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FREQUENCY RESPONSE CALIBRATION OF RECESS-MOUNTED PRESSURE TRANSDUCERS

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ABSTRACT

A technique is described for measuring the frequency response of pressure transducers mounted inside a model, where a narrow pipette leads to an orifice at the surface. An acoustic driver is mounted to a small chamber which has an opening at the opposite end with an O-ring seal to place over the orifice. A 3.18 mm (1/8 inch) reference microphone is mounted to one side of the chamber. The acoustic driver receives an input of white noise, and the transducer and reference microphone outputs are compared to obtain the frequency response of the pressure transducer. Selected results are presented, in the form of power spectra for both the transducer and the reference, as well as the amplitude variation and phase shift between the two signals as a function of frequency. The effect of pipette length is discussed, as well as the use of this technique for identifying both blocked orifices and faulty transducers.

INTRODUCTION

Measurement of time-dependent pressure distributions on surfaces has always been important in aerodynamics. One method is to mount flat transducers directly on the surface. While simplifying installation and providing maximum frequency response, this approach produces undesirable flow disturbances. Another method is to place flat transducers in surface recesses. This technique preserves a smooth surface, but is difficult to apply to models (such as helicopter or turbomachinery blades) with small leading edge radii of curvature and thin trailing edges. Transducers with diaphragms parallel to the surface also may have undesirable sensitivity to local strains. An alternate approach is to mount a cylindrical transducer inside the body and use a thin tube to connect the transducer to a small opening on the surface. Not only does this approach minimize the problem of affecting the aerodynamics, but it also provides for nearly a point measurement of the pressure. However, a long tube can cause propagation delays between a pressure change at the surface and the resultant fluctuation seen at the face of the transducer. In addition, the combination of an orifice at the surface of the body, coupled with a thin pipette leading to a small cavity at the sensing area of the transducer, produces a Helmholtz resonator. If only steady-state or low frequency pressure measurements are desired, these effects are of less concern to the researcher. However if high-frequency fluctuating airloads are desired, such as for aeroacoustic applications, then these effects must be examined and, if possible, measured. In this paper, a technique to experimentally determine, in situ, the frequency response of recess-mounted pressure transducers will be described.

Much of the work concerning the response of pressure transducers mounted beneath small orifices has been concerned with the time delay associated with a change in the static pressure at the surface being detected by the transducer. Sinclair and Robins (Ref. 1) devised a theory to compute this time delay in manometer-based measurement systems using capillaries to connect surface orifices to the larger diameter manometer tubes. They then experimentally verified these results using a controlled pressure valve connected to a large air tank. A differential pressure could be obtained at the orifice by adjusting the valve, and the time required for the sensing manometer to measure the new pressure was recorded, with the results agreeing quite well with their theoretical calculations. More recently, Wagner and Dale (Ref. 2) examined a similar problem for the specific case of low dynamic pressures measured in hypersonic tunnels. They developed a technique to design the measurement system so as to minimize the time delay, and used a similar experimental approach to evaluate their optimum designs. Bershader (Ref. 3) used a shock tube to examine the dynamic response of pressure transducers mounted with an orifice at the surface and a narrow pipette leading to a small chamber at the face of the transducer. This technique obtained very good results, but required the transducers to be mounted in the wall of the shock tube. Hence, it could not be used for situations where it is required to examine the response of transducers already mounted in models. Manley (Ref. 4) developed a technique for examining the frequency response of pressure transducers using acoustic pressure waves. A microphone was driven with a signal, so it acted as a sound source instead of the usual sound sensor. A pressure transducer was mounted in a fixture, along with a reference sensor, and a series of pure tones was used to measure the transducer's frequency response. Again, this technique, although innovative, required access to the transducer, and thus was not suitable for in situ applications, although it did allow for measurement of transducer response up to high frequencies (30 kHz).

Tijdeman (Ref. 5) developed a very good theory for calculating the response of a recess-mounted pressure transducer, including effects due to flow over the orifice, but the theory, as have all others to date, requires the precise physical dimensions of the orifice, pipette, and recessed chamber to provide an accurate calculation. Since a small change in some of these parameters can radically affect the frequency response, approximations are not suitable. Irwin, et al (Ref. 6) developed a technique to examine, in situ, the response of a single sensor. Using a fluidic signal generator with a white noise input, along with a reference transducer, the transfer function of a single sensor was obtained. Spectral techniques were then used to correct the measured data. This technique showed good results, but for limited ranges of frequency (less than 100 Hz) and velocity (15 m/s (50 ft/s)).

As part of a joint effort between the Army's Aeroflightdynamics Directorate, NASA's Ames and Langley Research Centers, United Technologies Research Center (UTRC), and the Sikorsky Aircraft Division of United Technologies, a model helicopter rotor was tested in a large acoustic wind tunnel, the Duits-Nederlandse Windtunnel (Ref. 7). The 2.87 m (9.4 ft) diameter model rotor was fabricated by UTRC and Sikorsky to match the aerodynamic and dynamic properties of a current technology main rotor. A total of 176 cylindrical pressure transducers were mounted in the four-bladed rotor, using the recess-mounted approach described above. The blades have a chord of 91.4 mm (3.6 in) and a maximum thickness of 8.64 mm (0.34 in). Since one of the primary objectives of the test was to obtain simultaneous acoustic and blade pressure measurements for validation of acoustic prediction methods, the frequency response of the transducers as mounted in the blades was a major concern. The transducers were mounted with the "shortest possible" pipette length, so exact dimensions were not available for each transducer. The dimensions of the internal cavities also varied from transducer to transducer. Thus, any calculations would only be approximations, which, although useful as a guide, would not be acceptable as a complete validation of the frequency range of the data set. In an effort to more completely verify the frequency response of the transducers, a technique to measure this response in situ was developed.

With such a large number of transducers, it would be desirable to design calibration techniques that simultaneously examined the complete blade set, or at least an entire blade. The static calibration of the transducers was obtained in this manner, by placing the complete set of blades inside an environmental chamber, and measuring the output at eight pressure levels. The calibration was repeated at several temperatures representative of expected operating conditions. A least-squares linear curve fit was used to determine sensitivity and offset voltages at each temperature. During testing, the time-dependent pressures at each transducer were determined from the measured output voltages and blade temperatures. The steady-state calibration was checked during testing by placing a graphite sleeve over each blade, and pressurizing the sleeve to four different pressures. A similar approach was used by Watts (Ref. 8) for a single pressure-instrumented blade of a full-scale rotor.

