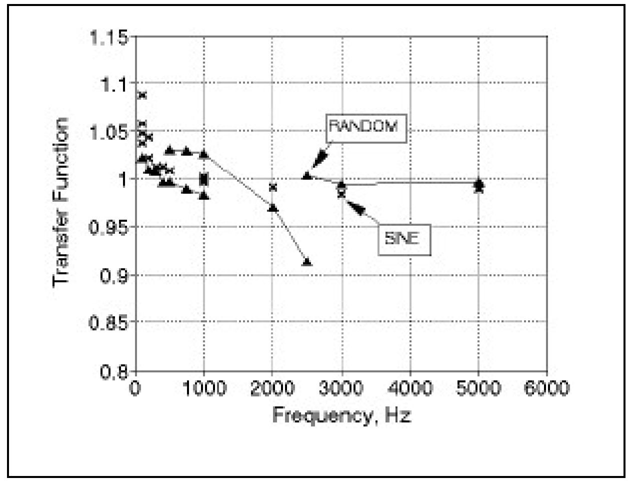

Figure 7. Probe A Corrected Gain Data, Sine and White Noise.

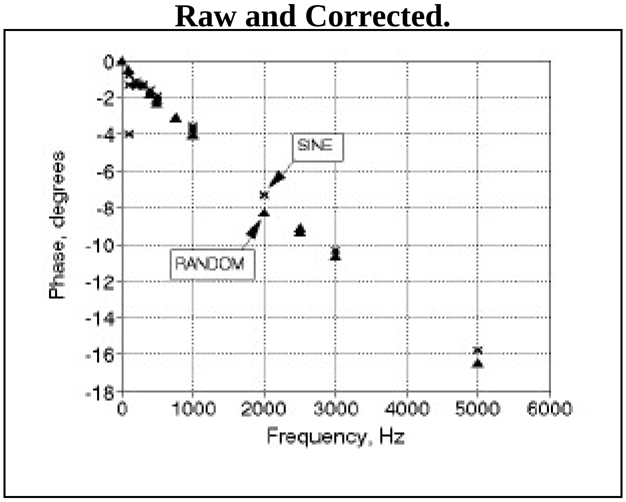

Figure 8. Probe A Corrected Phase Data,

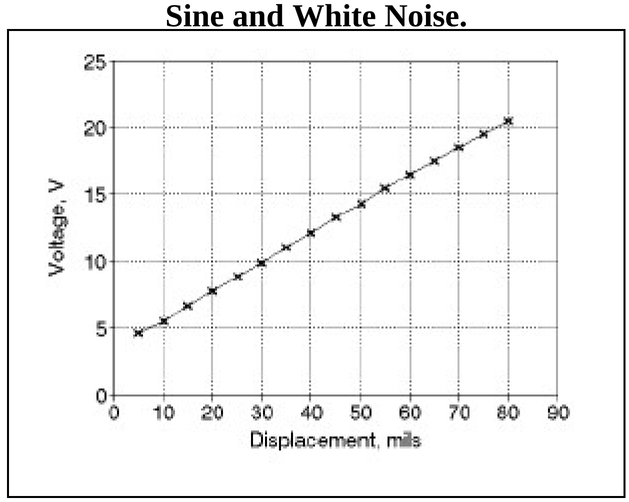

Figure 9. Probe B Static Calibration Curve.

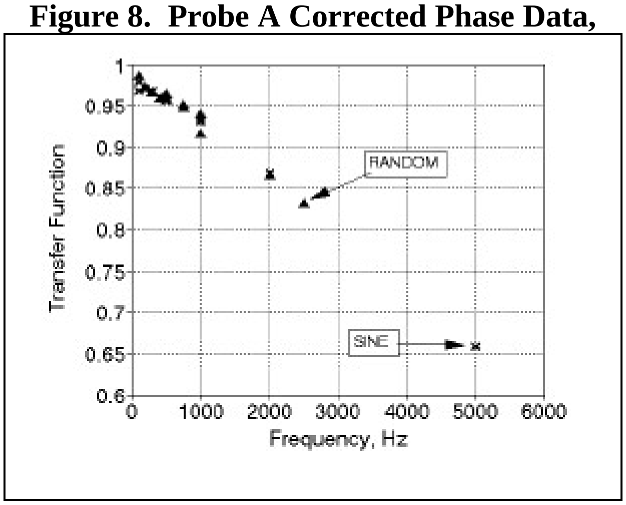

Figure 10. Probe B Corrected Gain Data, Sine and White Noise.

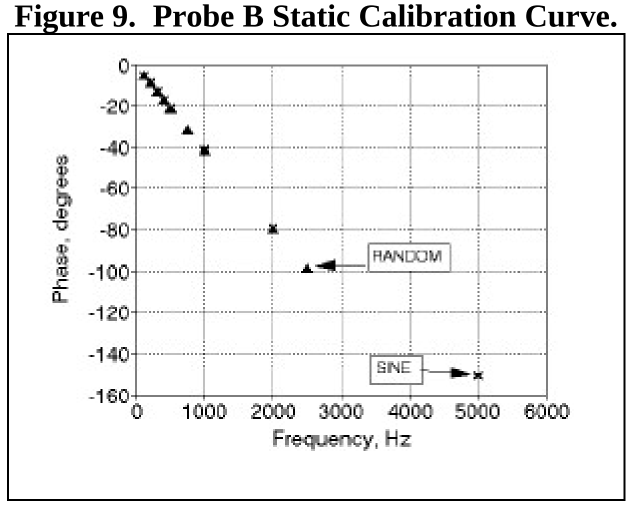

Figure 11. Probe B Corrected Phase Data, Sine and White Noise.