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SOME SIMPLE PROPAGATION MODELS FOR LINEAR AND PARAMETRIC SOURCES IN SHALLOW WATER

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Abstract

Existing theory is extended to model the average field of sound propagating from directive sources in a shallow water waveguide. The role of narrow beam sources in the excitation of modes is explored. Sample calculations are given.

Introduction

In several papers, Weston[1,2] has advanced a simple energy flux method, first suggested by P. J. Westervelt, for the purpose of understanding and giving perspective to several characteristic regimes of shallow water propagation. Although this method is based on elementary geometric considerations, the work of Brekhovskikh[3] may be cited for precise equivalents, obtained from first principles, which support many of the same conclusions. Recently, Shang Er-chang[4] has used a different approach but has arrived at similar results. All of these models are applicable to linear radiations from omnidirectional sources.

The present paper extends Weston's method to include finite beamwidth sources typical of both conventional linear and parametric sources operating in isothermal water. Although the results obtained deal only with the average field intensity as predicted from consideration of generic energy flow and loss mechanisms, they are nonetheless quite useful, both as instructive tools and as simple models for engineering design work.

The incorporation of parametric theory in the present paper is quite flexible in that practically any model that accounts for parametric generation in the freefield provides a viable starting point to the theoretical framework.

Linear Source Models

A shallow water medium of depth H overlays and includes an absorptive sedimentary bottom, having a critical grazing angle ϕ_c that defines a limit for "total" internal reflection. As always, $\phi_c = \text{arc cos } c_w/c_s$, where c_w and c_s are the mean sound velocities in the water and sediment media, respectively. The water is assumed to be shallow in the acoustic sense, that is, the ratio H/λ, where λ is the wavelength, is less than a few decades.

The sound source is aimed horizontally from a position S near middepth, and has a halfpower beamwidth of $2\phi_{1/2}$. This source has a nearfield extending to a range $R_o = \pi a^2/\lambda$, where a is an effective source dimension. For the purpose at hand, it is not necessary to model the transducer nearfield since an extrapolation to a 1 m source level will suffice.

Some Simple Propagation Models for Linear and Parametric Sources in Shallow Water

We begin with the sonar equation for the sound pressure level at range R_o, in the form,

$$SPL = 10 \log P + 170.8 + DI - 10 \log R_o^2 \quad , \qquad (1)$$

where P is the acoustic power radiated, and DI is the directivity index of the transducer. Some may prefer to set R_o = 1 m in these equations; this would make no difference at long ranges.

At ranges $R > R_o$, the radiation proceeds initially into a region of spherical spreading, where the propagation loss becomes

$$L = 10 \log R^2/R_o^2 + \alpha_w R \quad , \qquad (2)$$

Here, α_w denotes attenuation in the water column. The extent of the spherical spreading region may depend on several conditions.

For fairly large source beamwidths, spherical spreading may apply only out to the range associated with the critical angle of the bottom. Thus, for $\phi_{1/2} > \phi_c$, where $\phi_{1/2}$ is the halfpower angle of the beam, we take the extent of this region as $R_o < R < H/2\phi_c$. This simply means that energy has a tendency to be radiated into the bottom at high grazing angles. The geometry for large beam insonification is sketched in Fig. 1.

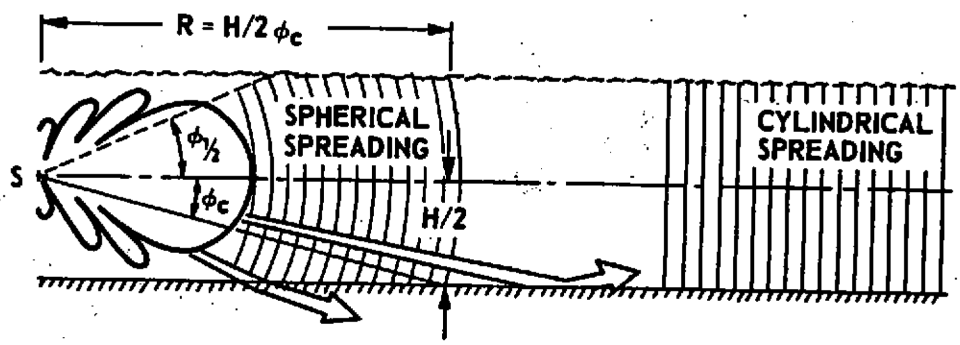

FIGURE 1. LARGE BEAM INSONIFICATION SHOWING SPHERICAL AND CYLINDRICAL REGIMES

For smaller source beamwidths, such that $\phi_{1/2} \lesssim \phi_c$, spherical spreading applies out to the range at which the beam effectively "fills" the water column, i.e., over the span $R_o < R < H/2\phi_{1/2}$. The geometry for this case is sketched in Fig. 2.

