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NRL Memorandum Report 3601

# Measurement of the Acoustic Impedance of the Ocean Bottom

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→ Transducer circuit theory is used to derive a means for measuring the impedance of a locally reacting surface. A directional source, linear or parametric, insonifies a finite area in a reference plane at which the impedance is specified. Computer programs are referenced for calculating the required diffraction constants and radiation impedance for the test geometry. ←

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# MEASUREMENT OF THE ACOUSTIC IMPEDANCE OF THE OCEAN BOTTOM

## Background

We describe a means for measuring the acoustic impedance of a finite area of a boundary. The finite area A is the area in a reference plane at which the impedance is measured, the effective area of insonification. If the surface is rough the locus of the reference plane is where the average displacement within A is zero. A directional source is used to insonify the area A. Its radiated power P is

$$P = \int \frac{p^2(\theta, \phi) d^2}{\rho c} \, d\Omega = \frac{p_a^{\,2} d^2}{\rho c} \Omega_o \qquad \text{Eq. 1}$$

| | |
|---|---|
| $p_a$ | beam axis sound pressure |
| d | axial distance from source |
| $\Omega_o$ | solid angle of insonification |
| $\rho c$ | wave impedance |

$$A \cos \theta = \Omega_o d_1^{\,2} \qquad \text{Eq. 2}$$

| | |
|---|---|
| A | area of insonification |
| $\theta$ | angle of incidence to reference plane |
| $d_1$ | axial distance from source to reference plane |

Morse and Ingard[1] discuss scattering from surface irregularities in terms of an area A. Their equation 8.3.6 assumes a plane wave incident on A for a patch on a surface having a surface admittance $\beta_o$ everywhere except A and $\beta$ on A.

For a rough surface having random variations in admittance, Fig 8.10, they show that the first term in their equation representing the admittance variation has its maximum in the direction of the specular reflection. The second term representing the roughness has its maximum, a function of the correlation length to wave length, on a cone surrounding

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the specular reflection angle. They suggest that the area $A$ may be the only area which is "illuminated" by the beam of sound. From this latter suggestion we suggest that transducer circuit theory can be used to derive a means for measuring the impedance of a locally reacting surface. The impedance is determined at the specular angle; the roughness is determined from the cone of maximum scattered sound. If the sound speed in the bottom is greater than the sound speed in the ocean layer then the impedance will show a sharp maxima at one angle of incidence, thus giving a measure of one more parameter when the sound source is highly directional[2]. Alternatively if the density can be determined from core samples then the speed of sound can be computed from the impedance and density.

## Progress

The reference surface is treated as an equivalent circuit driven by the Thévenin sound pressure or the pressure at an infinite impedance surface. The impedance terms in the circuit are the radiation impedance and acoustic impedance-to-be-measured as referred to the reference plane, Fig. 1.

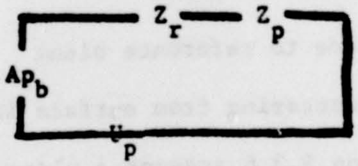

Fig. 1

| | |
|---|---|
| $A$ | effective area on the reference surface |
| $P_b$ | blocked or Thévenin pressure |
| $Z_r$ | radiation impedance of $A$ |
| $Z_p$ | acoustic impedance to be measured |
| $U_p$ | volume velocity due to $Z_p$ |

By definition the diffraction constant, $D$, is the ratio of the blocked to the free field pressure or

$$p_b = Dp_{ff}$$

$p_{ff}$ is the beam axis sound pressure in equation 1 at the ocean bottom when d is the distance from the source to the bottom. The free field pressure is determined from a calibrated source or a hydrophone placed on the axis from the source to the area A. The boundary transmits a reflected pressure back toward the source in the case of normal incidence.

$$P_d = D(U_i - U_p) \frac{\omega\rho}{4\Pi d}$$

where

$p_d$ reflected pressure measured at a distance d back on the axis normal to A.