Several concepts for dynamic calibration of an entire blade were proposed, but none could meet the requirements of rapid fabrication (to obtain results before the wind tunnel test was performed), and transportability (to allow the calibration device to also be available at the wind tunnel). The final design, which will be described here, involved coupling the approach used by Manley (Ref. 4), using acoustic pressures as the fluctuating source, with the in situ approach of Irwin et al (Ref. 6) to measure the frequency response of an individual pressure transducer.

EXPERIMENTAL SET-UP

Pressure Transducer Mounting

The pressure transducers used in the rotor blades for the test were 1.57 mm (.062 in) diameter Kulite transducers with a built-in cavity at the transducer sensing area. The nominal cavity is a 1.52 mm (.060 in) diameter, 1.52 mm (.060 in) long cylinder, with a 0.46 mm (0.018 in) diameter, 0.51 mm (.020 in) long cylindrical pipette leading from one side. Figure 1 shows a sketch of a rotor blade, along with the nominal Kulite geometry. Wherever possible, the outer edge of this pipette was flush-mounted at the surface of the rotor blade. However, because of blade geometrical restrictions (in particular near the blade trailing edge, where the blade thickness was less than the transducer thickness), it was not always possible to mount each transducer directly below the measurement location. In these cases, the 0.46 mm (0.018 in) diameter pipette was extended. The maximum pipette length, used to reach locations within 6% of chord of the trailing edge, was 12.7 mm (0.5 in).

Calibration Device

The approach selected for this task involved using acoustic pressure waves to obtain the frequency response of an individual pressure transducer, as it was mounted in the blade. An acoustic cavity was designed to have a nearly uniform sound field everywhere in the cavity throughout the frequency range of interest (50 Hz - 10 kHz). This cavity was cylindrical in shape, with 5.08 mm (0.2 in) diameter and 5.08 mm (0.2 in) length, and was machined into an aluminum block. A University Sound ID 60 watt acoustic driver provided the sound source, and was mounted at one end of the cylinder, while at the other end was a 4.76 mm (3/16 in) O-ring to place over the orifice of the transducer to be tested. In the sidewall of the cavity, near the O-ring end, was a 3.18 mm (1/8 in) B&K 4138 pressure microphone, which was used as a reference to compare to the pressure transducer response. Figure 2 shows a sketch of the test apparatus. A Dynaco power amplifier was used to power the acoustic driver, and any desired input signal could be used. To verify that the same acoustic level appeared at both the reference microphone and the orifice, a second microphone was placed at the opening, and its output was compared to the reference. The two microphones showed identical levels, thus insuring that the measurement is the response of the transducer as mounted in the blade. A microphone was examined as a possible sound source, but the maximum output levels from a 12.7 mm (1/2 in) microphone were much lower (nearly 50 dB less) than those from the acoustic driver. In order to insure an adequate signal-to-noise ratio (SNR), the driver was selected as the sound source.

Instrumentation

A schematic of the instrumentation used for the test is shown in Figure 3. An input signal from either a frequency generator or a white noise generator passes through the power amplifier, which operates the acoustic driver. The reference microphone is operated by a microphone power supply, and the output is passed through both an instrumentation filter and an amplifier before being input to the data acquisition system. The pressure transducers were controlled by their own electronics, and each transducer's output signal was also input to the data acquisition system. The signal conditioning and data acquisition system for the pressure transducers and related instrumentation is described in Ref. 7.

The reference microphone was calibrated using a handheld calibrator such that 1.414 volts equaled 114 dB sound pressure level (SPL) at 1000 Hz, with the instrumentation amplifier gain for the microphone set at 40 dB. After calibration, the reference microphone, with its grid cap removed, was installed in the sidewall of the cavity, and a signal was input to the acoustic driver. A problem with this driver is that it does not have a "flat" frequency response (i.e., for a constant voltage level input, the driver produces different sound levels at different frequencies). To counteract this problem, when a pure tone was used as input, a level controller was used to vary the input signal amplitude so as to maintain a constant amplitude output from the reference microphone (refer to Figure 3 to see that the reference microphone also acted as a feedback signal to the level controller). The level was varied from 120 dB to 145 dB at several different frequencies to find the optimum level of operation for good signal-to-noise ratio (SNR) without overdriving the acoustic driver and without distortion from the amplifier. A sound pressure level of 134 dB on the microphone was found to be optimum for maximum SNR and safe operation of the electronics. The pure tone also provided a good check for the electronic noise floor of the pressure transducers, by examining the narrowband spectrum, and observing where the tone rises out of the noise. A typical plot is shown in the left hand side of Figure 4, where it is seen that the noise floor of this particular transducer is around 100 dB at lower frequencies, and drops to below 80 dB around 2 kHz. This is similar to the spectrum of the reference microphone, as seen on the right hand side of Figure 4, indicating that the noise floor for the pressure transducer is at or below that of the data acquisition system.

Measurement Approach

With the calibration device set up and functioning properly, it was possible to begin the frequency response check of the pressure transducers at discrete frequencies. The coupler was placed over a pressure transducer orifice, and a number of frequencies from 50 Hz to 10 kHz were investigated. The 134 dB sound pressure level was found to be sufficient to produce a good SNR over this frequency range, and produced a relative frequency response curve based on discrete points. This method of checking the frequency response of the transducer was necessary to establish the baseline data, but it was very time consuming to sample each frequency separately. Thus, the use of a white noise input, to examine the entire frequency range at once, was investigated. However, this method would only be valid if the SNR across the entire frequency range was sufficient to produce the same response curve as the one generated by discrete frequency insertion. Using white noise also meant that the level controller could not be used, because it can only amplify/attenuate the entire signal, and not selectively adjust different frequency bands.

The sine wave oscillator and level regulator were replaced by the white noise generator and the amplitude was adjusted to 134 dB OASPL. As described earlier, the frequency response of the acoustic driver to white noise input is quite nonlinear. However, the amplitude and SNR were sufficient for the pressure transducers across the entire frequency range of interest.

