ACOUSTIC PRESSURE DISTRIBUTION ON THE BOTTOM OF A 
HEDGE-SHAPED OCEAN(U) NAVAL POSTGRADUATE SCHOOL
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ACOUSTIC PRESSURE DISTRIBUTION ON THE BOTTOM OF A WEDGE-SHAPED OCEAN

by

Li Yu-Ming

December 1987

Thesis Advisor: A. B. Coppens

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Title: Acoustic Pressure Distribution on the Bottom of Wedge-Shaped Ocean

Abstract: The pressure amplitude distribution along the interface between a wedge-shaped fluid layer overlying fast and slow fluid bottoms were investigated using computer models based on the method of images. The pressure amplitude along the bottom rapidly falls off for distances closer to the apex than that at which adiabatic-mode theory predicts cut-off for the lowest mode. This distance is termed the "dump distance" for acoustically fast-bottom condition. In the case of a slow bottom, because the speed of sound ratio is greater than 1, the dump distance does not exist. To facilitate scaling the acoustic fields, a "scaling distance" is introduced: \( X_0 = \frac{\text{wave length}}{4\sin\theta \tan B} \) where \( \theta = \cos^{-1} \left( \frac{c_1}{c_2} \right) \), \( B \) is the angle of the wedge, \( c_1 = \) speed of sound in water, \( c_2 = \) speed of sound in bottom, and \( k_2 = \frac{w}{c_2} \). \( X_0 \) appears to have physical meaning as a useful scaling distance.
Acoustic Pressure Distribution on the Bottom of a Wedge-Shaped Ocean

by

Li Yu-Ming
Lieutenant, Republic of China Navy
B.S., R.O.C. Naval Academy, 1981

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING ACOUSTICS

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ABSTRACT

The pressure amplitude distribution along the interface between a wedge-shaped fluid layer overlying fast and slow fluid bottoms were investigated using computer models based on the method of images. The pressure amplitude along the bottom rapidly falls off for distances closer to the apex than that at which adiabatic-mode theory predicts cut-off for the lowest mode. This distance is termed the “dump distance” for an acoustically fast-bottom condition. In the case of a slow bottom, because the speed of sound ratio is greater than 1, the dump distance does not exist. To facilitate scaling the acoustic fields, a “scaling distance” is introduced: \( X_0 = \frac{\lambda}{4 \sin \theta_c \tan \beta} \) where \( \theta_C = \cos^{-1} \frac{c_1}{c_2} \), \( k_2 = \frac{\omega}{c_2} \), \( \beta \) is the angle of the wedge, \( c_1 \) = speed of sound in water, \( c_2 \) = speed of sound in bottom, and \( \lambda \) = wavelength in the wedge medium. \( X_0 \) appears to have physical meaning as a useful scaling distance.
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<tr>
<td>$\beta$</td>
<td>Wedge angle</td>
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<tr>
<td>$G$</td>
<td>Source angle measured upward from the interface</td>
</tr>
<tr>
<td>$D$</td>
<td>Receiver angle measured upward from the interface</td>
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<tr>
<td>$R_1$</td>
<td>Normalized source distance</td>
</tr>
<tr>
<td>$R_2$</td>
<td>Normalized receiver distance from the shoreline</td>
</tr>
<tr>
<td>$Y_0$</td>
<td>Normalized distance along the shore between the receiver and the source</td>
</tr>
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<td>$\rho_1/\rho_2$</td>
<td>Ratio of the medium density to the bottom density (density ratio)</td>
</tr>
<tr>
<td>$c_1/c_2$</td>
<td>Ratio of the speed of sound in the medium to the speed of sound in the bottom (speed of sound ratio)</td>
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<tr>
<td>$\alpha/k_2$</td>
<td>Wave number in the bottom divided into the absorption in the bottom.</td>
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ACKNOWLEDGMENT

I wish to thank Professors James V. Sanders and Alan B. Coppens for their support and perseverance in this endeavor.
I. INTRODUCTION

Acoustic propagation in an ocean with a sloping bottom is of growing concern both for theoretical reasons and because of the importance of knowing the performance of acoustic sensors located over the continental slope. This problem has been studied by many scientists [Ref. 1-8], but many have examined only cases of a fluid wedge for which both surfaces are acoustically impenetrable.

In the case of a fluid wedge for which both surfaces are acoustically impenetrable, mathematical examination of the problem has been performed by Bradley and Hudimic [Ref. 1] using both image theory and normal-mode theory.

For practical interest for underwater acoustics, the top boundary may still be approximated as an impenetrable, pressure-release surface, but the bottom surface can no longer be considered to be perfectly reflecting. From a mathematic point of view, this generalization of the boundary conditions has an important repercussion: The wave equation is no longer separable and standard normal-mode theory can no longer be applied.

This research will focus on four tasks:

1. Use the models to reevaluate the fast-bottom case which was done by Lesesne [Ref. 9].

2. Provide output in graphic form for ease of interpretation.

3. Change from the fast bottom model to a slow bottom model and evaluate whether a scaling factor is useful or not.

4. Compare results to others' research.
II. DEVELOPMENT

A. DESCRIPTION OF THE THEORY

1. Image Theory

The approach used in this research is to determine the amplitude and phase of the pressure in the fluid by the method of images [Refs. 8-10]. In 1978, with the aid of a computer model, Coppens, Sanders, Ionnou, and Kawamura [Ref. 11] predicted and measured the pressure amplitude and phase in the up-slope direction along the bottom of a wedge-shaped fluid layer overlying a fast fluid bottom. The geometry is shown in Figure 1.

