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The Measurement of Small Wavefront Deviations Introduced by a Panel

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Wavefront deviation of a low-frequency sound beam introduced by passage of the beam through a rubber panel was measured at angles of incidence from 0 to ±20 deg. The technique of measurement is described, and results and measurement problems are discussed. Resolution of the measurements is estimated as 0.01 deg, but this value probably can be improved to 0.001 deg by incorporating the changes described.

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THE MEASUREMENT OF SMALL WAVEFRONT DEVIATIONS INTRODUCED BY A PANEL

Introduction

When a sound wave passes through a panel whose characteristic impedance differs from that of the medium surrounding it, the direction of propagation changes, if the panel material is not of homogeneous composition and uniform thickness. Although this change normally is small for a sonar dome material, determining the magnitude of it is of vital concern to the Navy because it affects the sonar's performance. The actual bearing error caused by a dome arises from two factors: (1) nonuniform thickness and/or nonhomogeneity of the dome material, and (2) the dome's structural configuration. The effect of the first factor, for a panel supplied by the B. F. Goodrich Co., is the subject of this report.

If the deviation caused by the first factor in a plane panel is measured and used as a screening test to eliminate unsatisfactory material, the time and expense of a full dome test may be saved.

Measurement Technique

Figure 1 shows the arrangement used to measure wavefront deviation introduced by the 183-cm-square by 2.8-cm-thick wire-reinforced rubber panel. Two USRD type H52 hydrophones, suspended 100 cm apart from a horizontal bar, were used to detect the orientation of the wavefront. The USRD type J11 projector was independently suspended at distance D_1 from the hydrophones and pulsed with two cycles of the operating frequency at the repetition rate 10 pps. This relatively low rate was necessary to reduce the reverberation to a level below that of the ambient noise in the lake. The panel was located at distance D_2 from the projector.

The signals from the hydrophones were amplified by two Princeton Applied Research Model 113 preamplifiers to 2 V rms and then used as start-stop triggers for the Hewlett-Packard Model 5326B timer-counter. This timer has a resolution of 0.1 μs and can be set to trigger on either the first positive-going or the first negative-going zero crossover. For these measurements, the negative-going zero crossover was used, as shown in Fig. 2.

The bar supporting the two hydrophones was fixed at 1 deg from the perpendicular to the centerline (β = 1 deg in Fig. 3) such that the left hydrophone was nearer the projector. Thus, the signal received

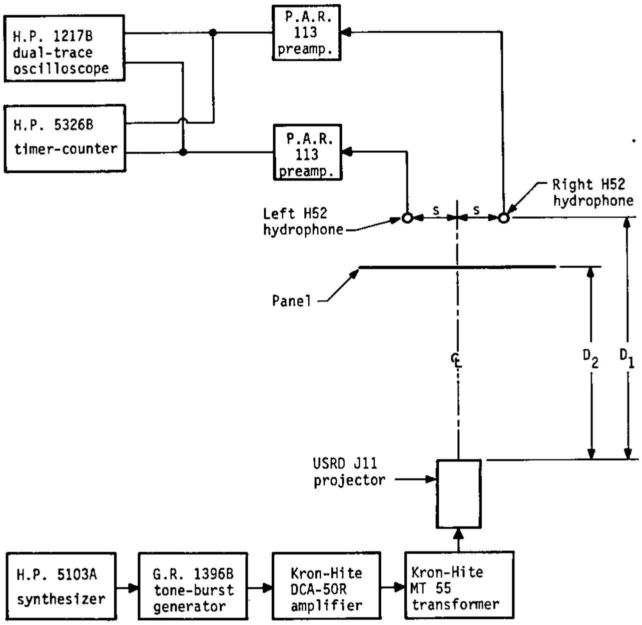

Fig. 1. Acoustic and electronic equipment used to measure wavefront deviation.

by the left hydrophone (channel A of Fig. 2) was used to start the timer and that from the right (channel B) was used to stop it. Then, if the time interval t_0 is measured without the panel in place, and the time interval t_p is measured with the panel in place, the difference $t_p - t_0 = \Delta t$ can be used to calculate the deviation of the wavefront.