Data Acquisition and Reduction

The pressure transducer and reference microphone signals were simultaneously digitized at a sample rate of 20 kHz. Anti-aliasing filters were used to eliminate any frequency content above 10 kHz. The digitized data were then transformed into the frequency domain using 1024 point FFTs, with 20 ensemble averages used for each channel. The power spectrum of each signal was computed, along with the phase from the cross-spectrum of the two signals. However, the amplitude portion of the cross-spectrum was not as informative as a delta-dB plot of the pressure transducer power spectrum minus the reference microphone's power spectrum. This allows for easy comparison of the amplitude response of each of the pressure transducers with respect to the microphone spectrum, which is constant for all tests. A sample white noise response is shown in Figure 5 for a transducer located near the mid-chord region of a blade. The response of the pressure transducer with respect to the reference microphone was comparable with both sine wave and white noise inputs. This meant that the response function of the pressure transducers could be measured using white noise, thus saving considerable data acquisition time. Data were then acquired for each transducer, one at a time, with an amplitude response plot generated, and raw digital data stored on tape for later processing.

RESULTS

The data of Figures 5-7 show typical pressure transducer responses from various positions on the blade. Figure 5 shows a transducer in a position at the middle of the blade, such that the pipette length is around the nominal .02 inch. As discussed previously, the nonlinear frequency response of the acoustic driver is indicated by the wide variation in amplitude as a function of frequency for both the pressure transducer and the reference microphone. The delta-dB curve shows that this particular pressure transducer has a fairly linear response at the lower frequencies, but above 4 kHz it slowly approaches resonance, although the resonant peak appears to be somewhat above 10 kHz. The phase response curve also indicates a slow change from a 0° shift at lower frequencies to a drop beginning around 8 kHz. This is a fairly typical response for a transducer mounted with a "short" pipette. Some transducers with similar mountings have resonances as low as 8 kHz, while others have much higher resonant frequencies, such that over the range 0-10 kHz, the response is nearly flat. These results indicate the frequency response is very sensitive to the installation geometry details.

Figure 6 shows a typical response for a pressure transducer mounted at the trailing edge of a blade. These transducers all show a resonance of as much as 10 dB between 3 and 4 kHz, with some rolloff of response above that. In addition, they also reveal a -180° phase above the resonant frequency, which should be expected. Again, Figures 5 and 6 show typical results for most of the 176 transducers tested. However, a few results provided some useful diagnostic information, and will be discussed next.

Figure 7 shows a "bad" response curve. This transducer responded to static pressure changes, and had even maintained its static pressure calibration, but showed almost no frequency response whatsoever. This was apparently due to blockage of the orifice by small particles or debris. While this problem was seldom encountered, it shows the utility of a dynamic response check (in addition to a static calibration) in diagnosing problems and explaining anomalies in the data. After cleaning the orifices for those few transducers having such results, many of them exhibited the "typical" results seen in Figures 5 and 6.

Calculations were performed by William G. Chapin of NASA Langley's Instrument Research Division using the Tijdeman-Bergh equations (Ref. 5), and the results were transmitted in an internal memorandum dated September 9, 1987. Amplitude and phase response was predicted for the estimated geometries of the transducers used in Figures 5 and 6, and the results were quite similar, with resonant frequencies predicted of around 13 kHz and 3 kHz, respectively. This demonstrates the validity of using acoustic pressures to measure the frequency response. While these calculations were performed assuming no flow over the orifice, Tijdeman's formulation also provides the capability to examine Mach number effects on the frequency response. Additional calculations by Chapin indicate that, at flow conditions expected over the blades, the response can change in both amplitude and phase. Typically, the frequency response tends to degrade at higher frequencies, as though a low pass filter with a very slow rolloff was being applied to the signal, with the filter set slightly below the resonant frequency measured under no-flow conditions. Hence, measurements made using this technique indicate a frequency range over which experimental data are valid, but should not be used in an attempt to correct that data.

Sample blade pressure data from the wind tunnel test are presented in Figures 8 and 9. Figure 8 contains data presented in Ref. 9, and shows pressure coefficient as a function of azimuthal position for one transducer during a simulated descent condition. Both the ensemble (or phase-locked) average of 64 rotor revolutions (Figure 8a) and three instantaneous time histories for single revolutions (Figures 8b-8d) are shown. Each time history is composed of 1024 individual samples, and was acquired by using the output of a 1024 per revolution shaft encoder to synchronize the analog-to-digital converter. A large low frequency (one to three per revolution) signal is present, caused primarily by periodic changes in blade cyclic pitch and relative velocity. Higher frequency, impulsive pressure variations caused by interactions between the blade and the tip vortices from preceding blades are present in the first and fourth quadrants (azimuth angles of 0-60 and 270-330°). Also present are random fluctuations near 360°. The impulsive variations are periodic with azimuth, and therefore are observed both in the individual cycles and in the ensemble average, while the random fluctuations are removed by averaging. The equivalent ensemble averaged narrowband spectrum (obtained by averaging spectra computed for 16 individual cycles) is shown in Figure 9, where the low frequency peak is due to the periodic variation, the impulses produce the humps between 500 Hz and 2 kHz, and the random fluctuations produce the broadband portion of the spectrum above 2 kHz. Further discussion of the blade pressure results may be found in Ref. 9.

It should be noted here that those transducers producing "bad" response curves (such as Figure 7) passed static calibration checks, and usually measured the lower frequency variations, but failed to accurately capture the impulsive interactions or random fluctuations. In extreme cases the output had no unsteady content at all.

CONCLUSIONS

A technique is described for measuring, in situ, the frequency response of a recess-mounted pressure transducer as a test of the valid frequency range of the measured data. Both the hardware design and the experimental approach are presented. Results validate previous work indicating the importance of mounting dimensions to the frequency response of each individual pressure transducer.

The use of this approach to identify or diagnose problems, either transducer failure or blocked orifices, was demonstrated. The portability of the system, allowing field use, should be emphasized. Although other techniques may provide similar results, this approach may be used with the transducers remaining in the blades, examines frequency response beyond 10 kHz, and can be used during experiments as quality checks. Because flow effects cannot be examined, this technique should not be used, nor was it intended, to correct measured data, but it does indicate the frequency range where the measured data should be reliable, and can serve as a diagnostic tool to examine anomalies in the measured data.