$U_i$ volume velocity of the incident free sound field

$\omega$ angular frequency

$\rho$ density of the acoustic medium

$$\frac{\omega\rho}{4\Pi d} = \frac{\rho c}{2d\lambda}$$

and $U_i = Ap_{ff}/\rho c$

$\rho c$ the wave impedance

Fig. 1

$$Z_p = (ADp_{ff}/U_p) - Z_r \qquad \text{Eq. 3}$$

$$U_p = (Ap_{ff}/\rho c) - (2d\lambda p_d / D\rho c) \qquad \text{Eq. 4}$$

and in Eq. 3

$$Z_p = ADp_{ff}\rho c[Ap_{ff} - 2d\lambda p_d/D]^{-1} - Z_r \qquad \text{Eq. 5}$$

The diffraction constant D is calculated for the geometry of the measurement surface. It is calculated, as a radiation problem, utilizing one of the computer programs SHIP or CHIEF.

As stated previously Morse and Ingard assume a plane-wave over the area A. In this approach the sphericity of the wave can be included in the calculation of the diffraction constant D. From the method of images one can readily see that the incident wave sphericity applies to the reflected wave.

If the effective area A has a radius a and ka > 10, $k = \frac{\omega}{c} = \frac{2\pi}{\lambda}$, the wave number, then $Z_r \to \rho c$ and the diffraction constant D = 2. For this frequency range the area A can be in an infinite rigid baffle or unbaffled; $Z_r$ and D are unchanged. Thus Eq. 5 for the condition ka > 10 becomes

$$Z_p = \left[\frac{Ap_{ff} + d\lambda p_d}{Ap_{ff} - d\lambda p_d}\right] \rho c \qquad \text{Eq. 6}$$

This fact is important to the measurement of the acoustic impedance of the ocean bottom. The impedance of the region around A (not *insonified*) has no effect on the measurement when ka is large and the boundary is locally reacting.

The above has been derived for normal incidence of the sound on the ocean bottom. For specular reflection A is obtained from Eq. 2 and the diffraction constant D is a function of the angle of incidence.

For other than normal incidence the impedance can be expressed as $Z\cos\theta$, Eq. 6.3.5 in reference 1. Stickler[2] shows that when the sound speed in the bottom ($c_b$) is greater than the speed of sound in the ocean layer ($c_o$) there exists a critical angle $\theta_c$

$$\theta_c = \sin^{-1}(c_o/c_b)$$

and

$$z(\theta) = (\sin^2\theta_c - \sin^2\theta)^{-\frac{1}{2}}$$

which is typically in the range of 60° incidence. His $z(\theta)$ is a normalized, dimensionless impedance and the bottom is treated as a fluid medium.

Equation 5 can be rewritten to yield a measure of the back scattering cross section $\sigma$

$$\sigma = \frac{{p_d}^2 d^2}{{p_{ff}}^2} = \frac{A^2 D^2}{4\lambda^2} \left[1 - \frac{D\rho c}{Z_p + Z_r}\right]^2 \qquad \text{Eq. 7}$$

thus showing that the back scattering cross section is a function of the impedance of the bottom.

The reflection coefficient r

$$r = \frac{p_d}{p_{ff}} = \frac{AD}{2d\lambda} \left[1 - \frac{D\rho c}{Z_p + Z_r}\right] \qquad \text{Eq. 8}$$

Suppose in Eq. 8, for normal incidence, the boundary is in the near field of the source-receiver. The incident pressure $p_{ff}$ is the average pressure in the collimated beam and the area A is the area of the piston source and the area of insonification. The average wave impedance is $\rho c$. The radiated power of the reflected wave

$$P = \frac{{p_{ref}}^2 A}{\rho c}$$

In Eq. 8 the radiated power of the reflected wave

$$P = 4\pi {p_d}^2 d^2 / R_\theta \rho c$$

$R_\theta$ is the directivity factor for the insonified area A. For plane wave incidence and reflection

$$R_\theta = \frac{4\pi A}{\lambda^2}$$

and the relationship between $p_{ref}$ and $p_d$ can be shown to be

$$p_d = p_{ref}\left(\frac{A}{d\lambda}\right)$$

$p_{ff}$ is now $p_{inc}$ the incident sound pressure. Eq. 8 can be rewritten as

$$\frac{p_{ref}}{p_{inc}} = \frac{D}{2}\left[1 - \frac{D\rho c}{Z_p + Z_r}\right]$$

