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QUARTERLY PROGRESS REPORT NUMBER 1, FOR APRIL, MAY AND JUNE 197--ETC(U)
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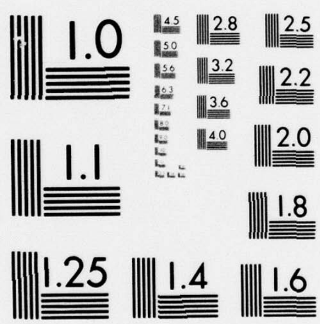

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22 July 1971

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UNDER CONTRACT N00024-71-C-1266
April, May, and June 1971

NAVAL SHIP SYSTEMS COMMAND
Contract N00024-71-C-1266
Proj. Ser. No. SF 11552002, Task 8118

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APPLIED RESEARCH LABORATORIES
THE UNIVERSITY OF TEXAS AT AUSTIN
AUSTIN, TEXAS 78712

ABSTRACT

In Section I a status report is given on the experimental measurements of forward scattering by acoustically penetrable rough surfaces. Plastic molds from the existing pressure release surfaces have been made. One penetrable rough surface has been cast. The other surfaces will be completed as soon as the acoustical parameters of the first one have been studied. In Section II the acoustic waveguide problem for lossy boundaries is solved in terms of a contour integral. The eigenvalue equation is given as a function of the reflection coefficients of the lossy boundaries.

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I. PRELIMINARY WORK ON THE EXPERIMENTAL MEASUREMENTS OF FORWARD SCATTERING BY ACOUSTICALLY PENETRABLE SURFACES

In preparation for the experimental forward scattering measurements of acoustically penetrable random surfaces, the existing pressure release surfaces were used to make plaster molds. From these molds surfaces of the same statistical properties as the pressure release surfaces but different acoustical properties are to be cast. Initial plans called for molds of the smoothest and the roughest of the three surfaces (rms heights = 0.091 in., 0.182 in., and 0.364 in. and identical correlation lengths) to be made. However, the roughest surface could not be used for mold making because of deterioration of the surface coating. Consequently, plaster molds of only the smoothest and intermediate surface were made. Casting of these surfaces using an acoustically penetrable material is in progress. In addition, an acoustically penetrable plane surface will be made for data comparison.

The material which will be used to simulate a liquid bottom (low shear wave velocity bottom) is a mixture of Scotchcast 221® polyurethane and No. 5 sandblasting sand in the proportion 1:1 by weight. The selection of suitable materials and the measurement of their acoustical properties were carried out during the previous contract year and are reported in detail in Appendix A of the Final Report under Contract N00024-70-C-1279, "Scattering and Propagation of Acoustic Waves in the Presence of Rough, Penetrable Boundaries." A penetrable surface has been cast from the mold of the smoothest surface (rms height = 0.091 in.); however, further casting has been temporarily halted to allow for an evaluation of the acoustic parameters of the new surface. This is necessary because of the unforeseen settling of the sand in the casting material. The original check of the acoustical properties used small volumes of material and showed no evidence of settling. However, during the recent casting, large volumes of material were used and settling of the sand was observed. Since settling of the sand creates a density gradient in the surface, a casting method which maintains the homogeneity of the mixture is presently being sought.

Upon completion of the surface castings and evaluation of the acoustic parameters of these surfaces, the experimental forward scattering measurements will begin.

II. NORMAL MODE SOUND PROPAGATION IN AN INHOMOGENEOUS MEDIUM WITH LOSSY BOUNDARIES

A. Introduction

The acoustic field of a cw point source located in an inhomogeneous medium with lossy boundaries is given as a contour integral. Singularities of the contour integral are given by the dispersion equation (period equation, eigenvalue equation, etc.). Lossy boundaries are introduced through effective reflection coefficients. By applying phase integral techniques, the dispersion equation is given in terms of the reflection coefficients of the lossy boundaries.