Baek [Ref. 12] used the same model in 1984 to predict pressure amplitude and phase everywhere within the wedge in the up-slope direction. In the same year, Lesesne [Ref. 9] implemented a model developed by Coppens and Sanders which is not limited to up- or down-slope prediction.

For the wedge-shaped duct, the images which lie on a circle (see Figure 2) are eventually going to appear in the region where the source is located and which, by the established boundary conditions, can contain only the source. However, following Sommerfeld [Ref. 13], the concept of an extended Riemann surface is introduced. The extension of the $\theta$ coordinate by introduction of Riemann sheets allows for an infinite (if need be) number of images.

The source and each of the images radiate a spherical wave of the appropriate phase. The phase coherent summation of these waves
yields the total pressure and phase to be found at any field point in the wedge.

The total pressure of all the images and the source along a line of constant x from the apex can be determined by the method of images (see Figure 2).

\[
\tilde{P}_N(x) = \sum_{n=1}^{N} (-1)^{\text{INT}(N/2)} [g_{n-2} \exp(\text{i}k_1x \cos(\theta_n - D))] + g_n \exp(\text{i}k_1x \cos(\theta_n + D)) \quad (1)
\]

where

\[
N = \text{INT}(180/\beta),
\]
\[
\beta = \text{the wedge angle},
\]
\[
D = \text{the receiver angle},
\]
\[
G = \text{the source angle}.
\]

\[
\theta_n = (n - 1)\beta + G, \quad n = 1,3,5,7...
\]
\[
\theta_n = n\beta - G, \quad n = 2,4,6,8...
\]
\[
g_n = \prod_{m=1,3,5...}^{n} R(\theta_m) \quad m \text{ odd}
\]
\[
g_n = \prod_{m=2,4,6...}^{n} R(\theta_m) \quad m \text{ even}
\]
\[
g_{-1} = g_0 = +1.0
\]
The $g_{n-2}$ and $g_n$ are path parameters from the nth image and $R(\theta_n)$ is the reflection coefficient of the bottom with grazing angle $\theta_n$. (For details, see Ref. 12.)

The successive reflection of sound from the surface and bottom is accounted for by multiplying the sound field radiated by each image by the plane wave reflection coefficients corresponding to reflections encountered by the wave as it propagates toward the field point.

For the fast bottom, all distances are normalized to the distance $X_0$, measured from the apex, at which the lowest mode would attain cut-off in the adiabatic approximation. This distance $X_0$ is called the dump distance [Ref. 12] (see Figure 2).

$$X_0 = \frac{h}{\tan \beta} = \frac{\lambda}{4 \cdot \sin \theta_c \cdot \tan \beta}$$

$\lambda$ = wavelength in wedge medium
$\theta_c$ = $\cos^{-1} \frac{c_1}{c_2}$ = critical angle
$\beta$ = wedge angle
$h$ = water depth at dump distance

For this model, we use wedge angles of the form $\pi/n$ where $n$ is an integer and consequently no diffraction term exists [Refs. 14-15]. If $n$ is not an integer, then there will be a diffracted wave which will always arrive at a later time than the latest image contribution [Ref. 14].
2. **Normal Mode With Ray Bundles**

V. K. Kuzentsov's [Ref. 7] normal-mode-with-ray-bundles approach treats the entire domain of the wedge as two zones with respect to the separation at $V_m$, where $V_m$ is the exit line of the normal mode from the wedge into the half-space. Its position corresponds to the critical wedge thickness for the given normal mode with the non-wave guide zone $r < r_m$. In the wave-guide zone, the normal modes behave as normal modes in an ideal wedge.

3. **Ray Tracing**

Tien et al. [Ref. 16] developed an analysis based on a ray approach. At the depth where the mode would be cut off, it is assumed that a ray reflects from the bottom of the wedge at the critical angle:

This ray is allowed to reflect from the surface and it reattains the bottom at a grazing angle which is the critical increased by twice the wedge angle. The intervening region of the wedge is filled with a large number of downward-traveling rays whose angles of incidence on the bottom are uniformly increasing between $\theta$ and $\theta + 2\beta$. Then, for each ray the transmission into the bottom is calculated. This process is repeated progressively toward the apex of the wedge. There is no attempt to preserve phase information, and the power of the beam in the bottom at each angle of depression is simply the sum of the powers transmitted by the appropriate rays. Calculations performed with the help of a computer again provide good agreement with their experimental observations as far as the angle of depression and beam width of the beam in the bottom were concerned, but this approach predicts that there should be no transmission of sound into the bottom until the cutoff depth is reached. [Ref. 17]

In the ray-tracing method, there is no attempt to preserve phase information, and the power of the beam in the bottom is simply the sum of the power transmitted by the appropriate rays.
4. Parabolic Equation

Jensen and Kuperman [Ref. 41] used the parabolic equation approximation to study up-slope propagation. Their numerical calculations suggested that there is negligible coupling between normal modes. They also obtained some very interesting graphs which show that the energy of a mode passing through cut-off was radiated as a beam into the bottom.

The only significant limitation of this method appears to be that inherent in the approximations necessary for applicability of the parabolic equation itself.

5. Buckingham’s Approach

In an A. B. Wood Memorial Lecture, Buckingham [Ref. 21] discussed acoustic propagation in a wedge-shaped ocean. Basically, he follows his previous papers [Ref. 18], modified to include a penetrable bottom. In the original paper [Ref. 18], both forward scattering and backward scattering exists in the acoustic field except when the receiver is located in the vicinity of the source. However, in the penetrable wedge there can be no significant backward-reflected component in the acoustic field [Ref. 21].