For normal incidence $D = 2$ and $Z_r = \rho c$

and $r = \dfrac{p_{ref}}{p_{inc}} = \dfrac{Z_p - \rho c}{Z_p + \rho c}$

the familiar equation for the reflection of a plane wave.

We have assumed, as a first approximation, that D and $Z_r$ can be derived for a reference plane from which the average displacement of the rough bottom is zero. We have assumed that propagation theory could be facilitated by assuming a plane boundary to the extent of the insonified area A, neglecting short range roughness. This assumption must be analyzed by one more knowledgeable in propagation theory.

Equations 5 and 6 describe a means for measuring the acoustic impedance of a finite area of the ocean bottom and specifying it at a reference plane. In Eq. 5, the size of the area A is determined by the directivity of the source. Impedance, as a function of penetration depth, is determined from pulsed sound measurements by analyzing the elongated reflected pulse. The impedance data as a function of depth is that measured at the reference plane as a function of time in the reflected pulse. The impedance and sound speed in the first layer is used to determine the impedance at the next layer from the value measured at the reference plane.

The use of a directional source resolves the ambiguity of angle and depth resolution that exists when an omnidirectional source is used.

For measurements at other than the specular angle Eq. 5 is changed to

$$Z_p = AD_1 p_{ff} \rho c \left[ Ap_{ff} - 2d\lambda p_d / D_2 \right]^{-1} - Z_r \qquad \text{Eq. 9}$$

where $D_1$ refers to the angle of incident sound, $D_2$ refers to the angle of reflected sound measurement and $Z_r$ is the radiation impedance calculated for the incident sound phase distribution on the area A. $D_1$, $D_2$, and $Z_r$ as a function of incident angle can be calculated with CHIEF.

The source should have a beam width of about 10° to obtain a reasonable angular resolution. At higher frequencies this is possible with a large piston source. At frequencies in the range of 1 kHz and below a parametric source will be required.

## Summary

The acoustic impedance of a boundary can be determined by pulsed sound measurement techniques with a directional sound source and hydrophone or with a transducer and transmit-receive switch. Computer programs SHIP and CHIEF can be used to calculate the diffraction constant and the radiation impedance appropriate for the test geometry. Measurement data consists of incident free field pressure and reflected pressure in magnitude and phase and the effective area of insonification on a reference plane in region of the boundary. Measurements of the specular reflection should yield the impedance of the bottom as a function of the angle of incidence. For the condition that the sound speed in the bottom is greater than the sound speed in the ocean layer the critical angle yields a measure of the sound speed in the bottom. This in combination with pulse time analysis of the reflected pulse measures the impedance at successive layer depths in the ocean bottom. Non-specular reflection measurements for normal incidence sound should yield a measure of bottom roughness when the roughness is of the order of the wave length of the incident sound. The technique is probably most applicable to shallow water propagation. Important advances often come from the realm between two scientific branches. It is hoped that this application of transducer equivalent circuit theory to the measurement of the characteristics of the ocean bottom is such an advance. The proposal is submitted for criticism and revision by those more familiar with the data requirements to describe propagation phenomena. If the approach is feasible an experiment should be designed for testing the theory.

## References

1. Morse and Ingard, Theoretical Acoustics, Chapter 8, Mc-Graw Hill, 1968

2. D. C. Stickler, "Measurement of the sound speed in bottom layers.", J. Acous. Soc. Am. Vol. 57, p. 585, March 1975