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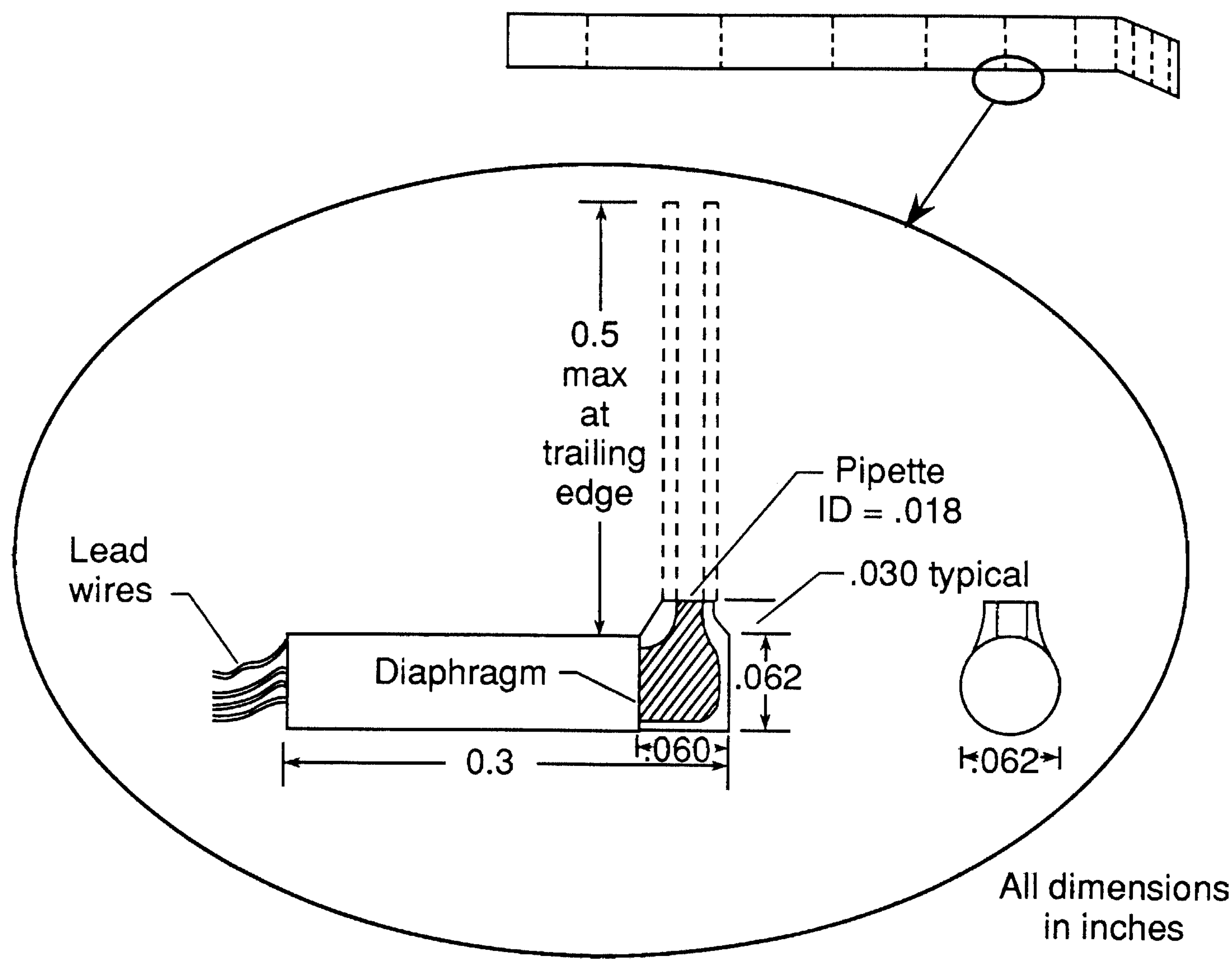

Figure 1. - Typical Pressure Transducer Mounting Geometry.

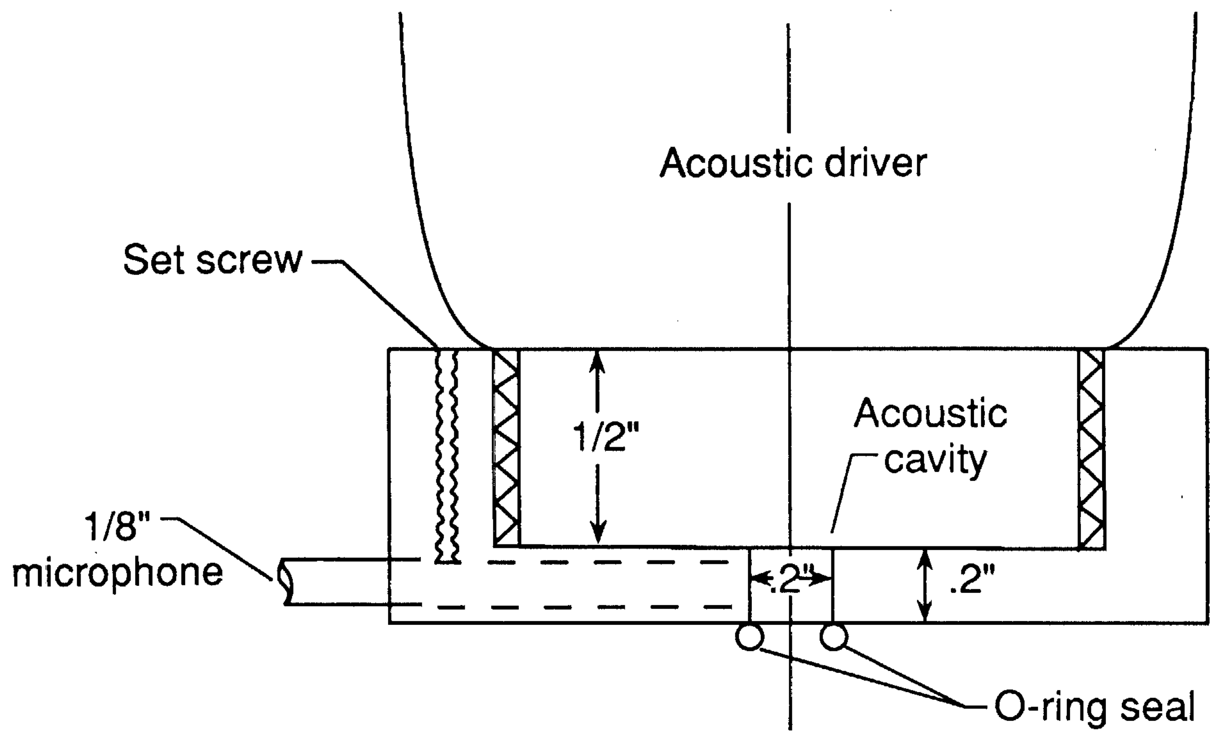

Figure 2. - Cross Section of Acoustic Calibration Apparatus.