Buckingham also used the Rayleigh law of reflection for fast bottom and derived an effective wedge with a pressure-release bottom (see Figure 31): The Rayleigh law of reflection is

\[
V = \frac{g \sin \alpha - j(\cos^2 \alpha - \cos^2 \alpha_c)^{1/2}}{g \sin \alpha + j(\cos^2 \alpha - \cos^2 \alpha_c)^{1/2}}
\]  

(1)
where \( g = \frac{\rho_2}{\rho_1} \alpha \) is the angle from the normal, and \( \alpha_c \) is the critical angle. Here, we are concerned only with grazing angles less than the critical, where total internal reflection occurs. When \( \alpha > \alpha_c \), there is a phase change on reflection, \( 2E \), which from equation (1) can be expressed as

\[
2E = 2 \tan^{-1} \left[ \frac{(\cos^2 \alpha - \cos^2 \alpha_c)^{1/2}}{g \sin \alpha} \right] \tag{2}
\]

Buckingham then points out that similar phase change would occur if the ray had been reflected from a pressure-release surface a distance \( \Delta \) below the actual interface (Figure 31):

\[
\Delta = \left( \frac{\pi}{2} - E \right) \frac{k \sin \alpha}{\Delta}
\]  

where \( k = \) wave number in the first fluid. At the critical angle, it is clear from equation (2) that \( E = 0 \), in which case,

\[
\Delta_0 = \frac{\pi}{2k \sin \alpha_c}
\]

B. DEVELOPMENT OF THE WEDGE MODEL

Originally, the fast-bottom model was modified from a computer model by Coppens, which was programmed in FORTRAN by Baek and designed to run on the IBM 3033. The slow-bottom model resulted from a modification of this program. For the slow bottom, the cut-off condition does not exist. However, using the following formula.
\[ \theta_0 = \cos^{-1}\left( \frac{1}{c_1/c_2} \right) \]
\[ c_1 = \text{velocity sound in water} \]
\[ c_2 = \text{velocity sound in bottom} \]

A scaling factor is introduced which uses the same idea that was in the fast-bottom model but with the speed of sound ratio inverted.

C. DEVELOPMENT OF THE GRAPHIC PROGRAMS

At this stage, it became necessary to consider alternate forms of data presentation. Because of the large volume of computed values, numerical output had become ineffective for recognizing details. The graphic package Disspla [Ref. 20], available on the IBM 3033 computer, was used in conjunction with these programs.

Graphical plots of the data are essential for a clear understanding of the problem. A purpose of this research was to utilize graphics to better determine the physical concepts necessary to interpret the aspects of sound propagation in a wedge-shaped ocean with a penetrable bottom.

Disspla is an option which uses “function calls” from a FORTRAN program to generate graphs. Disspla’s use of FORTRAN allows function calls to be written into a program or to be written as separate programs. The data used to compute the graphs can, therefore, be generated within the FORTRAN program or read in from a data file. The latter method was employed since it offered more versatility.

The size of the data file array or the number of points used did not prove to be a limitation on the graphs that were generated. By holding all but two parameters constant, a plot of pressure amplitude versus
the remaining variable was obtained. The position of the receiver on the bottom was usually varied to map the pressure field for a given source location.

The Disspla package supports this, but several problems had to be overcome. The Pocket Guide of Disspla describing this option was incomplete and very confusing. After comparing the various options available, it was decided to use the mode of graphics in which a matrix is used to define the data.

At the beginning, it was necessary to determine the optimal number of matrix points which would provide smooth and reasonable plots. After running through hundreds of plots, it was decided to use 100 x 100 matrix points.

The other important limitation was that the array containing the data points must be initially dimensionalized to the exact size of the data file array. This information was normally passed from the data file during the programs. This made it necessary to initialize the size of the data file array before the graphics program was run.

1. **Pressure-Amplitude Graphics**

   a. The pressure amplitude was plotted as a function of the two receiver coordinates. This produced a 3-D plot. The clearest presentation was a series of 3-D graphs stacked one after another (see Figures 3-A and 4-A), which contain fast- and slow-bottom complementary cases. (In this context, “complementary case” means the two cases obtained by exchanging the relative values of $c_1$ and $c_2$.)

   b. When the receiver is close to the source, the spatial variation of the pressure amplitude is smaller than the increment, producing artificial structure to the graph. To allow a truer view of this portion of the pressure amplitude, smaller portions of the field
can be viewed with higher resolution without increasing computer time (see Figures 5 and 6).

c. When a fuller view was necessary, the models were modified to ignore the field close to the source (see Figure 7).

2. **Pressure Contours**

The second graphic program used was a contour plot. The following should be mentioned here:

a. The poly 3 interpolation method was used to produce the plots.

b. The number of matrix points in this program is the same as for the pressure-amplitude graphics.

c. The increment in the pressure amplitude between contour lines was controlled either automatically or by the user. (In Figures 3-B and 15-B, one can see the difference between the two methods.)

In an attempt to analyze the pressure distribution near the source, a polar graphic program was developed. Here, the receiver was positioned on circles centered on the source and moved out in radial increments. Although this polar form satisfactorily dispersed the pressure field near the source, it created very serious geometrical distortion (see Figure 8). As a result, it was not very useful.
III. RESULTS FROM THE PLOTS

A. DATA PRESENTATION

1. The 3-D Plots

   Generally, the source is fixed and the pressure amplitude is calculated as a function of receiver position. So, for the three axes of the graphs:

   1. The $R_2$ axis is the normalized receiver distance from the shoreline.
   2. The $Y_0$ axis is the normalized distance along the shoreline between the receiver and the source.
   3. The vertical axis is the pressure amplitude.

