Phase calibration of hydrophones

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(Received 26 February 1981; accepted for publication 30 April 1981)

In order to determine the waveform of an acoustic signal by analyzing the electrical output of the receiving hydrophone, the phase angle as well as the amplitude of the receiving hydrophone sensitivity must be known as a function of frequency. Unless the frequency is well below the lowest hydrophone resonance, this phase angle varies considerably with frequency. This paper describes the extension of conventional amplitude reciprocity calibration to include phase. It also describes a unique measurement configuration that eliminates phase errors resulting from uncertainties in measurement distances and sound speed. Several hydrophones are calibrated using the new procedure. Measured phase-angle results are in good agreement with theoretical results based on diffraction-constant calculations.

PACS numbers: 43.30.Yj, 43.30.Sf, 43.88.Kb

INTRODUCTION

In order to determine the waveform of an acoustic signal by analyzing the electrical output of the receiving hydrophone, the sensitivity of the hydrophone must be known as a function of frequency. Although the receiving sensitivity is often treated as only an amplitude, it also includes a phase angle. Unless the frequency is well below the lowest hydrophone resonance, this phase angle varies considerably (and nonlinearly) with frequency. This results in a relative shifting in the hydrophone output of the various frequency components in the acoustic signal, thereby changing the shape of the time waveform. The acoustic waveform can be recovered only if the phase shifts for each frequency component are known.

The calibration of hydrophones rarely involves the phase angle, possibly because of experimental difficulties encountered in its determination.[1] One such difficulty is accurately determining the distance between transducers used in the calibration. A very small distance error at higher frequencies can produce a relatively large phase error. Another difficulty encountered is accurately determing the sound speed in the measurement medium. Small errors in sound speed can also lead to large phase errors.

We describe in this paper a new procedure for accurately calibrating hydrophones. The procedure is a combination of conventional three-transducer reciprocity calibration[2] extended to include phase together with a special experimental configuration. This experimental configuration eliminates phase errors due to uncertainties in both the measurement distances and the sound speed. We also describe the successful phase calibration of several hydrophones using this procedure.

I. THEORY

The hydrophone calibration procedure described here is an extension of conventional three-transducer reciprocity calibration[2] to include phase. Use of this procedure requires three transducers (a projector P, the hydrophone H to be calibrated, and a reciprocal transducer T that can be used as both a hydrophone and a projector). A series of three projector-hydrophone measurements are made using either P or T as a projector and H or T as a hydrophone. The measurements are made under free-field conditions with the hydrophone located in the farfield of the projector. The three experimental setups are indicated in Fig. 1. The input current and output voltage values are complex, i.e., they include both amplitude and phase. The input currents in setups 1 and 2 are chosen to be identical. In this case i_P does not appear in the final expression for the sensitivity of the hydrophone and need not be measured.

For setup 1 the farfield pressure p_{PH} produced at H, which is located d_1 meters from P, is

$$p_{PH} = (i_P S_P d_0/d_1)\exp[jk(d_0-d_1)], \qquad (1)$$

where S_P is the transmitting current response of P and d_0 is the reference distance, normally equal to 1 m, at which the transmitting pressure is specified in the definition of S_P. The wavenumber $k=\omega/c$, where ω is the angular frequency in radians per second and c is the sound speed of the surrounding medium in meters per second. The assumed time dependence $\exp(j\omega t)$ has been suppressed for convenience. The open-circuit voltage produced by H is given by

$$e_{PH} = M_H p_{PH} = (M_H i_P S_P d_0/d_1)\exp[jk(d_0-d_1)], \qquad (2)$$

where M_H is the receiving voltage sensitivity of H.

Similarly, we obtain for setup 2:

$$e_{PT} = M_T p_{PT} = (M_T i_P S_P d_0/d_2)\exp[jk(d_0-d_2)], \qquad (3)$$

where M_T is the receiving voltage sensitivity of T. Combining Eqs. (2) and (3) yields

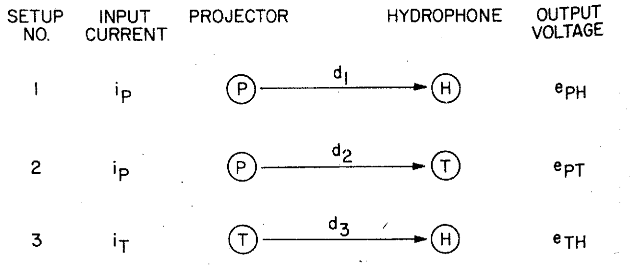

FIG. 1. Measurement setups required for the three-transducer reciprocity calibration.