Some Simple Propagation Models for Linear and Parametric Sources in Shallow Water

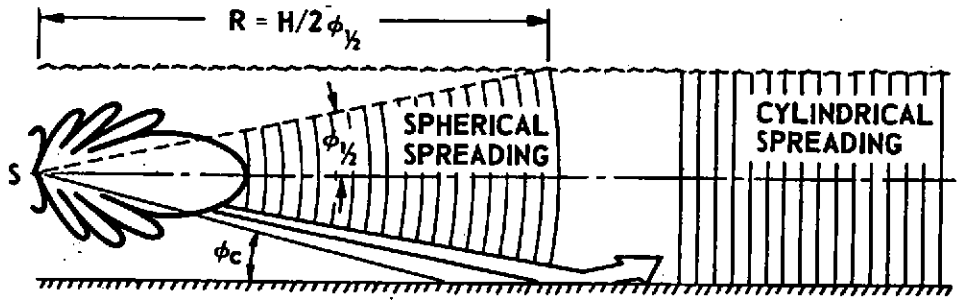

FIGURE 2. MODERATE BEAM INSONIFICATION SHOWING SPHERICAL AND CYLINDRICAL REGIMES

Beyond the region of spherical spreading, we enter one of cylindrical spreading, brought on by increased bottom reflectivity. Provided we are above the cutoff frequency (= $c_w/4H\phi_c$), the propagation loss becomes

$$L = 10 \log\left[(RH/2\phi)/R_o^2\right] + \alpha_w R \quad , \tag{3}$$

where $\phi = \phi_c$ or $\phi_{1/2}$, whichever is smaller.

For large beams, the cylindrical spreading region is usually quite limited in lateral extent and in some cases is insignificantly small. It will be shown that decreasing the source beamwidth increases the extent of this region. Normally, this region is characterized by the internal reflection of a large number of rays or modes. The finite attenuation of either conceptual entity upon bottom reflection ultimately leads to the next propagation regime, known as the mode stripping region.

Although the source emits a continuum of rays, the medium imposes a selection process upon their existence, much as a stringed instrument selects and resonates preferred harmonics of the notes played. In the case of shallow water propagation the analogous "harmonics" are the spatially selected modes, each of which consists of a pair of upgoing and downgoing waves ricocheting down the waveguide on unique angular paths.

Following Weston's approach,[1] we assume that for any allowed modal or eigenray angle ϕ_i, there is one loss producing bottom bounce each time the horizontal range cycles through an incremental distance $2H/\phi$. Thus at range R, there are $n = R\phi/2H$ bottom bounces. If the loss at each such event is taken as $\alpha\phi$ (in units of dB/rad.), then the bottom loss accumulates as

$$L_B(\phi,R) = \alpha\phi^2 R/2H = 10 \log \exp - \left\{\alpha\phi^2 R/8.68H\right\} \quad . \tag{4}$$

Weston[2] argued that the gaussian dependence on ϕ in the preceding equation should be tied in some way to the critical angle ϕ_c. This was done by allowing the exponent to take on the value $\pi/4$ at $\phi = \phi_c$, which provides for a little more than 3 dB angle dependent bottom loss at the range $R = 6.8H/\alpha\phi_c^2$.

The propagation loss in this region is found by substituting the resulting value for $\phi_c = \phi = \sqrt{6.8H/\alpha R}$ into Eq. (3), to yield

$$L = 10\ \log\left[R^{3/2}\,H^{1/2}\,\alpha^{1/2}\ /5.2R_o^{\ 2}\right] + \alpha_w R \quad . \tag{5}$$

This is a form of the well known three halves law appropriate for what is known as the mode stripping region. Thus, at ranges in the vicinity of $6.8H/\alpha\phi_c^2$, bottom losses have begun to strip off the modes through a gaussian absorption factor which is dependent on the steepness of the eigenray angles. This starting range for the applicability of Eq. (5) is of course applicable to the broad beam case, $\phi_{1/2} > \phi_c$. Although it is difficult to illustrate mode stripping, a sketch of a few modal eigenrays is offered in Fig. 3 for the case of insonification in a fairly narrow angular sector.