   The resolution of the plots is set by specifying a 100 x 100 matrix of pressure calculation, which means:

   \[
   100 = \frac{\text{The range of } R_2 \text{ (or } Y_0\text{)}}{\text{The increment of } R_2 \text{ (or } Y_0\text{)}}
   \]

   The smaller the range of $R_2$ (or $Y_0$), the smaller the increment of $R_2$ (or $Y_0$), the higher the resolution of the plots, and the smoother the plots.

2. The Contour Plots

   The axes of the contour plot are $X$ and $Y$, in which $X$ is equal to $R_2$ and $Y$ is equal to $Y_0$. The label values on the contour lines are the pressure amplitudes. The increments of the pressure amplitude and the resolution are also controlled by the value of CONMAK [Ref. 20] (see Figure 9-B).
There are many "tear drop" contours, as shown in Figure 4-B. The contours are caused by the limited resolution and disappear at higher resolution (see Figure 9-B).

B. GENERAL PROPERTIES OF THE PLOTS WHICH ARE THE SAME FOR BOTH MODELS

When $R_1$ is equal to an odd number, the pressure peak is directly under the source, as shown in Figures 10 and 13. When $R_1$ is equal to an even number, the pressure is a minimum under the source (see Figures 11 and 14). The explanation for this can be found by using only the source, the image character, and the first surface reflected path (see Figure 12).

The time dependence of the signal at a distance $d_1$ from the source is

$$P_1 = \frac{A}{d_1} e^{-j(\omega t - kd_1)}$$

and the time dependence of the signal arriving at $R$ from the image characterizing the first surface reflected path is

$$P_1^* = \frac{-A}{d_2} e^{-j(\omega t - kd_2)}$$

where $d_2$ is the distance from the image point to receiver. So,

$$P_T = P_1 + P_1^* = e^{-j\omega t} \left[ \frac{A}{d_1} e^{-jkd_1} - \frac{A}{d_2} e^{-jkd_2} \right]$$

$$= e^{-j\omega t} \left[ \frac{A}{d_1} - \frac{A}{d_2} e^{-j(kd_2-d_1)} \right]$$

23
Thus, the phase difference between the signals arriving at R from S and S' is

\[ k(d_2 - d_1) = \Delta \phi \]

When constructive interference occurs,

\[ \Delta \phi = 2n\pi, \quad n = 0, 1, 2, \ldots \]

and when destructive interference occurs,

\[ \Delta \phi = (2n + 1)\pi, \quad n = 0, 1, 2, \ldots \]

The set of points for which \( d_2 - d_1 \) has a constant value defines a locus along which \( \Delta \phi \) is constant. The locus \( d_2 - d_1 = \) constant is a hyperbola of revolution about the vertical axis connecting the source and the first surface-reflected image. The intersection of this surface and the plane representing the interface between the two media yields elliptical curves close to the source, which evolve into hyperbolic curves far from the source.

These features are observed in the pressure contour plots for the various cases.

The angle of intromission for which the reflection coefficient is zero will exist in the fast-bottom case for \( \rho_1 > \rho_2 \) or the slow-bottom case for \( \rho_1 < \rho_2 \). Figures 17 and 18 are for cases possessing angles of intromission; these appear to exhibit no significant pressure changes compared to the non-intromission conditions.
C. DIFFERENCE BETWEEN BOTH MODELS

With the fast bottom, the pressure pattern is much more irregular and the pressure decays with distance from the source less rapidly because, with the fast bottom, more images are totally reflected from the bottom.
IV. EVALUATION

The effects of changing the properties of the wedge and the source position on the prediction of the pressure field were evaluated. As a base-line case, the following parameters were used:

\[
\begin{align*}
\beta &= 10^\circ \\
G &= 5^\circ \\
D &= 0^\circ \\
R_1 &= 40 \\
\frac{\rho_1}{\rho_2} &= 0.9 \\
c_1/c_2 &= 0.9 \text{ (fast bottom)} \\
c_1/c_2 &= 1/0.9 \text{ (slow bottom)} \\
\alpha/k_2 &= 0.0001
\end{align*}
\]

Three-dimensional depictions of the pressure fields for these conditions as functions of \(R_2\) and \(Y_0\) are shown in Figures 3 and 4 for both fast- and slow-bottom cases. The corresponding contour plots are included.

Both models were tested by varying one parameter and holding the others constant. Comparison of pressure-contour plots as well as three-dimensional plots was then used to determine the effect of each parameter.

A. SPEED-OF-SOUND RATIO, DENSITY RATIO, AND ATTENUATION

The base-line case was first examined by changing the speed-of-sound ratio. The positions and number of crests exhibited simple and
clear patterns for the slow-bottom model (see Figure 19) and more complex patterns for the fast-bottom model (see Figure 20) as this ratio was changed from 0.9 (or 1/0.9) to 0.5 (1/0.5). The density ratio was then changed down to a value of 0.5. The positions and number of crests show only minor variation (see Figure 21). This suggests that the major features of the sound field in the wedge are relatively insensitive to minor variations in the characteristics of the bottom.

Finally, the value of $\alpha/k^2$ was increased from 0.0001 to 0.1. The pressure-pattern did not change significantly but, as expected, the amplitudes of the crests showed sharp decreases as the attenuation increases.