B. Fundamental Integral for the Acoustic Field

The wave equation for a point source, with angular frequency ω, located in a layered inhomogeneous medium is given by

$$\nabla^2 P - \frac{1}{C^2(z)} \frac{\partial^2 P}{\partial t^2} = -i\omega Q_o \delta(\bar{r}-\bar{r}_o) e^{-i\omega t} \quad , \tag{1}$$

where P represents the pressure, C(z) is the sound velocity (variable in the depth coordinate z), and $\delta(\bar{r}-\bar{r}_o)$ is the three-dimensional Dirac delta function. The strength Q_o of the source is equal to the density times the volume velocity. If cylindrical coordinates (r,θ,z) are assumed with azimuthal symmetry and a time factor of $\exp(-i\omega t)$ is suppressed, the following equation is obtained:

$$\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial P}{\partial r} \right) + \frac{\partial^2 P}{\partial z^2} + k^2(z) P = \frac{i\omega Q_o \delta(r) \delta(z-z_o)}{2\pi r} \quad , \tag{2}$$

where P now represents the time independent pressure. The wave number $k(z)$ is defined as $\omega/C(z)$ and the source is located at $z=z_o$ and $r=0$, as indicated in Dwg. AS-70-767. The vertical depth coordinate z varies from $0 \le z \le d$, and the range coordinate r varies from $0 < r < \infty$. Boundary conditions imposed on Eq. (2) are that

a) P must satisfy a radiation condition for $r \to \infty$

b) at the surface and bottom, the reflection coefficients be known

c) P and $\frac{\partial P}{\partial z}$ be continuous across any discontinuities in the velocity depth profile.

By means of a convolution of Green's functions the solution for Eq. (2) can be stated as

$$P(r,z,z_o) = \frac{\omega Q_o}{4\pi} \int_C \frac{\psi_1(z_<)\psi_2(z_>)H_o^1(\xi r)\xi d\xi}{W(\psi_2,\psi_1)} , \tag{3}$$

where ξ is the complex separation parameter, and where $z_<$ and $z_>$ denote the smaller or larger, respectively, of the variables z and z_o. The functions ψ_1 and ψ_2 are chosen to satisfy boundary conditions at $z=0$ and $z=d$. When boundary conditions are other than pressure release and rigid, the usual method is to state the boundary values as impedance conditions. For example Bucker[1] (in his Appendix A) states the boundary conditions as impedance conditions. By means of a pseudoisovelocity layer, Bucker relates his impedance conditions to plane wave reflection coefficients. He assumes various values for the boundary losses and calculates the reflection coefficients from the equations

$$SL = -20 \log_{10}|S|$$

and (4)