Let R_1 be the distance from the projector to the left hydrophone and R_2 the distance from the projector to the right hydrophone. Then $R_2 - R_1 = \Delta R = ct_0$, where c is the sound speed in water (1519 m/s at 30.2°C). From the law of cosines (see Fig. 3):

$$ct_0 = \Delta R = [D_1{}^2 + s^2 - 2D_1 s \cos(90 + \beta)]^{\frac{1}{2}} - [D_1{}^2 + s^2 - 2D_1 s \cos(90 - \beta)]^{\frac{1}{2}},$$

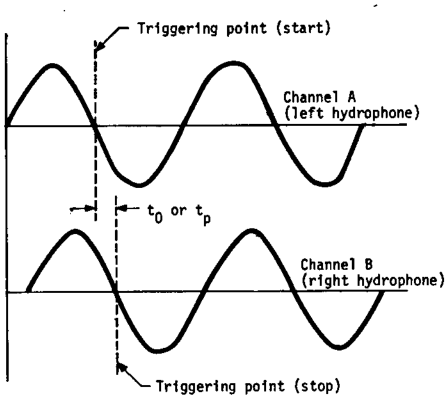

Fig. 2. Hydrophone signals.

where D_1 is the distance from the J11 transducer to the midpoint of a line connecting the two hydrophones, s is one-half the hydrophone separation, and β is the angle between the normal to the vertical plane of the hydrophones and the indicated centerline. For small angles, the relation between t_0 and β is linear, so we can write $\Delta\beta = \alpha\Delta t$, where α is the proportionality constant.

Without a panel, the direction of propagation of the wavefront is parallel to the centerline; with the panel in place, a change in the measured time interval implies an apparent change Δβ in the direction of propagation of the wavefront, as shown in Fig. 3.

For the final measurements on this panel, the distance D_1 was 300 cm and the hydrophone separation 2s was 100 cm. This separation was a compromise to maximize the angular resolution while still eliminating the effects of diffraction. These values give $\alpha = 0.0885$ deg/μs.

An examination of the geometrical arrangement of transducers and panel reveals that the acoustic path lengths through the panel are equal only when the projector is equidistant from each hydrophone and the panel is parallel to the vertical plane of the hydrophones. Hence, a time interval correction for path length difference may be necessary at the larger angles of incidence, if this difference cannot be neglected and the plane-wave deviation is required. Use of a near-field (plane-wave) array instead of the J11 projector would obviate the need for this correction.

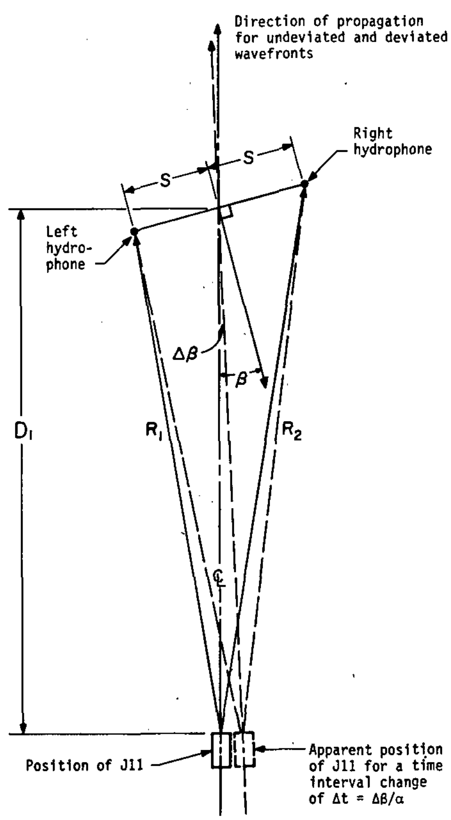

Fig. 3. Relation between time interval and angle β.

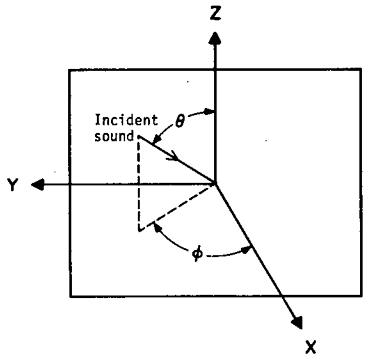

Fig. 4. Panel coordinate system.

Figure 4 shows the coordinate system assigned to the panel.

Procedure and Chronology

Preliminary observations revealed that it would be necessary to obtain a large sample of data points to improve angular resolution. A sample size of 100 measurements was used.