B. RECEIVER ANGLE

The reader should be aware of the fact that the program contained in the appendix was modified as simply as possible, to insure that pressure was calculated infinitesimally above the bottom. If it is desired to calculate the pressure for receiver angles not essentially zero, the leading statements and do loops must be modified.

C. WEDGE ANGLE

As the wedge angle decreases, the dump distance increases, the number of images increases, and therefore the CPU time increases. For example, for $\beta = 10^\circ$, the CPU times for fast-bottom and slow-bottom cases are about 520 seconds and 480 seconds, respectively. If $\beta = 7^\circ$, the CPU time increases to about 900 seconds (see Figures 22 and 23).
D. SOURCE ANGLE

Changing the distance of the source from the apex (but still with \( G = \beta/2 \)) had a great effect on the position of the crests and troughs. However, for the source at large distances from the apex, scaling the receiver position restores the original patterns. For example, if the source is moved outward to twice its original position, a plot with the length scales divided by two produces the same graphic presentation (see Figures 3 and 24 or 4 and 25). This is consistent with Lesesne's observation.

E. LLOYD'S MIRROR

Figures 29 and 30 show the field due to the source and the first image point only. The source and the first image are of equal strength. The first image is coherent with the source but \( \pi \) out of phase (see Figure 12). That produces the Lloyd's mirror. The pressure distribution observed is identical for both fast- and slow-bottom programs when they were modified to have the same apparent speed of sound in the wedge. These figures show that major features of the pressure field are due mainly to the source and first image when the receiver is close to the source.
V. CONCLUSIONS AND RECOMMENDATIONS

The theory of 3-D acoustic propagation in a penetrable wedge presented in this research is based on the method of images which includes the fast- and the slow-bottom models. One of the research goals was to test whether the scaling factor method can apply to the slow-bottom case.

A. CONCLUSIONS

For both the fast bottom and the slow bottom, when the receiver is near the source, strong spatial oscillations in pressure are present. These variations are mainly due to interference between the source and the first surface-reflected image.

The primary result of the fast-bottom model is the importance of interference evident in the form of strong spatial oscillation. When the bottom mismatch increases, more interference occurs, because more images contribute to the field.

Generally, investigation of this model showed that the scaling factor worked.

One observation is in violation of physical intuition—when the bottom mismatch increases, more interference should occur. Figures 26, 27, and 28 show the opposite, with less interference as the bottom mismatch increases.

The results for the fast-bottom model are more complex than for the slow-bottom case because the cut-off condition only exists in the
fast-bottom model, which yields more images which correspond to perfect reflections for the bottom.

The method of images does not yield an easy decomposition of the sound field into a form that can be closely associated with normal modes. On the other hand, the method of images provides intrinsically the phase interference effects associated with the superposition of effects that would be more difficult to extract from the adiabatic normal mode. The intrinsic inclusion of absorption in the substrate is an attractive and realistic feature of the image approach. In addition, the image approach appears to avoid the generation of caustics at turning points which are inextricably linked with the results of unmodified ray tracing approaches.

B. RECOMMENDATIONS FOR FURTHER INVESTIGATION

1. For the case of a real fast-bottom, identification of the normal modes of the system and investigation of the possibility of normal mode coupling is worth study.

2. Using the batch system to investigate the small wedge angle is worth study.

3. Changing the position and depth of the receiver is worth study.

4. For the slow bottom, experiments should be undertaken to compare with the theoretical predictions.
FILE: 3LS4 FORTRAN A1

DEBUG UNIT(6),SUBCHK
END DEBUG

C CROSS SLOP TRANSMISSION IN THE WEDGE WITH PENETRABLE LOSSY SLOW
C BOTTOM (NO GEOMETRICAL APPROXIMATIONS)

C DIMENSIONZ(M,M) (21,11), (Y0,R2)--(L,A)
DIMENSION Z(101,101)
COMMON WORK(50000)
INTEGER A,II,JJ,N
S,S2,IE,N,I
REAL*4 RR
1,R2,YO,Y1,YOSTA,YOINCR21NC,R2STA,RZ,RZ1,M,J,
1B,C(30),CC,C2,D,D1,D2,E(30),E1,E2,F(30),F1,F2,G,H,P1,P2,
1P1,P2,P(125,130),PH,Q1,Y2,R3,R8(80),R9(80),
1S(30),T,T4,T6,T1(80),TQQ,TQQ1,TQQ2,TQQ3,W,W0,W1,XL,Y,
1Z1,Z2,Z3,Z4,Z5,Z6,Z,EL,
DIST
CALL SETIME
PI = ARCSIN(-1.0)

C INPUT PARAMETERS
C N1 = # OF IMAGINE POINTS
C B = WEDGE ANGLE (DEG)
C G = SOURCE ANGLE (DEG)
C D = RECEIVER ANGLE (DEG)
C R1 = SOURCE DISTANCE (IN DUMP DISTANCES)
C R2 = RECEIVER DISTANCE (IN DUMP DISTANCES)
C Y0 = SHORE DISPLACEMENT (IN DUMP DISTANCES)
C D1 = RHO1/RHO2
C CC = C1/C2
C XL = ALPHA/K2
C A = # OF RECEIVER POSITIONS IN R2 DIRECTION
C L = # OF RECEIVER POSITIONS IN Y0 DIRECTION
C R2INC = INCREMENTAL INCREASE FOR R2
C Y0INC = INCREMENTAL INCREASE FOR Y0

CALL TEK618
CALL COMPRS
CALL PAGE(11,8.5)
B=10.
G = 1.0*B/4.