$$BL = -20 \log_{10}|R| ,$$

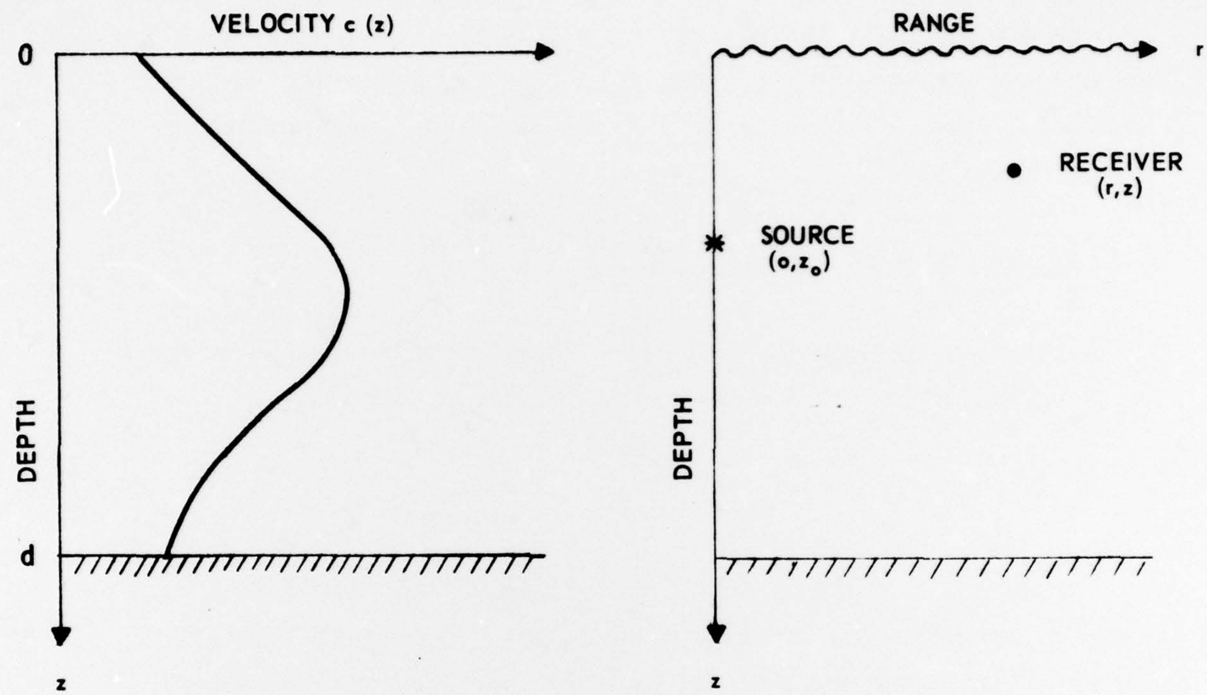


DIAGRAM OF WAVEGUIDE SHOWING LOCATION
OF SOURCE AND RECEIVER

ARL - UT
AS - 70 - 767
RLD - WDC
6 - 29 - 70

where SL and BL represent surface loss and bottom loss respectively, and where S and R are the surface and bottom plane wave reflection coefficients. Therefore by assuming various values for the surface and bottom losses, Bucker is able to arrive at impedance conditions at the boundaries.

C. The Wronskian Dispersion Equation

According to Appendix A of Bucker's paper the dispersion equation is given by setting the Wronskian equal to zero, that is,

$$W(\xi_n) = 0 \quad . \tag{5}$$

However, Eq. (5) does not always give the correct results. For example, in the case of surface duct propagation where no bottom is assumed (i.e., $z \to \infty$) and where an impedance condition is assumed at the surface, then

$$\psi_1(z) = n_1(z,\xi) - X^- n_2(z,\xi) \tag{6}$$

and

$$\psi_2(z) = n_2(z,\xi) \quad , \tag{7}$$

where n_2 and n_1 are traveling wave solutions to the z-component wave equation:

$$\frac{d^2 n}{dz^2} + \left[k^2(z) - \xi^2\right] n = 0 \quad . \tag{8}$$

Solution n_2 must represent an outgoing wave for $z \to \infty$ and n_1 represents an outgoing wave for $z \to -\infty$.

The function X^- is given by

$$X^- = \frac{n_1'(0,\xi) - \gamma n_1(0,\xi)}{n_2'(0,\xi) - \gamma n_2(0,\xi)} \quad , \tag{9}$$

where the impedance condition is given by

$$\gamma = \frac{\partial P}{\partial z} \Big/ P \Big|_{z=0} \quad . \tag{10}$$

In this case the eigenvalues should be given by the zeros of the Wronskian of ψ_2 and ψ_1:

$$W(\psi_2,\psi_1)\big|_0 = n_1' \, n_2' - n_2' \, n_1' = 0 \quad , \tag{11}$$

but the correct period equation is given by

$$n_2'(0,\xi) - \gamma n_2(0,\xi) = 0 \quad . \tag{12}$$

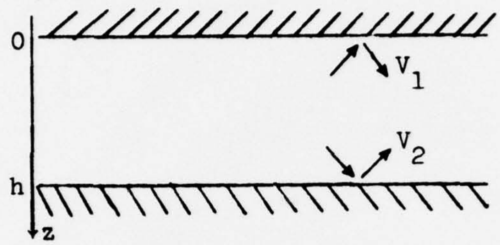
It appears that no general form for the secular equation can be given in terms of the Wronskian.

D. The Reflection Coefficient Dispersion Equation

The eigenvalue equation in terms of effective reflection coefficients is given by Brekhovskikh,[2] Budden,[3] and Wait.[4] The general form is stated as

$$V_1 V_2 e^{2ikh \sin \theta} = 1 \quad , \tag{13}$$

where V_1 and V_2 are effective reflection coefficients at the boundaries z=0 and z=h (as shown in the following sketch),



where the region between zero and h represents a homogeneous layer. The regions above z=0 and below z=h may be inhomogeneous. V_1 and V_2 are each functions of the modal parameter ξ. A form for V_2 (bottom reflection) has been given by Urick, Lund, and Bradley.[5] From classical scattering theory the form for V_1 (surface reflection) can be given as

$$V_1(\theta) = -e^{2(k\sigma \sin \theta)^2} \quad , \tag{14}$$

where σ is the rms height value for the rough ocean surface. If a peak to trough height H is known, then a good approximation for σ is given by the equation

$$\sigma = \frac{H}{2\sqrt{2}} \quad . \tag{15}$$

It is interesting that no suitable forms for an eigenvalue dependent impedance condition are found in the literature, a suitable form being one which is both surface property dependent and medium dependent. However, if the boundary conditions are specified in terms of reflection coefficients, then both the surface properties and the medium properties (through the angle θ) are included.