The procedure was to measure $\bar{t}_0$ (where the bar indicates an average), then measure $\bar{t}_p$ for some panel angle, and then measure $\bar{t}_0$ again. In this way, all measurements of $\bar{t}_p$ were bracketed by measurements of $\bar{t}_0$. The $\bar{t}_0$ values were connected by a smooth line to permit interpolation for $\bar{t}_0$ at the actual time $\bar{t}_p$ was measured. Had the $\bar{t}_0$ values been stable, this procedure would not have been necessary.

As pointed out in the preceding section, a correction for the different path lengths through the panel might be necessary for larger panel angles. The initial data were corrected using the value 1388 m/s for the sound speed in the panel, as determined by extrapolation from a curve supplied by B. F. Goodrich. With this value of sound speed, the correction increased the resultant deviation rather than decreasing it--an unexpected result. An attempt was made to determine the validity of the correction; unfortunately, the problem could not be resolved in the limited time available. However, two conclusions were reached from the measurements: For $\phi = 340$ deg (the maximum angle of incidence), (1) the Δt, and thus the wavefront deviation, decreased as distance D_1 increased (Fig. 5), and (2) Δt generally decreased as the frequency increased, passing through $\Delta t = 0$ between 5 and 7 kHz.

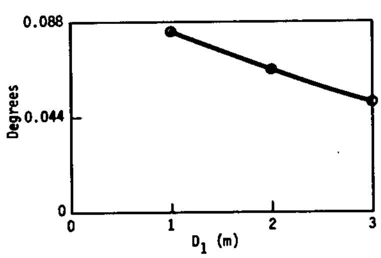

Fig. 5. Wavefront deviation as a function of distance D_1; 3.5 kHz; $\theta = 90°$, $\phi = 340°$.

To minimize the error caused by path length differences, the final measurements were made at 300 cm, the largest distance possible without diffractive interference.

These measurements were made first for incident sound angles $\theta = 90$ deg and $\phi = 0, 5, 10, 15, 20,$ and 340 deg. The panel then was removed from the water and rotated in its plane to measure the incident angles $\phi = 0$ deg and $\theta = 70$ and 110 deg. These measurements were repeated the following day, and then one week later to allow time for the panel to stabilize acoustically. The final measurements were made for the angles $\phi = 0$ deg and $\theta = 70, 80, 90,$ and 110 deg. The results are shown in Table 1.

There are several possible explanations for the observed frequency dependence of the deviation. First a deviation resulting from different acoustic path lengths through the panel generally will be frequency-dependent when the characteristic impedance of the panel is different

Table 1. Wavefront deviation as a function of angle of incidence. All tabulated values in degrees.

Incident sound angle		95% confidence interval		
ϕ	θ	Lower bound	Mean	Upper bound
0	90	-0.013	-0.003	0.008
5	90	-0.023	-0.013	-0.004
10	90	-0.029	-0.019	-0.007
15	90	-0.048	-0.036	-0.025
20	90	-0.060	-0.049	-0.038
340	90	0.044	0.052	0.061
0[a]	70	-0.107	-0.096	-0.086
0	110	0.034	0.043	0.053
0[b]	70	-0.105	-0.094	0.083
0	110	0.079	0.090	0.101
0[c]	70	-0.076	-0.068	-0.060
0	80	-0.029	-0.022	-0.015
0	90	-0.018	-0.011	-0.004
0	110	0.082	0.090	0.098

[a]Initial measurements after reimmersion in water.

[b]Repeat measurements, next day.

[c]Repeat measurements, after one week.