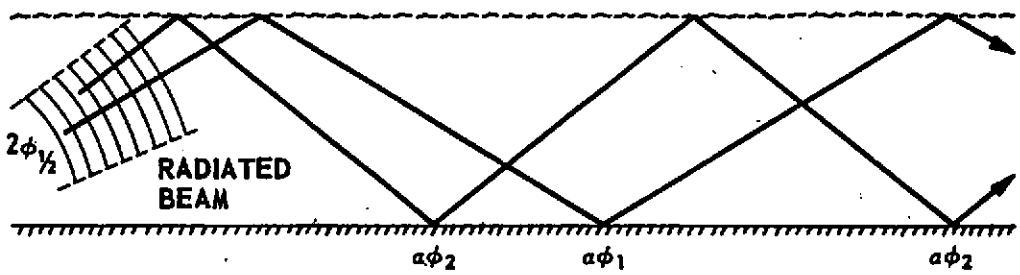

FIGURE 3. MODE STRIPPING FOR THE SMALL BEAMWIDTH CASE SHOWING ONE EIGENRAY COMPLEMENT FOR TWO MODES DEPICTED

A similar criterion may be applied to the narrow beam case, $\phi_{1/2} \lesssim \phi_c$. Here, we allow the exponent in Eq. (4) to take on the value $\pi/4$ at the angle $\phi = \phi_{1/2}$, which provides for a little more than 3 dB angle dependent bottom loss at the range $R = 6.8H/\alpha\phi_{1/2}^2$. The resulting propagation loss is identical to Eq. (5). The only difference between the two cases is the range at which Eq. (5) might become applicable.

Since the stripping of the higher ordered modes is accentuated by the steepness of their eigenray angles, these modes are eventually attenuated, leaving only one propagating mode. By the time this has occurred, the surviving mode will itself have suffered some angle dependent attenuation. Although the sole surviving mode is sometimes not that of lowest order (depending for example on bottom peculiarities), we here assume that it is the first mode, again in consonance with Weston's analysis.[1]

For many real bottoms with phase shifts near π radians, the modal angle for the first mode is $\phi_1 = \lambda/2H$. Taking this as the angle at which about half of the energy of the first mode is itself stripped off, we can again use the exponent of Eq. (4) to determine the range at which this occurs. For broad beams, the result is $R = 27H^3/\alpha\lambda^2$. Beyond this range, the surface and the bottom try to contain a sound field propagating at a constant angle, and we are back to cylindrical spreading plus some attenuation losses. The adaptation of Eq. (3) to this case leads to

$$L = 10 \log \left[(RH/2\phi_1)/R_o^{\,2}\right] + n\alpha\phi_1 + \alpha_w R \quad ,$$

or (6)

$$L = 10 \log RH^2/\lambda R_o^{\,2} + R\lambda^2\alpha/8H^3 + \alpha_w R \quad ,$$

where the second term represents the bottom loss of the first mode.

In the event that one has a very narrow beam, i.e., $\phi_{1/2} \lesssim \phi_1$, the starting range of the single mode region is not determined as above. Obviously, in order to get such a highly directive radiation to propagate, it would be necessary to aim it at one of the eigenray angles appropriate for the excitation of some mode. This case is illustrated in Fig. 4. In practice, it is only necessary to employ one beam in the vicinity of an eigenray angle, rather than the two beams shown. For the first mode, this beam may encompass both eigenray angles. If this is done, it is reasonable to assume that modal propagation would begin after the beam has spread to the point of filling up the water column. In this case, the starting range becomes $R = H/2\phi_{1/2}$.