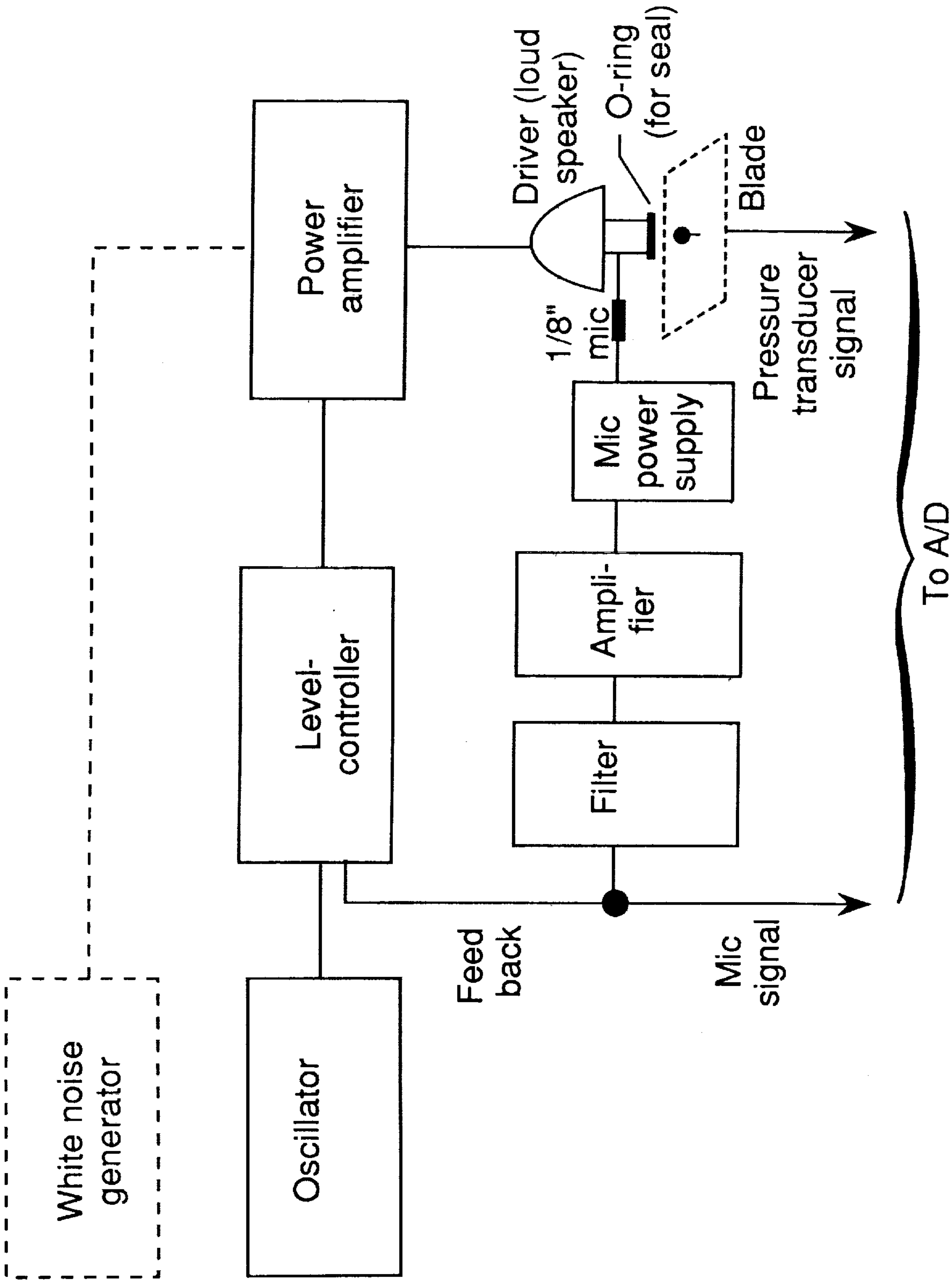

Figure 3. - Instrumentation Setup for Frequency Calibration.

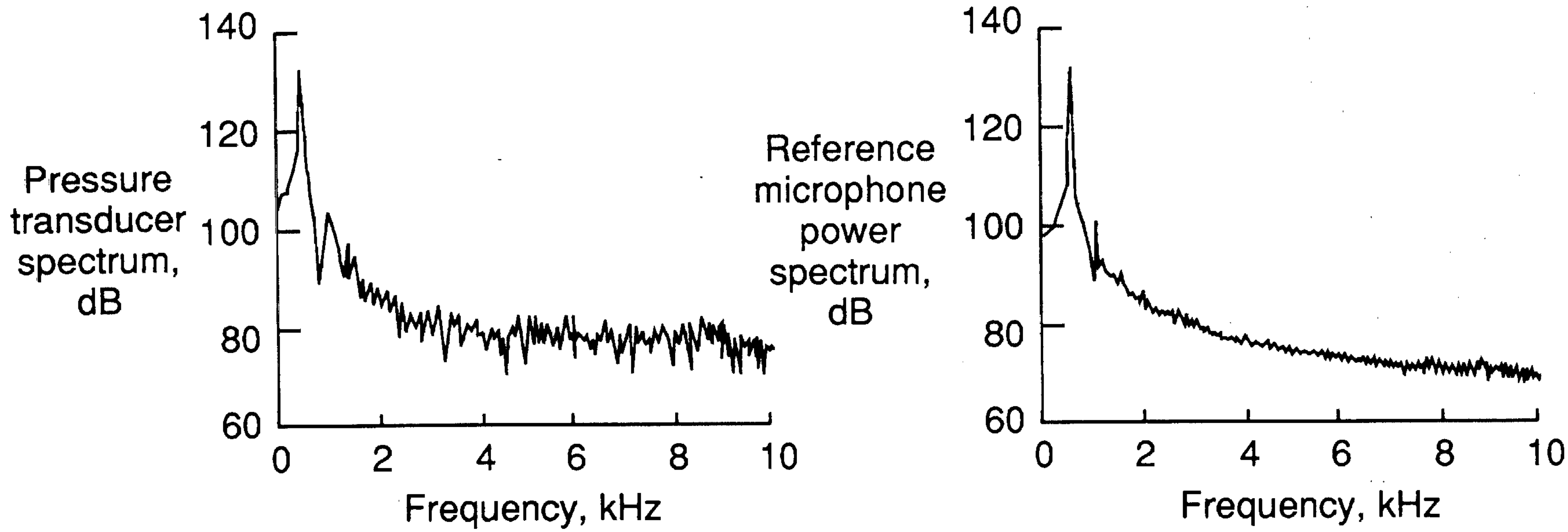

Figure 4. - Sine Wave Insertion Showing Effective Background Noise Levels.