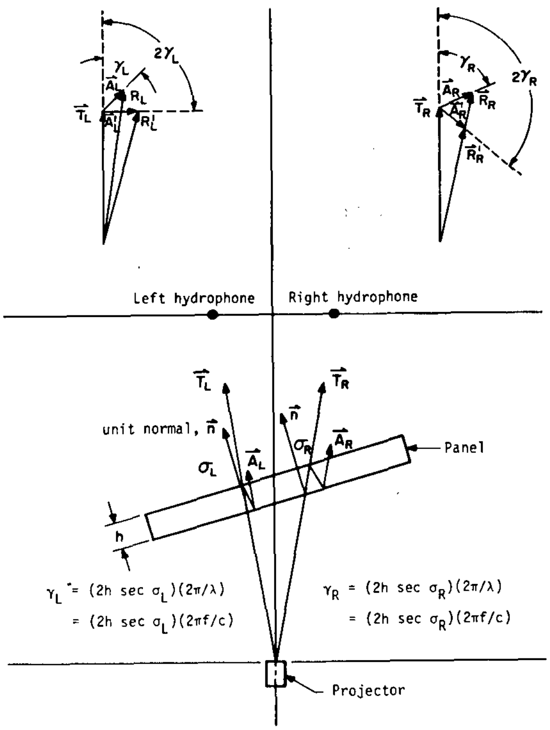

Fig. 6. Schematic diagram showing possible reason for frequency dependence of the deviation.

from that of the water and internal reflections are present. Figure 6 depicts the arrangement of transducers and panel with phasor diagrams representing the complex amplitude of signals arriving at each hydrophone.

The resultant transmitted signal R arriving at each hydrophone is the complex sum of the first transmitted signal $\vec{T}$ and the successive transmitted signals caused by multiple internal reflections. As a first-order approximation, transmitted signals occurring after the second one A will be omitted; hence, $\vec{R}_L = \vec{T}_L + \vec{A}_L$ and $\vec{R}_R = \vec{T}_R + \vec{A}_R$. The phase angle γ between $\vec{T}$ and $\vec{A}$ is proportional to frequency and path length through the panel. Thus, γ_L and γ_R represent the phase angles of $\vec{A}_L$ and $\vec{A}_R$ for a frequency f, and $2\gamma_L$ and $2\gamma_R$ are the corresponding phase angles for the frequency 2f. From the phasor diagram, it is obvious that $\angle(R_L, R_L') \neq \angle(R_R, R_R')$; that is, the phase shift occurring because of a change in frequency is not the same for both paths through the panel, and hence the deviation is frequency dependent.

Another possibility is mode conversion (that is, compressional to shear and/or surface waves), which could result in anomalous propagation within the panel. The panel also could have acted as a mass impedance to the incident wave, moving as a membrane or piston and generating additional waves out of phase with the transmitted wave.

Data Analysis

Figure 7 shows two typical histograms, one for t_0 and one for t_p. Theoretically, the lake noise causing early or late triggering of the start and stop channels should produce a Gaussian distribution of time intervals, and the histograms support this view. The values of $\bar{t}_0$ and $\bar{t}_p$ were empirically determined to be statistically independent; hence, the variance of $\Delta t = \bar{t}_p - \bar{t}_0$ is the sum of the variances of $\bar{t}_p$ and $\bar{t}_0$. Ninety-five percent confidence intervals calculated from the data are included in Table 1 with the mean value of the deviation for each angle of incidence.

On the basis of a total of four measurements made on two different days at the panel angle $\phi = 340$ deg, the repeatability of the mean value for Δt was ±0.08 μs or ±0.007 deg.

Figure 8 is a graph of the first six measurements listed in Table 1 with the data plotted in terms of time interval instead of degrees. It is obvious from the graph that Δt, the difference between the solid line and the dots, varies smoothly with angle; it is not subject to significant random fluctuations.

From these considerations, the resolution of the measurements is estimated as 0.01 deg.

It appears from Fig. 5 that it is not possible to obtain the plane-wave deviation at a 3-m measurement distance; however, it should be pointed out that a plane wave incident upon a plane surface is an unrealistic simulation of a dome, whether transmitting or receiving.

Problems and Proposed Improvements

Two problem areas became recognized during the measurements. First, the dispersion exhibited by the data was great enough to require taking a large number of data points for each condition. The evidence suggests that data dispersion was caused by two conditions: (1) insufficient signal-to-noise ratio (a noise spike 40 dB below the signal level can cause the timer to start or stop nearly 0.5 μs sooner or later than it would with a noise-free signal) and (2) rotational oscillation of the hydrophone shaft. Existence of the latter condition was confirmed by rotating the hydrophone shaft 90 deg and checking dispersion. (With the hydrophone bar parallel to the direction of sound propagation, a small oscillation of the shaft would not affect the time interval.) At this orientation, data dispersion was significantly reduced.