31
G = 5
D = 0.0
R1 = 10.
R2 = 5.
Y0 = 0.
D1 = .9
C
D1 = 1/.9
C FOR SLOW-BOTTOM CASE
CC = 1/0.9
C FOR FAST-BOTTOM CASE
CC = 0.9
C
CC = .5
XL = .0001
A = 100
L = 100
R2INC = .1
Y0INC = .1
C
C **********************************************************MAIN PROGRAM**************************************************************
C
YOSTA = Y0
R2STA = R2
W = 0.0
WRITE(6,300) B,G,D
300 FORMAT (3X,'B = ',F5.2,3X,'G = ',F5.2,3X,'D = ',F5.2,3X)
310 FORMAT (1X,F5.2,1X,F5.2,1X,F5.2)
WRITE(6,400) R1
400 FORMAT (3X,'SOURCE RANGE = ',F8.2)
410 FORMAT (1X,F6.2)
WRITE(6,500) D1,CC,XL
500 FORMAT (3X,'DENSITY RATIO = ',F8.6,3X,'SPEED RATIO = ',F8.6,3X,
       'ALPHA/K2 = ',F8.6)
510 FORMAT (1X,F6.4,1X,F6.4,1X,F6.4)
WRITE(6,600)
600 FORMAT (5X,'42,6X,'Y0',10X,'P')
C
WRITE(22,700) R2,Y0
700 FORMAT (1X,F6.2,1X,F6.2)
N1 = (180/B + .00001)
T6 = 180/PI
B = B/T6
G = G/T6
C2 = CC-2
C
HM=0
HH=1
     D =HM*B/A
     DD = B/A
     V = 2*B/10
     IF(D.LT.V) GO TO 110
     IF(D.GE.V) GO TO 120
110
     DX = D
C
THIS DO LOOP CALCULATES THE TMETA(N) AND THE IMINAGE SLANT
RANGES R8(N) AND R9(N).
C
32
DO 55 HH = 1.10
D = DX+(HH-1)*B/(10.0*A)
DD = B/(10.0*A)

S1 = 1

T4 = P1/(2*TAN(ARCOS(1/CC))*TAN(B))
TQQ = TAN(B)

FOR SLOW-BOTTOM CASE
TQQ1 = ARCOS(1/CC)

FOR FAST-BOTTOM CASE
TQQ1 = ARCOS(1/CC)
TQQ2 = TAN(TQQ1)
TQQ3 = 2*TQQ2*TQQ

T4 = PI/TQQ3
Q1 = 1/SQRT(2.0)

LP1X=L+1
IAP1X=A+1
DO 20 M=1,LP1X
DO 10 J=1,IAP1X

D2 = (Y0**2)+(R**2)+(R2**2)
R3 = 2*R1*R2

DO 30 N = 1,N1
IF(S1.GT.0) Ti(N)-FLOAT(N-I+B-G)
IF(S1.LT.0) Ti(N)=FLOAT(N)-B-G
Si =-S1
R8(N) = SQRT(D2-R3*COS(Ti(N)-D))
R9(N) = SQRT(D2-R3*COS(Ti(N)+D))

DO 30 CONTINUE

SUM PRESSURE OVER ALL IMAGINES

P1 = 0.0
P2 = 0.0
DO 40 N = 1,N1
S2 = (-1)**(IFIX(N/2+.0001))
W1 = 2*C2-XL

FEFL COEFFS ALONG WITH UPPER PATH

I1 = IFIX((N-9999)/2)
DO 41 I = 1,I1
S(I) = ABS(R1*SIN(T1(N)-2*FLOAT(I)*B))
+R2*SIN(2*FLOAT(I)*B-D))/R8(N)
C(I) = SQRT(1+(S(I)**2))
T = S(I)/D1
W0 = (-C2+(C(I)**2))
Y = SQRT((W0**2)+(W1**2))
Z(M,J) = ABS(W0)
IF(Y.LE.Z(M,J)) Y = Z(M,J)
Y1 = Q1*SORT(Y+W0)

33
Y2 = -Q1*SQRT(Y-W0)
E(I) = ((T**2)-(Y2**2)-((Y1**2))/(((T-Y2)**2)+(Y1**2))
F(I) = (2*Y1*T)/(((T-Y2)**2)+(Y1**2))

41 CONTINUE

C PRODUCT OF REFLECT COEFFS ALONG NTH UPPER PATH

C FOR SLOW-BOTTOM CASE

T = T*R8(N)

C FOR FAST-BOTTOM CASE

T = T*R8(N)/CC

C REFL COEFFS ALONG NTH LOWER PATH

C PRODUCT OF REFLECT COEFFS ALONG NTH LOWER PATH

C AN2 = TAN(F(I)/E(I))*T6)

43 CONTINUE

C PRODUCT OF REFLECT COEFFS ALONG NTH LOWER PATH

C
E1 = E2
F1 = F2

44 CONTINUE

C***********************************************************************
C FOR SLOW-BOTTOM CASE
T = T4*R9(N)
C FOR FAST-BOTTOM CASE
T = T4*R9(N)/CC  FAST BOTTOM
C***********************************************************************
P1 = P1 + S2*(E1*COS(T)+F1*SIN(T))/R9(N)
P2 = P2 + S2*(F1*COS(T)-E1*SIN(T))/R9(N)

40 CONTINUE
Z(M,J) = SQRT((P1**2)+(P2**2)) R1
IF(W.LT.Z(M,J)) W=Z(M,J)
WRITE(6,200) R2,Y0,Z(M,J)

200 FORMAT (3X,F7.3,3X,F7.2,3X,F9.5,3X,F9.5)

C***********************************************************************
R2 = R2+R2INC
C***********************************************************************
DIST = SQRT ((J-41)**2) + (M-1)**2
IF (DIST.LE.20.) Z(M,J) = 0.
C***********************************************************************

10 CONTINUE
Y0 = Y0 + Y0INC
R2 = 5.

20 CONTINUE
CALL SURF3D(Z,NX,NY)

Y0 = 0.