For the situation where there is no homogeneous region, the parameter h is allowed to approach zero. V_1 and V_2 are then effective upgoing and downgoing reflection coefficients referred to the same level. Since the Wronskian evaluation does not depend on any specific level, neither does the level for V_1 and V_2. Equation (13) then becomes

$$V_1 V_2 = 1 \quad . \tag{16}$$

So long as there existed a homogeneous layer between zero and h, the lossy boundary value problem in terms of effective reflection coefficients was straightforward. When the medium is inhomogeneous, then it is not so clear how to include both boundaries when the two reflection coefficients are referred to the same level. However if phase integral methods are used to obtain the period equation, then the reflection coefficients can be referred to the two boundaries. The phase integral period equation should give fair estimates for the generally complex eigenvalues. Bartberger and Ackler[6] have discussed the value of the phase integral condition for the Furry-Pedersen type of velocity depth profiles.

The phase integral period equation can be stated as[7,8]

$$V_1(o)\, V_2(d)\, e^{2i \int_o^d \sqrt{k^2(z) - \xi^2}\, dz} = 1 \quad , \tag{17}$$

which is a generalization of the usual condition without the V's. It is instructive to write Eq. (17) in a transverse resonance form:

$$2 \int_o^d \sqrt{k^2(z) - \xi^2}\, dz = 2n\pi + i\ln V_1(o) V_2(d) \tag{18}$$

$$(n=0,1,2,\ldots) \quad .$$

This form is essentially the same as Bucker[9] derived several years ago. The usual phase integral conditions can be obtained from Eq. (18). For example if $V_1(o) = e^{-i\pi} = -1$ (free surface) and $V_2(d) = e^{-i\pi/2}$ (mode trapped by continuous refraction due to the inhomogeneous medium at some point d), then Eq. (18) becomes

$$\int_o^d \sqrt{k^2(z) - \xi^2}\, dz = \pi(n + 3/4) \qquad (n=0,1,2,\ldots) \quad . \tag{19}$$

When the modes are completely trapped because of continuous refraction due to the inhomogeneous medium, then $V_1(o) = V_2(d) = e^{-i\pi/2}$ and Eq. (18) becomes

$$\int_o^d \sqrt{k^2(z) - \xi^2}\, dz = \pi(n + 1/2) \quad . \tag{20}$$

It should be noted that when the modes are trapped because of the medium, then the lines z=o and z=d are caustics of the guided ray system and the $\pi/2$ values give the phase change of a ray upon touching the caustic.

By separating Eq. (18) into real and imaginary parts it is possible to obtain forms for $\mathrm{Re}(\xi_n)$ and $\mathrm{Im}(\xi_n)$. The form for $\mathrm{Im}(\xi_n)$, which is the result of boundary losses and leakage, can sometimes be expressed in terms of equivalent ray cycle distance. These values for ξ_n are only approximate and will only be used for estimates to the exact values. The exact values must be obtained from $V_1V_2 = 1$. Present work is being directed in obtaining an alternate form for $V_1V_2 = 1$.

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22 July 1971

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Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
Applied Research Laboratories
The University of Texas at Austin
Austin, Texas 78712

2a. REPORT SECURITY CLASSIFICATION
[redacted]

2b. GROUP
---

3. REPORT TITLE
6 QUARTERLY PROGRESS REPORT ~~NO. 1, UNDER CONTRACT N00024-71-C-1266~~ for April, May and June 1971.
(number)

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
9 Progress report for April, May, and June 1971.

5. AUTHOR(S) *(First name, middle initial, last name)*
---

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
11 22 Jul[redacted]1971	19	9

8a. CONTRACT OR GRANT NO.
15 N00024-71-C-1266

b. PROJECT NO.
17 SF 11552002, Task 8118

c.

d. 16 F11552

9a. ORIGINATOR'S REPORT NUMBER(S)
--- 12 17p.

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
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10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES
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12. SPONSORING MILITARY ACTIVITY
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Department of the Navy (NAVSEA 06H1-4)
Washington, D. C. 20360

13. ABSTRACT

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

[redacted]

Security Classification

404 434

mt

[redacted]
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Penetrable rough surfaces Waveguide propagation Lossy boundaries Dispersion equations Phase integral methods						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

[redacted]
Security Classification