$$e_{PH}/e_{PT} = (M_H d_2/M_T d_1)\exp[jk(d_2 - d_1)]. \quad (4)$$

Since T is a reciprocal transducer, we have $M_T = JS_T$, where J is the complex spherical wave reciprocity parameter given by Beranek[3] as

$$J=(4\pi d_0/ j\omega\rho)\exp(jkd_0), \quad (5)$$

where ρ is the density of the surrounding medium. From setup 3 we obtain

$$e_{TH}=M_H p_{TH} =(M_H i_T S_T d_0/d_3)\exp[jk(d_0 - d_3)]. \quad (6)$$

Combining Eqs. (4) and (6) with the use of Eq. (5) produces the following expression for the receiving voltage sensitivity of the hydrophone H:

$$M_H=\{[(4\pi e_{PH} e_{TH} d_1 d_3)/(j\omega\rho e_{PT} i_T d_2)] \times \exp[j(\omega/c)(d_1 + d_3 - d_2)]\}^{1/2}. \quad (7)$$

The difficulty in determining the phase of M_H using this method lies in accurately determining both the sound speed and the measurement distances d_1, d_2, and d_3. For example, at 100 kHz in water an error of only 1 mm in any one of the distances gives a phase error of about 12°. However, we can avoid this difficulty by positioning all three transducers P, H, and T in a straight line with H located between P and T. This assures that $d_2 = d_1 + d_3$. Then Eq. (7) simplifies to

$$M_H=[(4\pi e_{PH} e_{TH} d_1 d_3)/(j\omega\rho e_{PT} i_T d_2)]^{1/2}. \quad (8)$$

Since the distances and sound speed no longer appear explicitly in a phase term in Eq. (8), the accuracy of the phase of M_H calculated using Eq. (8) is limited only by the accuracy of the phase measurements of the voltages and current.

II. EXPERIMENT

A special measurement framework was constructed to position the transducer P, hydrophone H, and reciprocal transducer T in a straight line as shown in Fig. 2. The mounting hanger for H was designed so that it could be easily rotated or removed from the framework when desired. We used USRD type F30 transducers[4] for both P and T. This is a piston-type transducer with an active rectangular area about 5.0×3.8 cm that is designed to operate over a frequency range from 10 to 150 kHz. Both F30 transducers were mounted facing toward H. The distances d_1 and d_2 are nominally equal to 1 m. This assures that the hydrophone H is well within the farfield of both F30 transducers at frequencies up to 150 kHz.

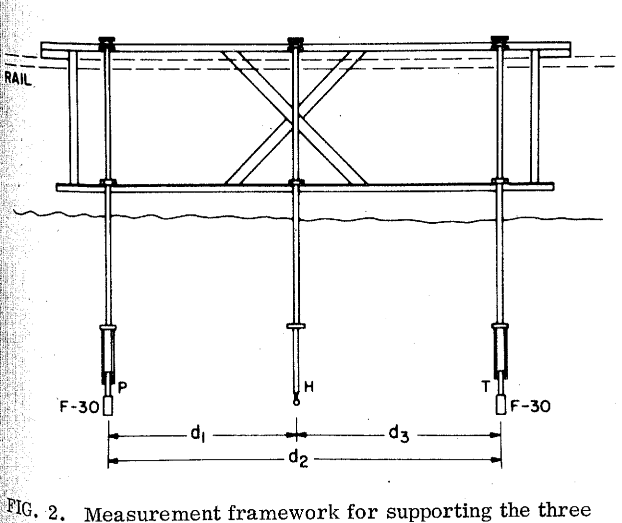

FIG. 2. Measurement framework for supporting the three transducers in-line.

A block diagram of the instrumentation used is shown in Fig. 3. One channel of the digital oscilloscope monitored the frequency synthesizer output as a reference signal. The other channel was connected to an amplifier that monitored either the output voltage or the input current via a current transformer. The resulting digitized voltage or current waveform was transferred to a desktop computer. Here a single-point discrete Fourier transform (DFT) was performed to determine the amplitude and phase angle relative to the reference signal.

The logistics for making the measurements were as follows:

(1) The transducers were mounted as shown in Fig. 2 with H facing toward P. The output voltage of H was measured with P being driven (e_{PH}).

(2) The hydrophone H and its hanger were removed from the framework. The output voltage of T was measured with P being driven (e_{PT}).

(3) The hydrophone and its hanger were replaced in the framework and positioned so that H faced toward T. The output voltage of H was measured with T being driven (e_{TH}).

(4) The input current to T (i_T) was measured.

