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A Technique to Measure Breathing Wave Speeds Using End Point Excitation

Andrew J. Hull
Submarine Sonar Department

Naval Underwater Systems Center
Newport, Rhode Island • New London, Connecticut

Preface

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F. J. Kingsbury
F. J. Kingsbury
Head, Submarine Sonar Department

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This report describes a simple method to measure the breathing wave speed in a towed array. The array is subjected to end point excitation, and a transfer function between a hydrophone channel and an accelerometer is measured. The local minimum associated with the first breathing wave null across the hydrophone channel is identified. Because both the length of the hydrophone channel and the frequency at which the null occurs are known, the breathing wave speed can be calculated. This method can be implemented at the Axial Vibration Test Facility of the Naval Underwater Systems Center, New London, Connecticut.

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INTRODUCTION

The breathing (or bulge) wave that is caused by the interaction of the hose wall and the fill fluid in a towed array is energy traveling down the array at a nearly constant speed. At sea, the principal origin of the bulge wave is excitation by the turbulent boundary layer. In the laboratory, the bulge wave can be generated by end point excitation of the array. The end of the array is vibrated, which excites a bulge wave at the end shell and at other locations in the array where hose-filling objects are present. The bulge wave amplitude is attenuated by the array hosewall and generally consists of only traveling wave energy.

In an initial attempt to measure breathing wave speeds, array hoses were equipped with special fittings, filled with water, and hit on the end with a hammer. Strain gages mounted to the wall of the hoses detected the passing wave and measured the time it took the wave to travel a specified distance. The bulge wave speed was then calculated. This technique did not test the array with the interior core inside. The core, however, has a significant effect on the breathing wave speed, and therefore approximations had to be made to determine its influence

More recent experiments have been conducted in the Axial Vibration Test Facility at the Naval Underwater Systems Center in New London, Connecticut. This test facility has a rail from which an array can be suspended. A shaker is attached to the forward end of the array to provide a displacement-driven boundary condition, and the aft end is terminated with kevlar rope. The aft end can be adjusted to provide different tensions in the array. The entire unit is surrounded by a temperature-controlled PVC duct that allows the hosewall response to be measured as a function of temperature. The forward and aft end of the array are fitted with impedance heads to record force and acceleration data, which are then input into a four pole impedance model that calculates extensional wave speeds. However, it was found that this method did not provide a means to identify the breathing wave speed.

This report presents a new technique to measure the breathing wave speed in the Axial Vibration Test Facility using the transfer function of the pressure from a hydrophone channel divided by the end point acceleration. This method is extremely easy to implement, can be run quickly, and uses the actual array rather than the hosewall. The effects of the array interior core are also incorporated in this measurement technique.

SYSTEM MODEL

The system model represents a hydrophone channel in a fluid-filled array being driven by end point excitation at one end. This transfer function is

$$\frac{P(\omega)}{a} = E(\omega) + B(\omega) \ , \tag{1}$$

where $P(\omega)$ is the pressure of the hydrophone channel, a is the acceleration at the end point, $E(\omega)$ is the extensional wave energy, and $B(\omega)$ is the breathing wave energy. If the hydrophone channel under consideration is located at or near the forward end of the array, extensional and breathing wave energy reflected off the aft end of the array will be dissipated and will not enter into the pressure field at that hydrophone. The dominant wave energy near the forward end of the array will then consist of two aft-traveling waves.

The extensional wave term is

$$E(\omega) = \frac{1}{j}\sum_{m=1}^{j} \frac{\rho_f g_c \beta c_B^2}{\omega c_E} exp\left(\frac{-\delta_E x_m \omega}{2c_E}\right) exp\left(\frac{x_m \omega i}{c_E}\right), \tag{2}$$

where j is the number of hydrophones in the group, x_m is the positive distance from end point to individual hydrophone (m), ρ_f is the fill fluid density (kg/m^3), g_c is the gravitational constant (9.807 m/sec^2), c_B is the breathing wave speed (m/sec), c_E is the extensional wave speed (m/sec), ω is the frequency (rad/sec), δ_E is the extensional wave loss factor (dimensionless), and β is equal to $\nu(\alpha/2-\nu)/(1-\nu^2)$, where ν is Poisson's ratio (dimensionless) and α^2 is the ratio of the circumferential to longitudinal modulus (dimensionless). The extensional wave term is in units of Pa/g.