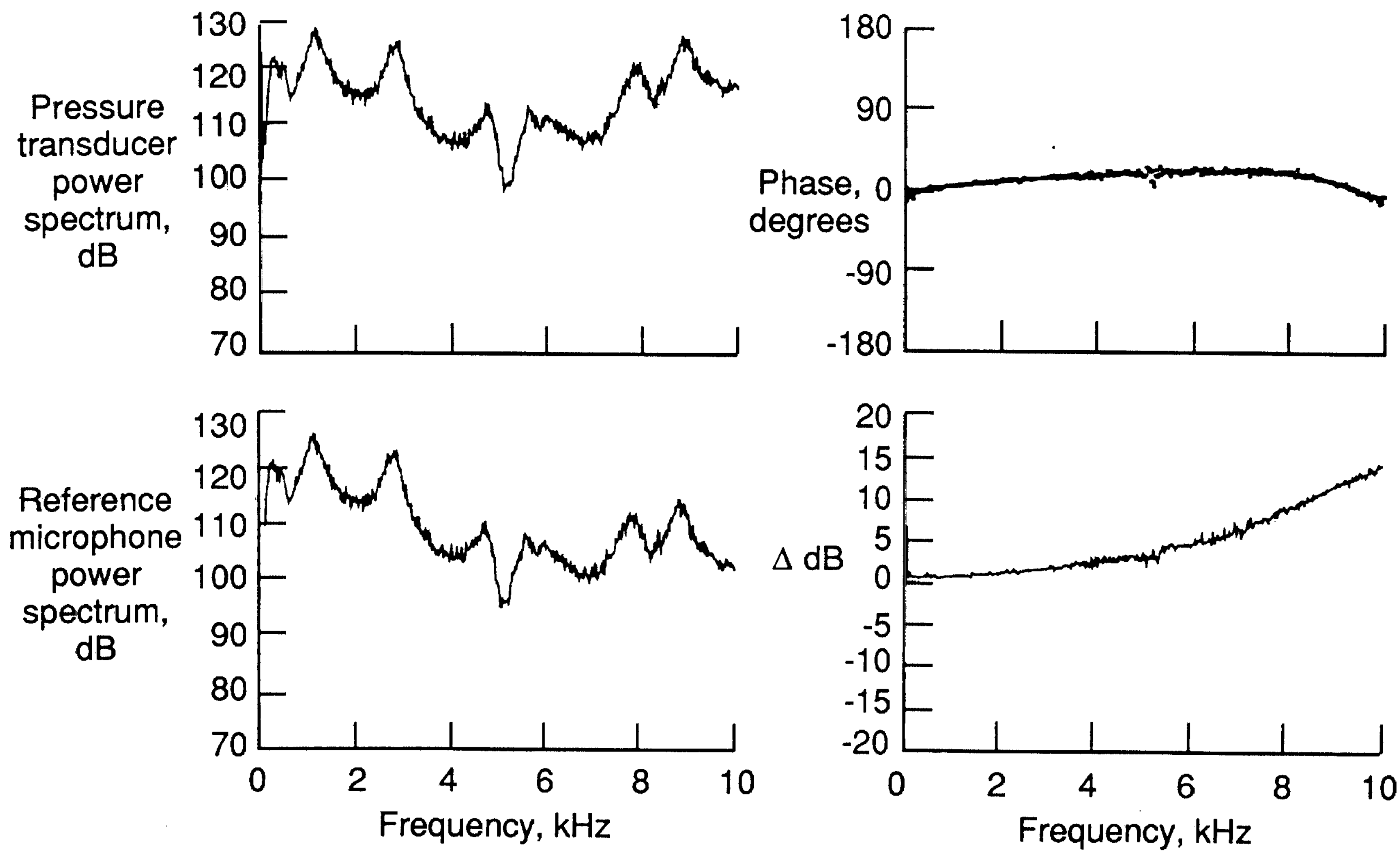

Figure 5. - Typical Kulite Response for Short Pipette Lengths.