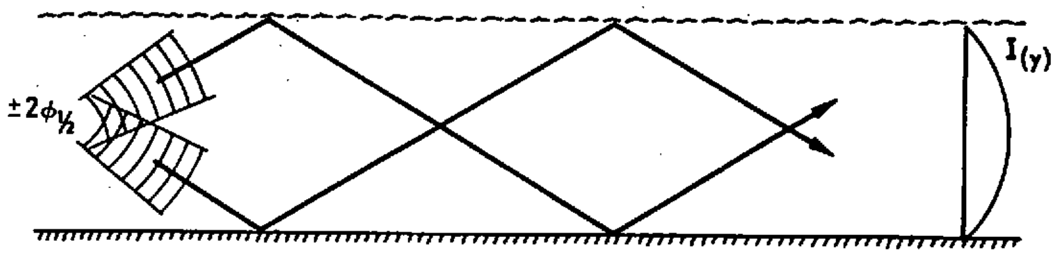

FIGURE 4. SINGLE MODE EXCITED BY VERY NARROW BEAMS CENTERED ON EIGENRAY PAIRS

Although Eqs. (2), (3), (5), and (6) describe successive propagation regimes, it should be remarked that these may not always follow in succession. In particular, the use of an extremely narrow beam appears to circumvent some of these regions. Given that $\phi_{1/2} \approx \lambda/4a$, one can use the inequality defining the extent of the spherical spreading region to show that it would be skipped provided $a \gtrsim 2H/\pi$. Similarly, the mode stripping region would be skipped, provided $\phi_{1/2} \lesssim \phi_1$.

Parametric Source Models

The application of parametric arrays to shallow water (waveguide) propagation differs in several respects to that of linear sound sources. Physical and engineering aspects of this problem have been discussed in previous papers[5,6] which have presented theory on preferential mode selection as well as the results of experiments in both a laboratory tank and in a natural lagoon.

Drawing from previous experience, it is useful to make one restriction concerning the length of the parametric interaction volume in the shallow water waveguide. Since there is usually a phase shift near π radians at both the surface and bottom (at low grazing angles), one must consider the problem of destructive interference of parametric sources and their images within this volume. This problem has been treated for the freefield case,[7] and is illustrated in this context in Fig. 5. Since 180° phase shifts in each primary have no effect on the phase of difference frequency generation, it can be argued that difference frequency sound generated after a phase reversal is simply 180° out of phase with that reflected from the previous segment of the interaction volume.

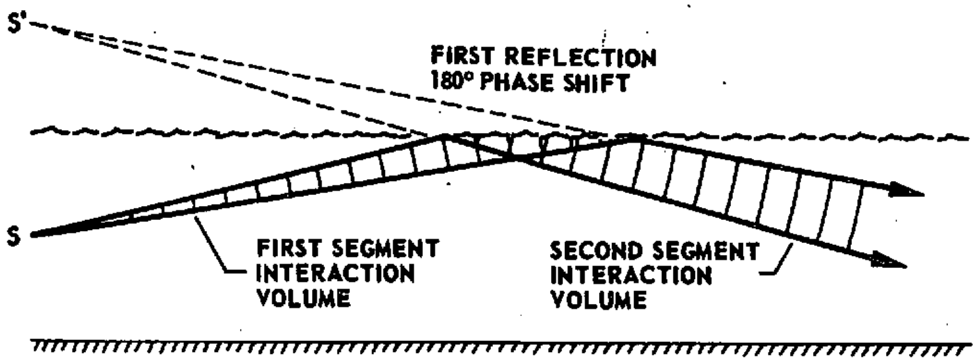

FIGURE 5. THE PROBLEM OF PHASE REVERSAL WITHIN A PARAMETRIC INTERACTION VOLUME

For the case of a shallow water waveguide, it is convenient to avoid the parametric image interference problem by limiting the effective length of the interaction volume, L_A. This can be done by design by simply restricting L_A to distances $\gtrsim R_{BF}$, where R_{BF} denotes the range at which the parametric beam "fills up" the water column. For a source at middepth, $R_{BF} = H/2\phi_{1/2}$. This case is illustrated in Fig. 6. Since L_A has an exponential taper, the definition of effective length can be neither exact nor critical. Some might prefer defining L_A as the 1/e absorption distance of the primaries, i.e., $L_A = 1/\bar{\alpha}_p$, where $\bar{\alpha}_p$ is the mean primary absorption coefficient. Although this is a safe and neat definition, it is probably overly restrictive, since there is always some bottom bounce loss which serves to further truncate the parametric array in much the same way as does the water column absorption. Perhaps a better choice is the -3 dB absorption range $L_A = -(\ell n\ 1/\sqrt{2})/\bar{\alpha}_p$. When this is equated to R_{BF} one obtains $\bar{\alpha}_p \lesssim -2\phi_{1/2}(\ell n\ 1/\sqrt{2})/H$, which enables the primary frequency f_p to be determined through $\bar{\alpha}_p = \bar{\alpha}_p(f_p)$. In practice, it may be convenient to truncate the parametric array with finite amplitude attenuation. This enables one to vary the array length by varying the transmitted power.