The breathing wave term is

$$B(\omega) = \sigma exp(\phi i)\left[\frac{1}{j}\sum_{m=1}^{j} \frac{-\rho_f g_c c_B}{\omega} exp\left(\frac{-\delta_B x_m \omega}{2c_B}\right) exp\left(\frac{x_m \omega i}{c_B}\right)\right], \tag{3}$$

where δ_B is the breathing wave loss factor (dimensionless), σ is the breathing wave efficiency generation term (dimensionless), and ϕ is the phase angle (rad) between the extensional wave generation at the end point and the breathing wave generation point in the array. If the breathing wave is generated by the forward end shell, then ϕ is zero and σ is equal to one. The effects of nonzero ϕ and nonunity σ are discussed in the next section. The breathing wave term is also in units of Pa/g.

A model of the first channel of an array using equations (1), (2), and (3) is shown in figure 1. The array modeled was an eight-element per channel array with an interelement hydrophone spacing of 0.1 meters. The distance from the end of the array to the first hydrophone was 0.3 meters. The following constants were used: $c_B = 20$ m/sec, $c_E = 800$ m/sec, $\alpha = 0.1$ (dimensionless), $\nu = 0.45$ (dimensionless), $\rho_f = 760$ kg/m^3, $\delta_E = 0.01$ (dimensionless), and $\delta_B = 0.2$ (dimensionless). The origin of the breathing wave and the extensional wave is the end shell of the array; therefore, $\phi=0$ and $\sigma=1$. A model of the second channel of the array is shown in figure 2. It uses the same parameters as the model of the first channel, except that its first hydrophone is located 1.3 meters from the end of the array. Figures 1 and 2 do not correspond to any specific array, but will be used to illustrate how the measurement of the breathing wave speed is accomplished using only the magnitude of the transfer function. Although the phase angle is included in these figures, it is not used to measure the breathing wave speed.

The theoretical speed of the breathing wave for an array with no interior core is frequently given by the expression

$$c_B \approx \sqrt{\frac{\alpha^2 E t}{2\rho_f a}} , \tag{4}$$

where E is the longitudinal modulus of elasticity of the hosewall (N/m^2), t is the hosewall thickness (m), and a is the average hosewall radius (m). Equation (4), derived from thin shell equations using various approximations about the behavior of the array, is not an exact wave speed. Equation (4) can also be derived for an array with an interior core present:

$$c_B \approx \sqrt{\left(1 - \frac{b^2}{a^2}\right)\frac{\alpha^2 E t}{2\rho_f a}} , \tag{5}$$

where b is the average interior core radius (m). Equations (4) and (5) are frequently incorrect because they model only thin shells and ignore the effects of tension, bending stiffness, and even extensional wave influence on the breathing wave speed. Additionally, it is very difficult to determine the average interior core radius of many arrays. An alternative is to measure the breathing wave speed directly, as shown in the next section.