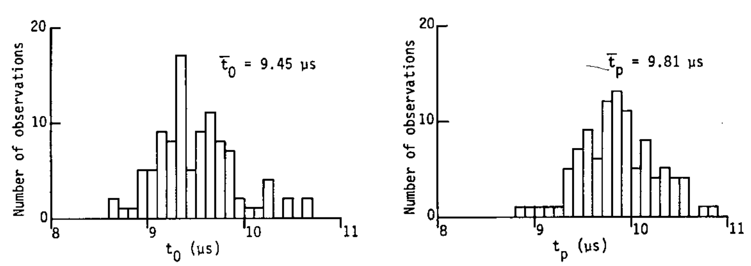

Fig. 7. Histograms for time intervals.

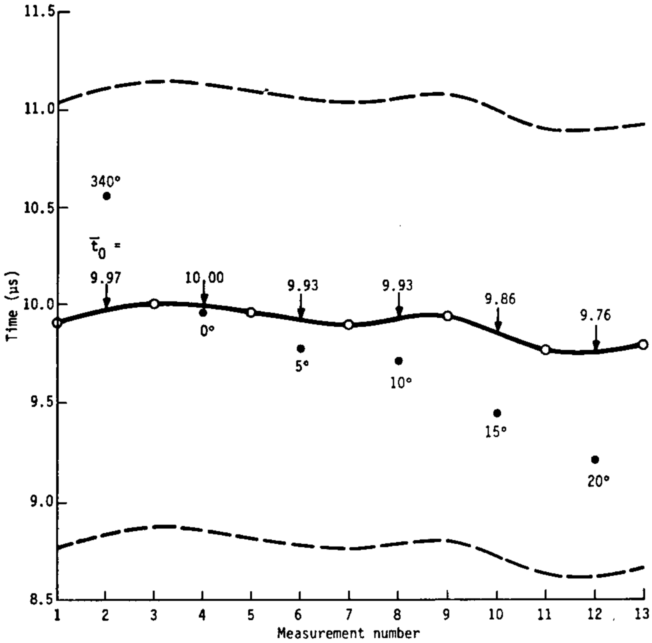

Fig. 8. Time interval as a function of measurement number; 3.5 kHz. Incidence angles are values of ϕ ($\theta = 90°$ for all points).

-0—0- without panel ($\bar{t}_0$)

• • • • with panel ($\bar{t}_p$)

- - - - 1.13 μs deviation (0.1° deviation)

In the interest of both time and confidence in the results, it is desirable to reduce dispersion to the point that large data samples are unnecessary. Reduction of dispersion by about one order of magnitude would be required.

The second problem was the drift in the system calibration $\bar{t}_0$ (see Fig. 8). Presumably, this drift was caused by a slow rotational movement of the shaft resulting from seismic-related movement of the pier structure, or possibly from small currents in the water initiated by the vertical movement of the panel between measurements of $\bar{t}_0$. Care was taken to minimize the latter possibility. Any effect caused by nonisothermal water was ruled out, inasmuch as the water temperature was 30.2°C from 0.5 m below the surface to the lake bottom.

It is believed that both conditions can be improved by about one order of magnitude. The disperson can be reduced by using an amplifier of higher power output and/or an F40A projector to increase the signal-to-noise ratio by about 20 dB. However, the use of the F40A probably would necessitate gating the signals after the first cycle, before using them to trigger the timer, because of the distorted first cycle of the F40A output. In addition, using a portion of the signal after the first cycle would require a wider panel to avoid diffraction; a panel 2.2 m by 2.8 m would allow the signal to be gated as far as 1½ cycles behind the leading edge on a 3.5-kHz frequency. If the dispersion is significantly reduced, it would also be necessary to use a timer with better resolution. Recently, a Hewlett-Packard 5345A high-resolution timer was acquired; this instrument has a time interval resolution of 2 ns.

The drift of $\bar{t}_0$, as well as the dispersion in the t_0 and t_p data, can be reduced by constructing a rigid framework within which the projector and both hydrophones are placed to decrease relative motion between transducers.

Conclusion

Angular deviation of a wave passing through a panel can be measured with a resolution of about 0.01 deg by the technique that has been described. If the improvements that have been discussed are incorporated, the accuracy probably can be increased to 0.001 deg.

The results of the measurements on this panel show that the deviation for diverging wavefronts depends upon both source-to-panel distance and frequency. Using this technique to reject questionable materials before the full-scale dome is constructed could save considerable time and expense later.