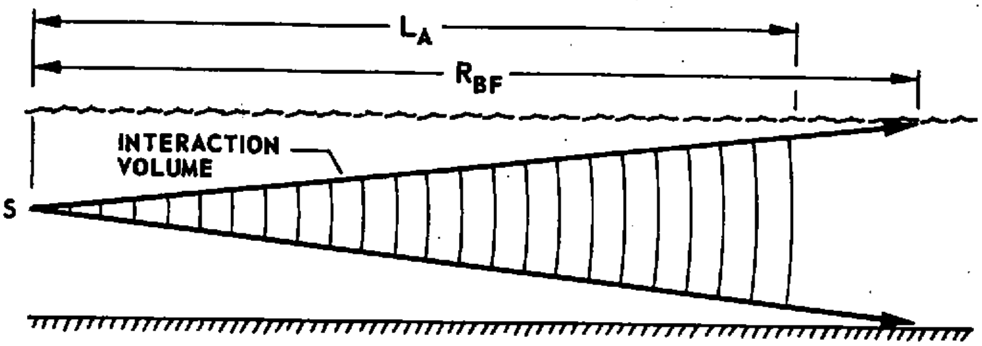

FIGURE 6. RESTRICTION OF PARAMETRIC ARRAY LENGTHS TO AVOID PHASE REVERSAL INTERFERENCE

Many theoretical models of parametric arrays operating in infinite media have been published. The complexity of these solutions usually increases with their generality and applicability to various problems. Given that the purpose of the present paper is to address shallow water applications with simple models, we shall favor the simplest parametric array descriptions.

Most parametric array models have their roots in the solution to an inhomogeneous wave equation[8] which can be written in terms of the difference frequency sound pressure level as

$$SPL_d\left(|\vec{R} - \vec{r}|, t\right) = 20 \log \left\{ \frac{-\rho_o}{4\pi} \int_V \frac{\partial q}{\partial t} \left[\frac{e^{ik_d|\vec{R} - \vec{r}|}}{|\vec{R} - \vec{r}|} \right] dV \right\} , \qquad (7)$$

Where $[\cdot]$ is the Green's function, $\vec{R}$ is a vector from the origin to the field point, $\vec{r}$ is a vector from the origin to the element of integration, V denotes the interaction volume, and q is the source strength density,

$$q(r,t) = \frac{\beta}{\rho_o^2 c_o^4} \frac{\partial}{\partial t} p_p^2(r,t) \quad . \qquad (8)$$

Here $\beta = 1 + \frac{1}{2}(B/A)$, where B/A is the parameter of nonlinearity, and ρ_o and c_o are the mean density and sound speed of the medium.

From Eq. (7), one can go in many directions with modeling. These include direct numerical integrations,[9] as well as the development of approximate closed form solutions. The latter are too numerous to survey here, but Professor Beyer's book is cited as one source of comparison.[10] Since parametric array modeling is a popular topic, the current proceedings as well as those of the International Symposia on Nonlinear Acoustics are also cited.[11]

It is perhaps useful to state Westervelt's original solution to Eq. (7), especially since we are emphasizing models of minimal complexity. This solution can be written

$$SPL_d(R_o,\theta) = 20 \log \left\{ \frac{\omega_d^2 p_1 p_2 S_o \beta}{8\pi R_o \rho_o c_o^4} \Big/ \left[\bar{\alpha}_p^2 + k_d \sin^4(\theta/2) \right]^{\frac{1}{2}} \right\} \quad , \tag{9}$$

where S_o is the cross sectional area of the beam of plane wave primary radiations; p_1 and p_2 are the peak primary pressure, θ is the angle variable, and the subscript "d" denotes difference frequency parameters. The half angle -3 dB) beamwidth of the difference frequency radiation is

$$\phi_{\frac{1}{2}} = 2\left(\bar{\alpha}_p/k_d\right)^{\frac{1}{2}} \quad . \tag{10}$$

Although Eqs. (9) and (10) are quite useful, they are limited by the assumptions stated in their derivation,[8] and should not be applied in cases involving either spherical diffraction[9,12] or finite amplitude attenuation.[13]

The procedure to be followed in applying any parametric model to shallow water propagation under the present assumption is to use the parametric free-field theory out to the range R_{BF} at which the beam completely fills the water column, where the interaction volume is by then truncated by either absorption in the water column, by finite amplitude attenuation or by boundary losses, or by some of each. From that point on, the propagation is governed by the linear theory discussed in the previous section. It should be remarked that this process is analagous to beginning with Eq. (1) which also computes absolute sound pressure levels as a function of range. It is therefore necessary to normalize when going from either of Eqs. (1), (7) or (9) to the otherwise self-normalizing propagation loss results of the previous section.