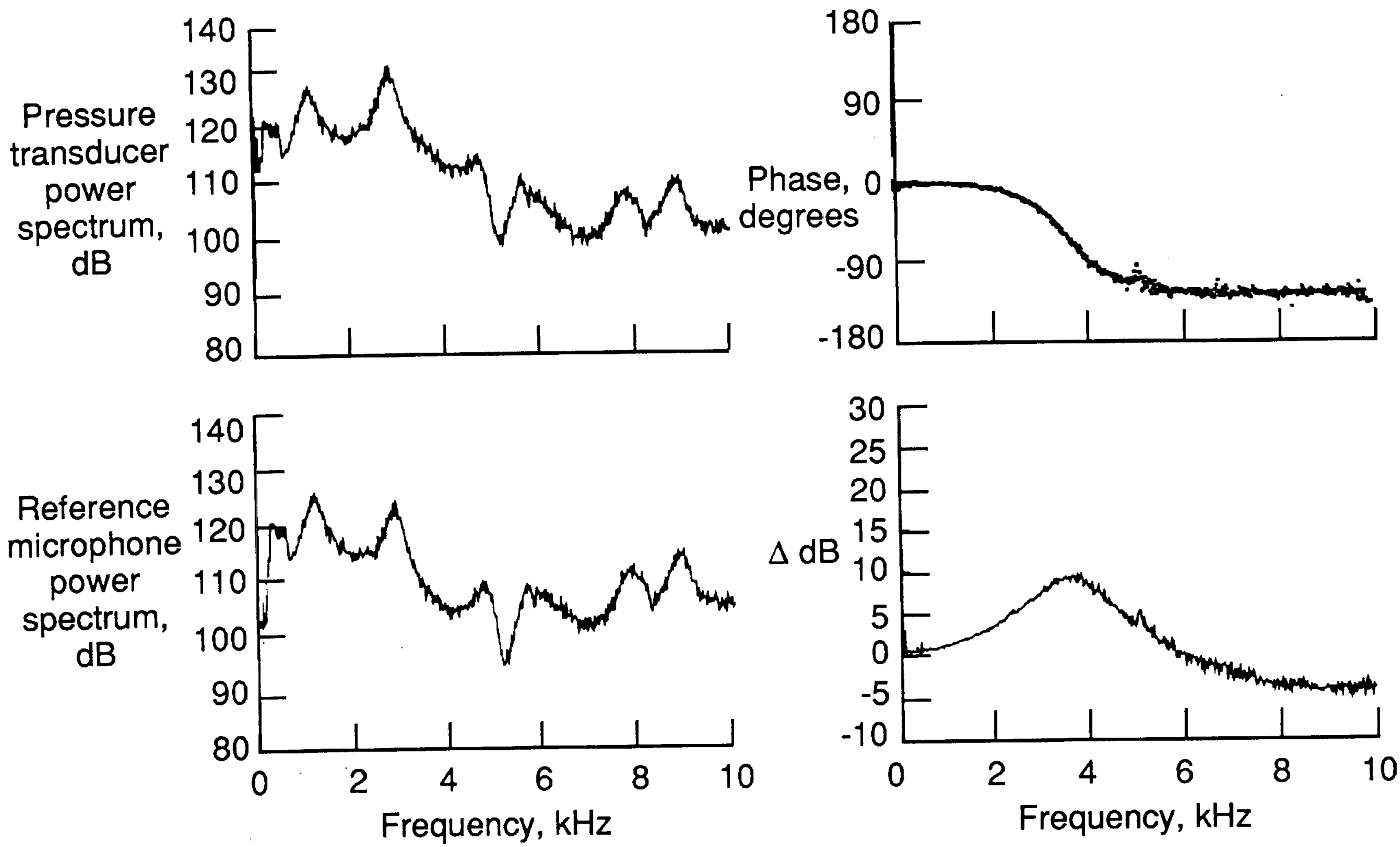

Figure 6. - Typical Kulite Response for Long Pipette Lengths (Near the Blade Trailing Edge.)

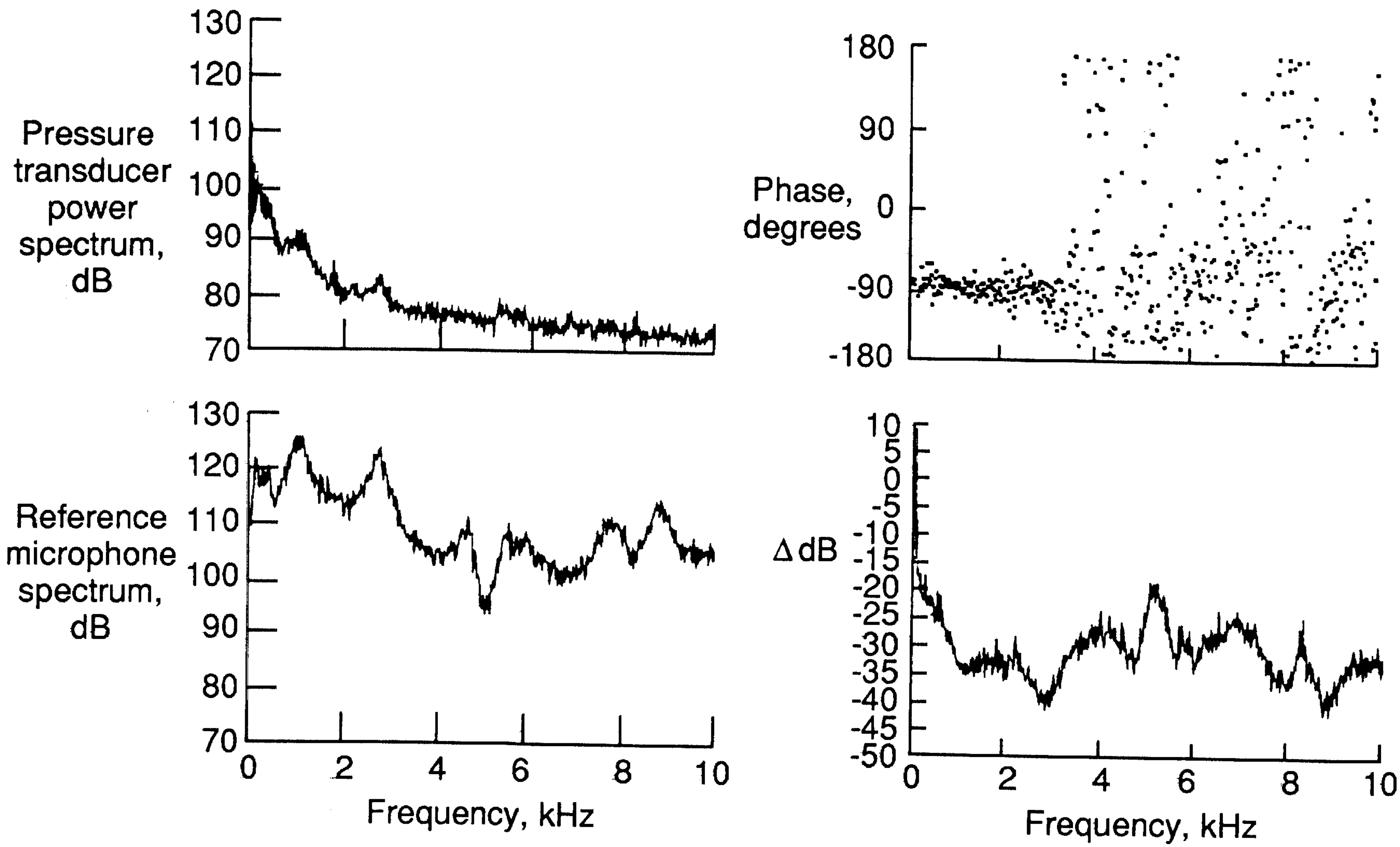

Figure 7. - Sample "Bad" Frequency Response.