55 CONTINUE
33 CONTINUE
STOP
END

C************************************************************************
C SUBROUTINE SURF3D(Z,NX,NY)
C************************************************************************
DIMENSION Z(101,101)
DIMENSION RZ(101,101)
COMMON WORK(50000)
C************************************************************************
C CHECK DATA STATEMENTS TO ET AXIS LIMITS:
C************************************************************************
DO 1 I-1,101
DO 1 J-1,101
1 RZ(J,I)=Z(I,J)
C************************************************************************
C PRODUCE CONTOUR PLOT:
C************************************************************************
CALL PAGE (11,8.5)
CALL SHDCHR(.90,1.,003,1.)
CALL AREA2D(9.5,6)
CALL NOBRDR
CALL BLOWUP(.85)
CALL XNAME('XXX',1)
CALL YNAME('YYY',1)
CALL HEADIN('CONTOUR PLOT$',100,1.,1)
CALL GRAF(5.1.,15.,0.,1.,10.)
CALL FRAME
CALL BCOMON(50000)
CALL CONMAK(RZ,101,101,.5)
CALL CONLIN(0,'SOLID','LABELS',1,1)
CALL CONANG(90.)
CALL POLY3
CALL CONTUR(2,'LABELS','DRAW')
CALL ENDPL(0)

--------------------------------------
CALL PAGE(11,8.5)
CALL AREA2D(9.5,6)
CALL MX1ALF('STANDARD','')
CALL MX2ALF('UCSTD','')

----------------------------------------
CALL X3NAME('R2 A+XIS$*',100)
CALL Y3NAME('YO A+XIS$*',100)
CALL Z3NAME('PRESSURE A+XIS$*',100)

----------------------------------------
CALL VOLM3D(5.,5.,5.)
CALL YINTAX
CALL XINTAX
CALL ZINTAX
CALL ZAXANG(0.)
CALL YAXANG(0.)
CALL XTICKS(5)
CALL YTICKS(5)
CALL HEADIN('SLOW BOTTOM',11,1.5,1)
CALL HEADIN('FAST BOTTOM',11,1.5,1)
CALL MESSAG ('C.P.U. = SECONDS$',100,6,5,0.)
CALL MESSAG ('VIEPTS IS 250,350,90$',100,6,5)
CALL MESSAG ('SURMAT IS RZ,1,101,101,101$',100,6,6)
CALL MESSAG ('SURVIS IS TOP$',10,6,5,5)
CALL MESSAG ('B(W.A.)-10,.G(S.A)-5,.D(R.A)=0 $',100,6,5)
CALL MESSAG ('RHO1/RHO2 = 9,ALPHA/K2=.0001 $',100,6,4.5)
CALL MESSAG ('C1/C2 -1, R1=10..42=5,.Y0=0.$',100,6,4)
CALL MESSAG ('R2INC = 1,Y0INC = 1,CMK = 5$,100,6,3,5)

----------------------------------------
CALL VUABS(250,350,.90.)
CALL SURVIS('TOP')
CALL GRAF3D(5.,1.,15.,0.,1.,10.,0.,5.,15.)
ALL BLSUR
C CALL SURMAT(RZ,XX,A+1,XX,L+1)
CALL SURMAT(RZ,1,101,101,101,0)
C
CALL ENDPL(0)
CALL DONEPL
CALL GETIME(IET)
EL = IET * .000026
WRITE (4,2) EL
2 FORMAT(20X,'TIME = ',E16.6,'SECONDS:')
RETURN
END
### SLOW BOTTOM

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X = not exist
APPENDIX C

FIGURES

Figure 1
Three-Dimensional Wedge Geometry
Figure 2

The Geometry of Image Solution
Figure 3-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 3-B
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 4-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters

VIEPTS IS 350,350,90
SURMAT IS RZ,1,101,101,101
SURVIS IS TOP
B(W.A.)-10.,G(S.A)- 5.,D(R.A)-0
RH01/RH02 -.9,ALPHA/K2-.0001
C1/C2 -.9,R1 - 40,R2 -0,Y2 -0
R2INC - 1.,Y0INC - 1. CMK-.5
Figure 5 B

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 6-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
SLOW BOTTOM

VIEWTS IS 350,350,90
SUMMIT IS 95,1,100,100,100
SUMMIT IS 100

BOUNDARY: T = 15.6, R = 5.0, M = 0.0
PHOTOGRAPHY = 0.9, ALPHA = Z.0001
CHOS = 17.6, R1 = 30, R2 = 0, Y0 = 0
RZING = 1.0, Y0INC = 1.0, CMK = 1.

Figure 7-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model
for the Indicated Values of Parameters
Figure 7-B
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
SURMAT IS RZ,181,181,1,6
SURVIS IS TOP
B(W.A.)=10.,G(S.A)= 5.,D(R.A)=0
RHO1/RHO2 =0.9,ALPHA/K2=.0001
C1/C2 = .8,R1 = 40,RXLO = 0
RXLINC = 1.,THETAINTVL = 1.