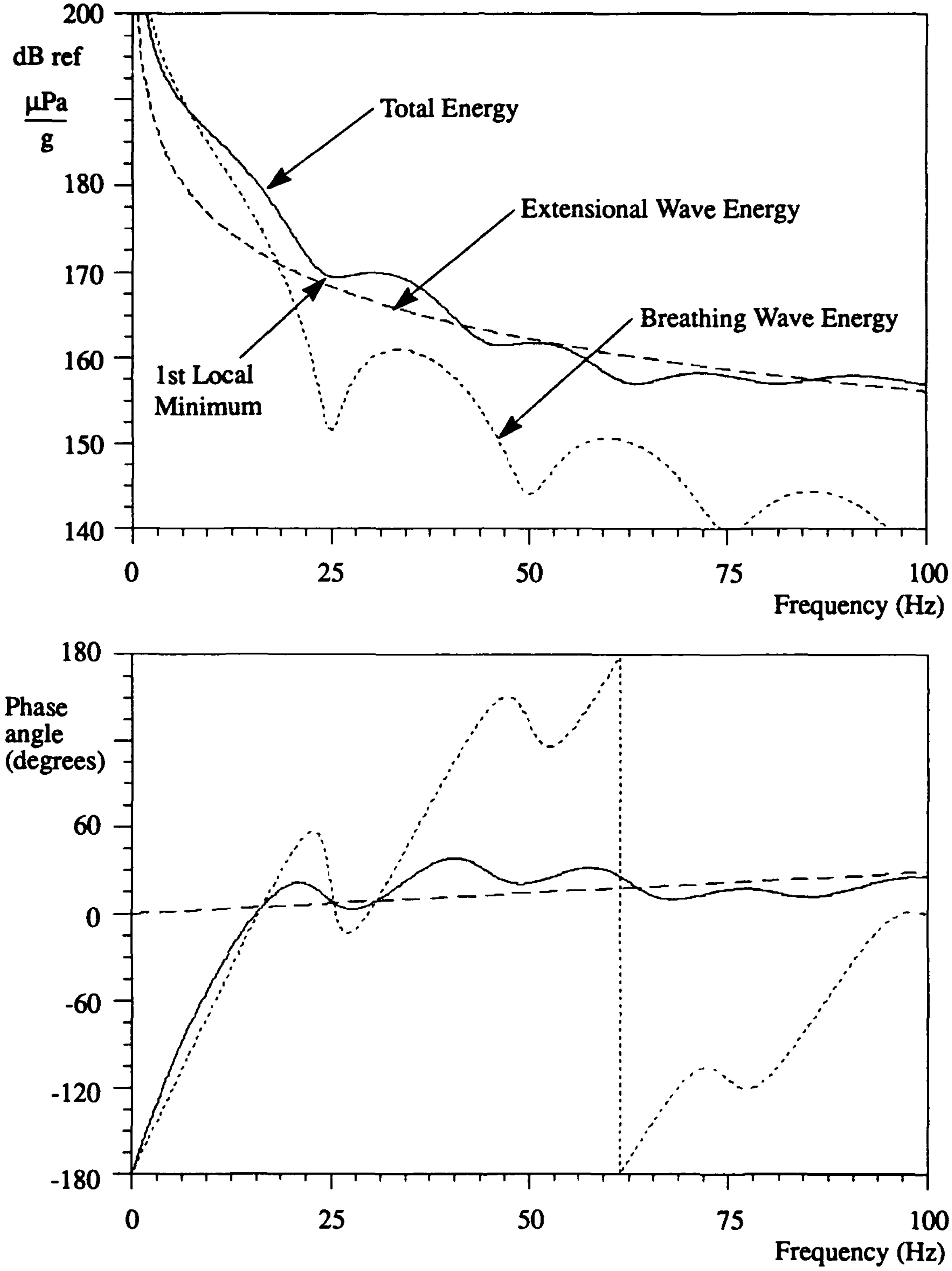

Figure 1. Transfer Function of Channel 1 Hydrophone Pressure Divided by End Acceleration - Magnitude and Phase Angle