Care should also be taken with respect to the half power angle $\phi_{\frac{1}{2}}$ of the parametric beam and its relationship to the choice of any of the propagation regimes defined by Eqs. (2), (3), (5) or (6). For example, the spherical spreading region, Eq. (2), would be skipped if $\phi_{\frac{1}{2}} \leqslant \phi_c$ and the mode stripping region, Eq. (5) would be skipped if $\phi_{\frac{1}{2}} \leqslant \phi_1$.

Examples

Two illustrations of the present models are discussed here in the context of a comparison between linear and parametric projection of acoustic beams in shallow water.

Some Simple Propagation Models for Linear and Parametric Sources in Shallow Water

The first, shown in Fig. 7, depicts sound propagating at 500 Hz from a 2.3 m diameter source excited with 80 kW of electrical power, assuming a 50% transducer efficiency. The water column is 50 m deep, overlying a sand bottom having a sound velocity 15% higher than water, a critical angle of 30°, and a bottom loss α of 12.4 dB/rad. The transducer is located near middepth, with a horizontal orientation.

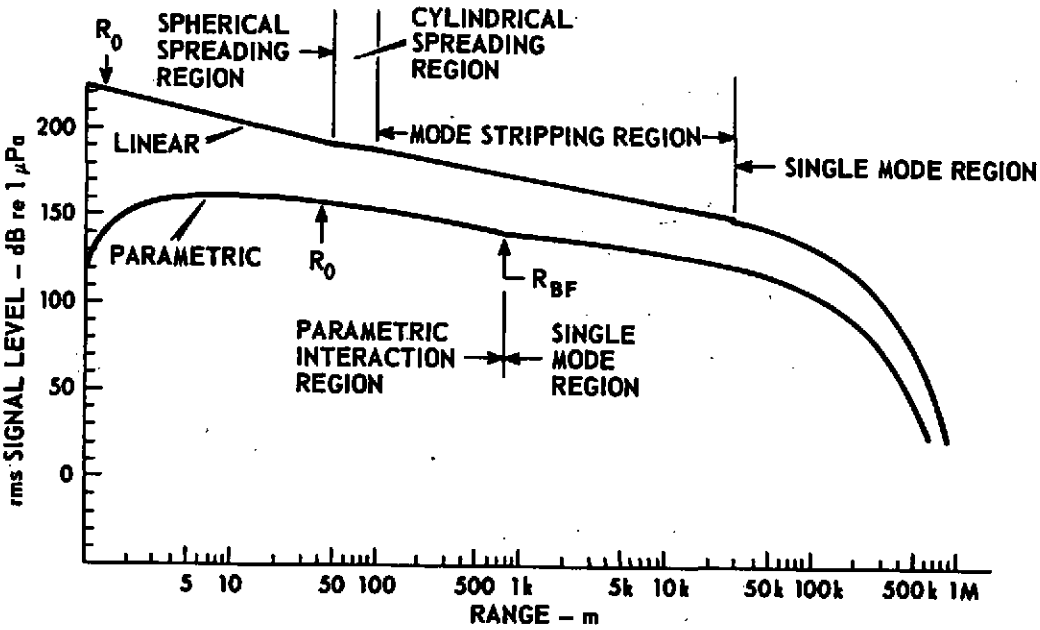

FIGURE 7. COMPARISON OF MEAN PROPAGATION CURVES FOR A 2.3 m diam SOURCE RADIATING LINEAR AND PARAMETRIC SIGNALS AT 500 Hz IN A SHALLOW WATER WAVEGUIDE, 50 m DEEP

Since the linear version of this source has a half power beamwidth of 80° ($\phi_{\frac{1}{2}}$ = 40°), spherical spreading applies out to the critical angle range, a distance of 48 m. For this case, mode stripping becomes significant at 100 m, while the single mode region emerges at 31 km. The 3 dB artifact at the start of this region is discussed in Ref. 1. Although the present models treat only the mean propagation curve, considerable multipath in the cylindrical spreading region and modal interference in the mode stripping region would be present and would appear as wild fluctuations about the mean, were they to be taken into consideration.