After determining the four complex quantities e_{PH}, e_{PT}, e_{TH}, and i_T by use of the DFT, the computer calculated [from Eq. (8)] the desired amplitude and phase angle of the hydrophone sensitivity. This procedure yields the phase angle relative to the axis of rotation of the hydrophone hanger. Because of this and the presence of interference from unavoidable reflections from the hydrophone hanger, the hydrophones should be calibrated in the same hanger that will support it later when it is being used for measurements. The calibration is representative of both the hydrophone and the hanger.

If the hydrophone being calibrated has front-to-back symmetry, a modified procedure slightly different

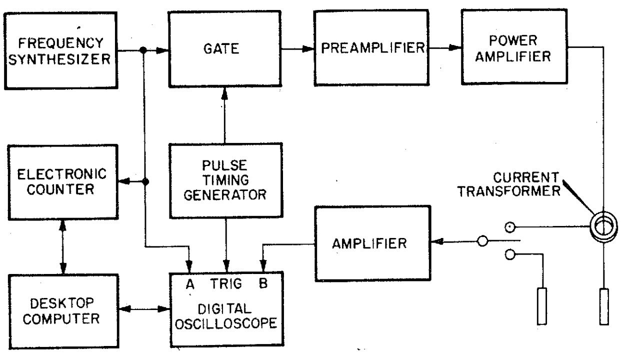

FIG. 3. Block diagram of electronic and computer instrumentation.

from that described above may be used. The modification involves measuring e_{TH} with the hydrophone facing toward P instead of toward T. The received voltage e_{TH} is then due to a sound wave incident from the back side of the hydrophone. In this case the phase angle of e_{TH} combines with that of e_{PH} in Eq. (8) to produce a resultant phase angle for M_H that is relative to the center of the hydrophone rather than to the axis of rotation.

We used the procedure described above to calibrate three hydrophones, a USRD type F42C, a USRD type F42D, and a USRD type F61. The active elements of the F42C and F42D are hollow piezoelectric ceramic spheres with diameters of 2.54 and 1.28 cm, respectively.[5] The active element of the F61 is a capped piezoelectric ceramic cylinder 2-cm high with a diameter of 2.60 cm (Ref. 6).

Figure 4 shows the resulting phase angle for the F42C hydrophone. The results of two different sets of measurements are given to indicate the repeatability of the results. A series of several measurements showed that the calibration results were repeatable to within ±2°. The solid curve in Fig. 4 represents the theoretical phase for an ideal, infinitely rigid, spherical hydrophone. Reciprocity relates this phase to that of the transmitting voltage response which in turn is simply related to the phase of the acoustic pressure radiated by a uniformly vibrating sphere. We obtain then from elementary radiation considerations the theoretical phase angle $\phi = ka - \tan^{-1}(ka)$, where a is the radius of the sphere.

Figure 4 shows general agreement between the theoretical and measured values for frequencies below the first mechanical resonance of the hydrophone. As the frequency approaches resonance, however, the hydrophone no longer acts like an infinitely rigid sphere and the theoretical model breaks down. The measured resonance peak in the corresponding amplitude response of this hydrophone occurred at about 85 kHz. Although

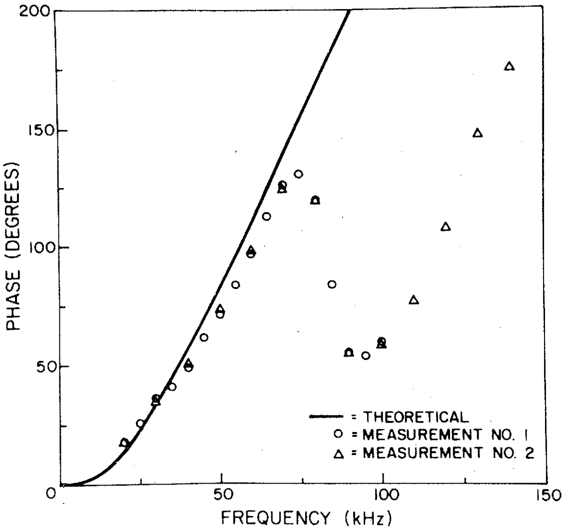

FIG. 4. Phase angle of the receiving voltage sensitivity of the F42C hydrophone plotted as a function of frequency. Measured results are indicated by circles and triangles, theoretical values by solid curve.