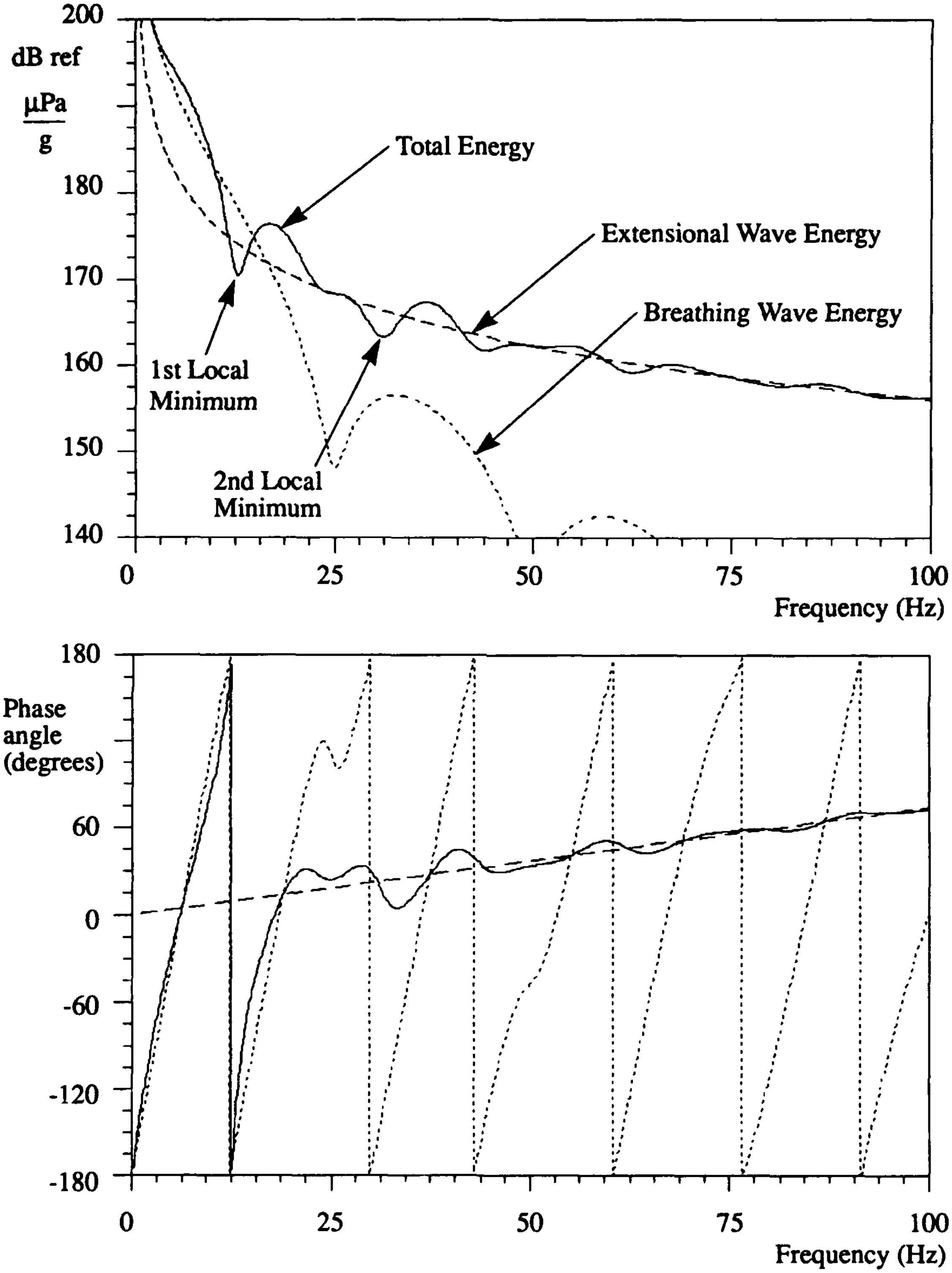

Figure 2. Transfer Function of Channel 2 Hydrophone Pressure Divided by End Acceleration - Magnitude and Phase Angle

BREATHING WAVE SPEED MEASUREMENT

This test requires measuring the transfer function of the hydrophone pressure divided by the end point acceleration. Although breathing wave energy is normally present in the entire array, the first channel most accurately measures the breathing wave speed. Here, the breathing wave energy field is strong because it is being generated by the end shell of the array, and the first local minimum of the transfer function (figure 1) corresponds to a breathing wave null (figure 3). The phase angle between the breathing wave and the extensional wave is also known at the end shell of the array (180 degrees at 0 Hz). It is possible to use other channels to measure the breathing wave speed without knowledge of the phase angle between the two waves, as the breathing wave nulls are not dependent on the phase angle. In other channels, the breathing wave is being generated by amplifier cans and other internal objects, and it is not as dominant. Also, constructive interference of two opposite-traveling breathing waves (or even an aft-traveling extensional wave and an aft-traveling breathing wave) may, however, cause problems identifying the local minimum that is associated with the breathing wave null (figure 2). Additionally, the local minimum that corresponds to a breathing wave null may not be the first local minimum (figure 2) and may have to be identified as a breathing wave null by some other method.