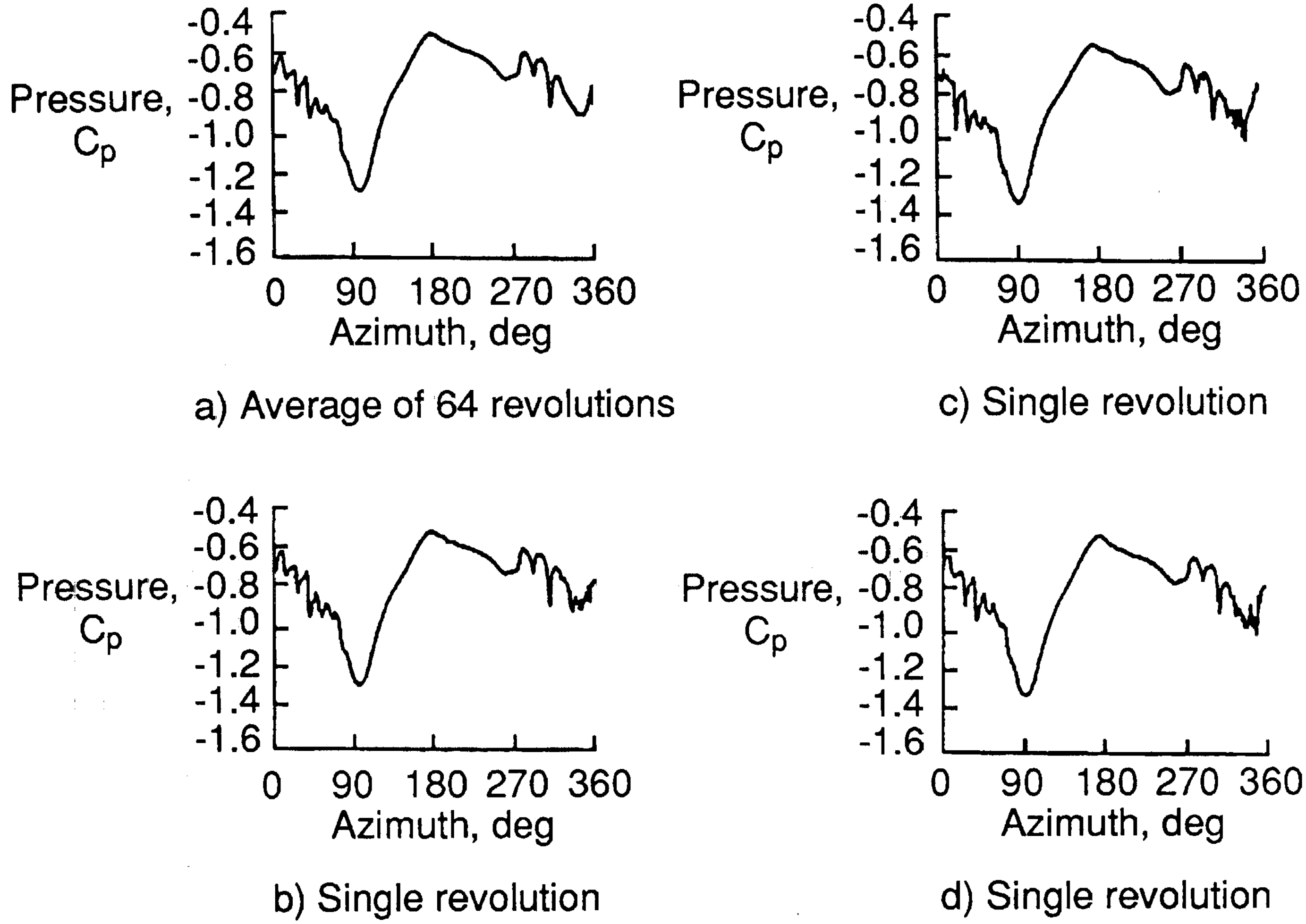

Figure 8. - Variation of Pressure Coefficient as a Function of Azimuth for a Single Transducer Location.

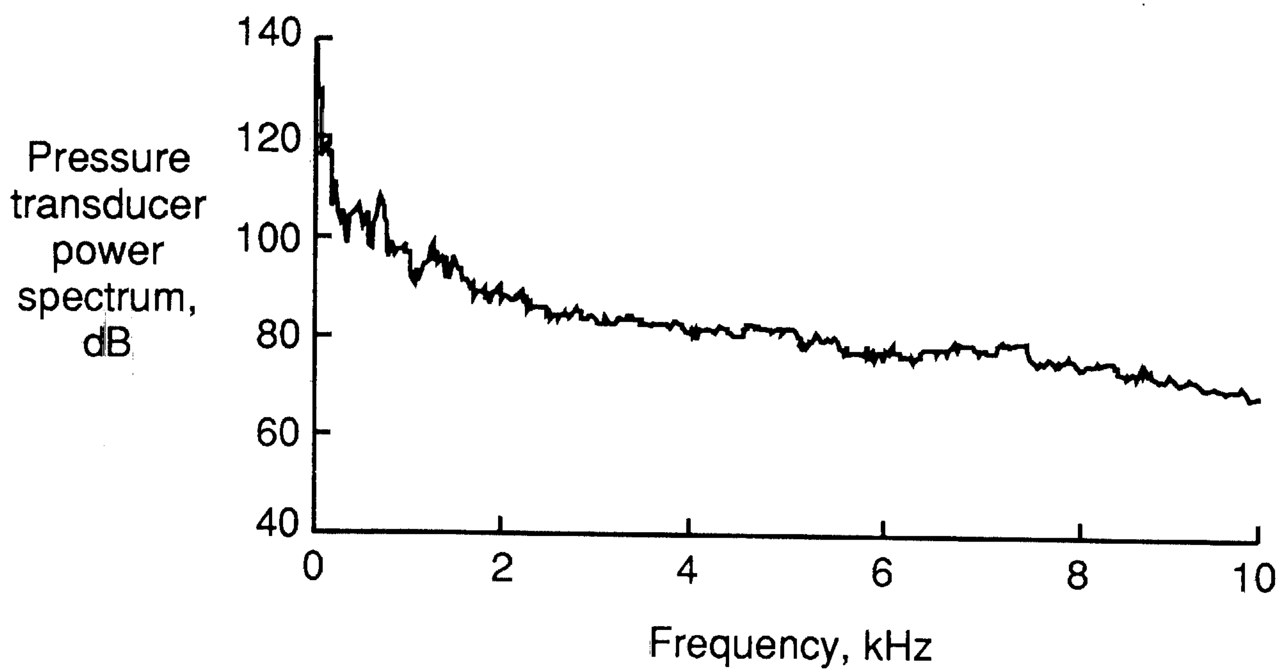

Figure 9. - Ensemble Averaged Spectrum for Data of Figure 8.

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15. Supplementary Notes

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16. Abstract

A technique is described for measuring the frequency response of pressure transducers mounted inside a model, where a narrow pipette leads to an orifice at the surface. An acoustic driver is mounted to a small chamber which has an opening at the opposite end with an O-ring seal to place over the orifice. A 3.18 mm (1/8 inch) reference microphone is mounted to one side of the chamber. The acoustic driver receives an input of white noise, and the transducer and reference microphone outputs are compared to obtain the frequency response of the pressure transducer. Selected results are presented, in the form of power spectra for both the transducer and the reference, as well as the amplitude variation and phase shift between the two signals as a function of frequency. The effect of pipette length is discussed, as well as the use of this technique for identifying both blocked orifices and faulty transducers.

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