Figure 8-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 8-B
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 9-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters

VIEPT is -0,350,90
SUMMAT IS RZ,1,101,101,101
SURVEY IS TOP
DIM.X=10.,DI(S,A)=5.,D(R,A)=0
RH01/RH02 = .9,ALPHA/K2=.0001
C1/C2 = .9,R1 =40,R2 =29.5,Y2 =66
R2INC = .02,Y0INC = .02,CMK = .05
Figure 10-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 10-B
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Fig. 11-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 11-11
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 12

Interference Pattern from a Point Source and an Image Point

S = Source point
R = Receive point
s' = Image point
Figure 13 A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 13-13

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 13-C

Pressure on Axis Response of Wedge
Figure 14-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters

SLOW BOTTOM

VIFRT: 15, 20, 25, 30
SUPER: 13, 21, 101, 101, 101
SUPVC: 15, 200
B1N.R1=10,015.A1=-5.,01R.A1=0
RH01/RH02 = 1.0, ALFHR/K2=0.0001
0.1/02 = 0.0, H4 = 1., R4 = 0., YO = 0.
R1INC = -1., R4INC = -1., CNK = -1.
Figure 14-13
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
FAST BOTTOM

VICTS IS 350,350,90
SURFAlt IS R2,1,101,101,101
SURVIS IS TOP
B(W,A) -10.,G(S,A) - 5.,O(R,A) - 0
RHO1/RH02 - .9,MLPHA/K2 - .0001
C1/C2 - .9,R1 - 40,R2 - 0,Y2 - 0
RZINC - 1.,YDINC - 1.,CMK - .5

Figure 15-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model
for the Indicated Values of Parameters
Figure 15-B

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 16-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 16-B

Equal-Pressure Contours on the Bottom of the Wedge
for the Indicated Values of Parameters
SLOW BOTTOM

VICEPS IS 250,350,90
SURMAT IS R2,1,101,101,101
SURVIS IS TOP
B(W.A.)-10,61S.A.-5.,D(R.A.)-0
RHOS1/RHOS2 -6.9,ALPHAV/K2-.0001
C1/C2 = 17.9,K1 = 1.,K2 = 0.,YO-0.
F2INC = -1,Y0INC = -1,CMK =-1.

Figure 17-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 18-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 18-B

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 19-B

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 20-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
SLOW BOTTOM

VIEPTS IS 350,350,90
SURNAT IS RZ,1,101,101,101
SURVIS IS TOP
B(R.A.)=-10.,G(S.A.)-5.,D(R.A.)-10
RH01/RH02 =-.5,ALPHA/K2=.0001
C1/C2 =1./9,R1=40.,R2=0.,Y0=0.
R2INC =1.,YOINC =1.,CMK =1.

Figure 21-A
Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
SLOW BOTTOM

VIEPTS is 250, 350, 50
SURNAT is RZ, 1, 101, 101, 101
SURVIS is TOP
B(W.A.) - 7, GIS, A1 - 5., D(R.A) - 0
RHO1/RHO2 - .9, ALPHA/K2 - .0001
C1/C2 - \( \frac{1}{3} \), R1 - 40., R2 - 0., Y0 - 0.
R2INC - 1., YOINC - 1., CMK - .5

Figure 22-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model
for the Indicated Values of Parameters
FAST BOTTOM

VIEPTS IS 250,350,90
SURMAT IS R2,1,101,101,101
SURVIS IS TOP
B(W.A.)=7.,G(S.A.)=5.,D(R.A.)=0
RH01/RH02 =0.9,ALPHA/K2=.0001
C1/C2 =.9,R1=40.,R2=0.,Y0=0.
R2INC =-1.,YOINC =-1.,CMK -.5

Figure 23-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 24-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model
for the Indicated Values of Parameters
Figure 25-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters

- VIEPTS IS 290,390,90
- SURMAT IS R2,1,101,101,101
- SURVIS IS TOP
- BW(A) = 10.,B(S.A) = 5.,D(R.A) = 0
- RH01/RH02 = .9,ALPHA/K2 = .0001
- CL/C2 = .9,R1 = 80,R2 = 0.,Y2 = 0
- R2INC = 2.,YOINC = 2.,CHK = 1.,

C.P.U. = SECONDS
Figure 25-B

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 26-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 26-13

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
Figure 27-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Figure 28-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters

Figure 28.13
Figure 29-A

Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
SLOW BOTTOM

VIEPTS IS 250,350,90
SURMAT IS RZ,1,101,101,101
SURVIS IS TOP
B(W.A.)-10,G(S.A)-5.,D(R.A)-0
RHO1/RHO2 -.9,ALPHA/K2-.0001
C1/C2 -1/9,R1 -40.,R2 -0.,YO-0.
R2INC -1.,YOINC -1.,CMK -1.5.

Figure 30-A
Pressure on the Bottom of the Wedge as Calculated by the Image Model for the Indicated Values of Parameters
ACOUSTIC PRESSURE DISTRIBUTION ON THE BOTTOM OF A WEDGE-SHAPED OCEAN(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA Y LI DEC 87
Figure 30-B

Equal-Pressure Contours on the Bottom of the Wedge for the Indicated Values of Parameters
(a) Total internal reflection of a ray and
(b) a reflection with the same phase shift from an
effective-release surface

(a) Wedge with penetrable bottom and apex 0
and "effective" wedge with pressure-release
bottom and apex 0.

Figure 31

Effective Pressure-Release Bottom
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