The breathing wave speed is determined by relating the first local minimum of the magnitude of the transfer function to the active length of the hydrophone channel (for the first hydrophone channel). Because the first local minimum of the transfer function occurs almost exactly at the null of the breathing wave, its frequency corresponds to a breathing wave equal to the length of the hydrophone channel. Or, alternatively, if the wavelength and the frequency of the breathing wave are known, the wave speed can be calculated. The formula to do this is

$$c_B = \frac{\omega_{min} L}{2\pi} , \tag{6}$$

where ω_{min} is the frequency of the local minimum (rad/sec) and L is the active length of the hydrophone channel. For the example in the previous section, the first local minimum occurs at $25.8(2\pi)$ rad/sec, and the active length of an eight-element group spaced at 0.1 meters is 0.8 meters. The breathing wave speed is then calculated to be $25.8(0.8) = 20.6$ m/sec, which is a 3-percent difference compared to the 20-m/sec breathing wave speed used to generate the example.

The small error in this method arises because the breathing wave null across the hydrophone is not a true zero null due to the loss term associated with the breathing wave.

As the breathing wave travels down the array, it loses energy monotonically with distance (and frequency). Figure 4 shows the breathing wave for the example. The wave loses energy as it travels down the array and the sum of the pressure measurements from the first four hydrophones is greater than the (negative) sum of the last four hydrophones.

It should be noted here that the other relative minima of the transfer function do not correspond to the nulls of the breathing wave energy and cannot be used to determine wave speeds. A more elaborate method would be to curve fit equation (1) to experimental data and allow the breathing wave to vary as a function of frequency, which may provide a frequency-dependent breathing wave speed.

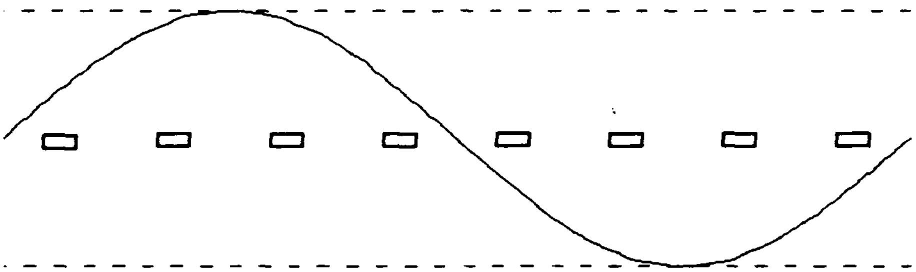

Figure 3. A Wave Null Across an Eight-Element Hydrophone Channel

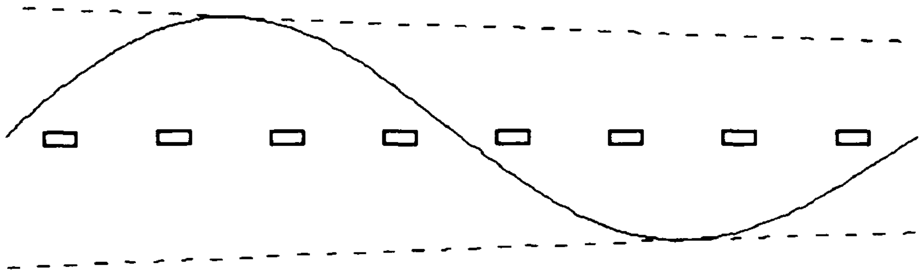

Figure 4. An Approximate Wave Null Across an Eight-Element Hydrophone Channel

CONCLUSIONS

The breathing wave speed can be determined from the first local minimum of the transfer function between the hydrophone pressure of the first channel and end point acceleration. This method is easy to use and accommodates actual towed arrays rather than just the array hosewall.

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