Parametric operation of this source, also depicted in Fig. 7, arises from nonlinear interaction of primaries radiated at 13.75 and 14.25 kHz. Given the same available electrical power and transducer efficiency, one would here radiate about 20 kW per primary tone. The peak primary source level during the constructive interference phase of the composite, two tone radiation extrapolates to 160 dB re 1 μPa at 1 m. Application of weak shock theory indicates this radiation would form a discontinuity near the Rayleigh distance of 40 m, with stronger shocks occurring in the spherical spreading field beyond. As a result, this parametric array is truncated by finite amplitude attenuation at a range of about 700 m.

The parametric propagation curve shown in Fig. 7 takes these factors into consideration, through appropriate solution(s) of Eq. (8). This includes a three-dimensional numerical integration in the primary nearfield. The far-field solution was executed by Professor Rolleigh,[14] who reduced the problem to a single integration which also contains a finite amplitude taper function.[15] Finite amplitude attenuation broadens the half power angles of the parametric beam to about ±2°, which leads to beam intersection with the bottom at 735 m. Since the eigenray angles for the first mode are centered at ±1.7°, most of the energy in the parametric beam should couple into the first mode of propagation.[5,6] The portion of the curve beyond the array truncation and/or beam intersection point is therefore constructed from Eq. (7), the single mode result of the present model. Preferential excitation of the first mode under these conditions minimizes multipath and multimode interference, and should make the mean propagation curve depicted here a good representation of the actual situation.

Although discrete modal excitation is an interesting phenomenon that has potential as a research tool as well as for clear channel communications, there are situations where it may be necessary to emphasize other aspects of the application of parametric arrays to shallow water sound. Perhaps the most important of these situations is the frequent requirement for higher parametric source levels. This can be achieved by decreasing the ratio of primary to secondary frequencies. For the 2.3 m transducer in the 50 m waveguide at hand, we might not wish to lower the primary frequencies as this would increase the length of the parametric array which may lead to destructive interference effects within the interaction volume. A better approach may be to raise the difference frequency. Choice of a 2 kHz difference frequency, for example, provides for a downshift ratio of 7, which compares to a value of 22 for the previous example at 500 Hz.

Propagation curves for a 2 kHz example are shown in Fig. 8, again comparing linear and parametric radiations. The half power angle for the linear source is 10° which is smaller than the 30° critical angle. This is in contradistinction to the previous case for a 500 Hz radiation. This diminishes the vertical angular extent of steep angle modes and increases the range span of the cylindrical spreading region. The mode stripping region is also expanded due to the reduction in wavelength and the consequent excitation of more modes.

Parametric operation of the source again leads to primary beams of half power angles near 2°. Since the modal angles are now $\pm n(0.43)°$, we should excite several modes with the parametric beam. However, the parametric beam is much smaller than its linear counterpart and this further increases the extent of the cylindrical spreading region. The mode stripping region for the parametric source is smaller than for the linear case simply because of the smaller beam and the smaller number of modes available there for stripping. This region ends at the same range for both linear and parametric sources.

Within the cylindrical spreading and mode stripping regions, many interference fluctuations not treated by the present model will exist. These should be less severe for parametric excitation.