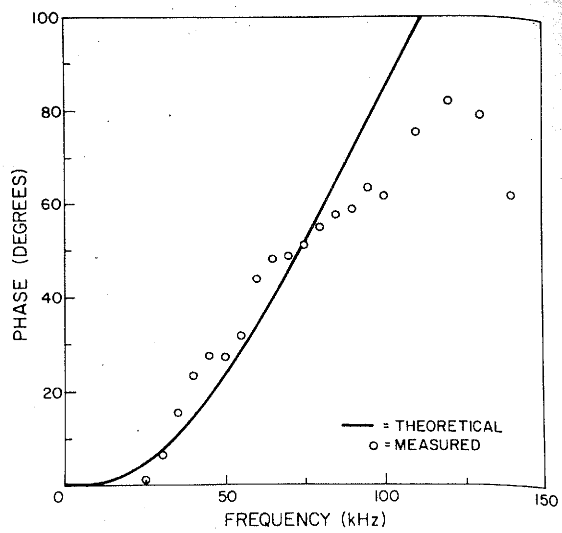

FIG. 5. Phase angle of the receiving voltage sensitivity of the F42D hydrophone plotted as a function of frequency. Measured results are indicated by circles and triangles, theoretical values by solid curve.

the calibration procedure produced the amplitude of the sensitivity in addition to the phase, we choose not to present those results here. Reference 5 contains typical sensitivity amplitude data for both the F42C and F42D hydrophones.

Figure 5 shows the results for the F42D. The phase for this hydrophone showed a greater variation from the theoretical phase for frequencies below resonance than did the F42C. This may be due to the fact that the active spherical element in the small F42D hydrophone was positioned closer to its hanger than was the case for the F42C. Thus we expect the F42D to be more influenced by sound reflected from the hanger. When we changed the mounting configuration of the F42D hydrophone in the hanger to test this hypothesis, the resulting phase curve changed noticeably, even at low frequencies. We emphasize again that the hydrophone should be calibrated in the same hanger that will support it later when it is

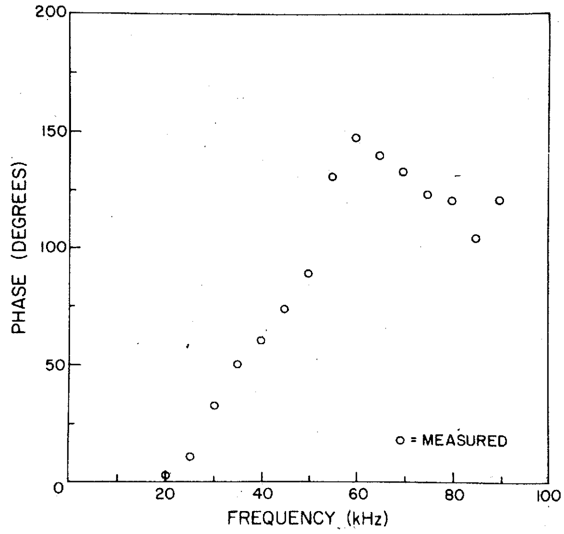

FIG. 6. Measured phase angle of the receiving voltage sensitivity of the F61 hydrophone plotted as a function of frequency.

being used for measurements.

Figure 6 shows the results obtained for the F61 hydrophone. The F61 was mounted so that the cylindrical axis of the active element was oriented vertically and aligned with the axis of rotation of the hanger. The phase angle of the hydrophone's sensitivity is then obtained relative to the axis of the hydrophone. A simple theoretical expression which gives the phase angle for the finite cylinder, similar to that of the sphere, is not available for comparison to experiment.

III. SUMMARY

We have described a procedure for accurately calibrating hydrophones. Although the emphasis of the description has been on determining the phase angle of the receiving voltage sensitivity, the procedure also produces the amplitude. The procedure is a combination of conventional three-transducer reciprocity calibration extended to include phase together with a special experimental configuration. The in-line arrangement of the transducers in this configuration eliminates phase errors that would otherwise occur due to uncertainties in both the measurement distances and the sound speed. We tested the procedure by successfully calibrating several hydrophones.

ACKNOWLEDGMENT

The authors gratefully acknowledge the valuable contributions of John Albrecht to the design and construction of the measurement framework.

[1]One notable exception is the measurement of the phase angle at extremely low frequencies in the vicinity of the low-frequency roll-off of the hydrophone sensitivity. See, e.g., A. C. Tims and T. A. Henriquez, "Hydrophone Phase Stability Analysis at Frequencies Below 100 Hz," NRL Rep. No. 8314 (July 1979).

[2]R. J. Bobber, *Underwater Electroacoustic Measurements* (Naval Research Laboratory, Washington, DC, 1970), pp. 28–30.

[3]L. L. Beranek, *Acoustic Measurements* (Wiley, New York, 1949), p. 120.

[4]I. D. Groves, "Twenty Years of Underwater Electroacoustic Standards," NRL Rep. No. 7735 (1974).

[5]L. E. Ivey, "NRL–USRD Series F42 Omnidirectional Standard Hydrophones," NRL Memo. Rep. No. 3969 (May 1979).

[6]Information on the USRD type F61 transducer is found in NRL Instruction Book No. 165 (September 1976).