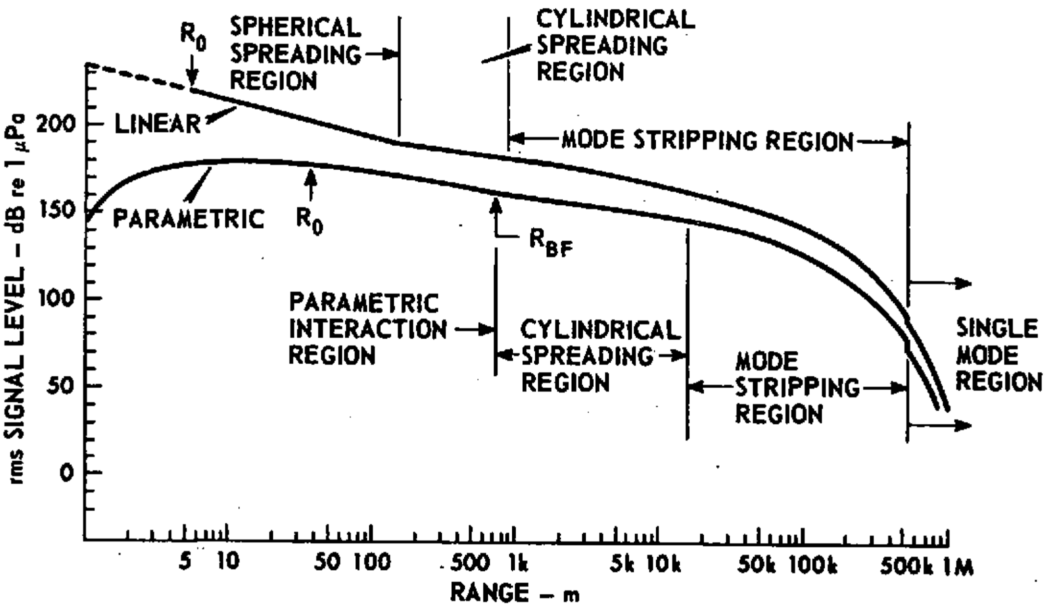

FIGURE 8. COMPARISON OF MEAN PROPAGATION CURVES FOR A 2.3 m diam SOURCE RADIATING LINEAR AND PARAMETRIC SIGNALS AT 2 kHz IN A SHALLOW WATER WAVEGUIDE, 50 m DEEP

Discussion

Although this paper has addressed only the mean axial propagation character of linear and parametric sources, many other aspects of the problem warrant consideration. When the problem of echo to reverberation becomes important, the high directivity of the parametric source begins to weigh favorably against equivalent broad beam linear sources. Wide bandwidth capabilities (for signal processing) as well as Doppler considerations[5] also appear to favor parametric sources.

Vertical strings of linear elements appear to offer better directivity than the linear array considered here. However, they are usually omnidirectional in the horizontal plane and are usually applied to single mode selection only as receivers.[16,17]

One should also consider the electroacoustic efficiency of linear transmitting arrays in the very low frequency regime. In the preceding discussion, an efficiency of 50% was assumed; however, this is usually only possible with very large resonant elements that would have dimensions of several meters at 500 Hz. Smaller elements have lower efficiencies and this may further favor the practicality of the parametric array for shallow water applications.

Much work remains to be done before these speculations can be evaluated. The present models are simple and adequate for many purposes but room for improvement exists. Experimentation is also in its infancy and must of course be conducted in order to further the understanding of the shallow water problem.

Summary of Results

Parameters:

a = transducer diameter

λ = wavelength

P = acoustic power

DI = directivity index

R = range

$R_o = \pi a^2/\lambda$ (the Rayleigh distance)

SPL = sound pressure level

ρ_o = static density

k_d = difference frequency wavenumber

$\vec{R}$ = vector from the origin to the field point

$\vec{r}$ = vector from the origin to the element of integration

V = volume of integration

q = source strength density

$\beta = 1 + \frac{1}{2}(B/A)$

where

B/A = parameter of nonlinearity

c_o = mean sound speed

t = time

p_p = primary pressure field

α_w = attenuation coefficient of water

H = water depth

$\phi_{\frac{1}{2}}$ = half angle beamwidth

ϕ_c = critical angle of bottom

α = bottom loss, dB/rad.

L = propagation loss

Some Simple Propagation Models for Linear and Parametric Sources in Shallow Water

Starting point for a linear radiation at a farfield point $R_o = \pi a^2/\lambda$:

$$SPL = 10 \log P + 170.8 + DI - 10 \log R_o^2 \tag{1}$$

Starting point for a parametric radiation in the interaction region:

$$SPL_d(R) = 20 \log \left\{ \frac{-\rho_o}{4\pi} \int_V \frac{\partial q}{\partial t} \left[\frac{e^{ik_d|\vec{R} - \vec{r}|}}{|\vec{R} - \vec{r}|} \right] dV \right\} , \tag{7}$$

where

$$q(r,t) = \frac{\beta}{\rho_o^2 c_o^4} \frac{\partial}{\partial t} p_p^2(r,t) , \tag{8}$$

which includes an appropriate finite amplitude taper function for the peak interference maxima in the composite primary pressure $p_p(r,t)$.

Spherical spreading region:

$$L = 10 \log R^2/R_o^2 + \alpha_w R$$

valid for $R_o < R < H/2\phi$ where $\phi = \begin{cases} \phi_c \\ \phi_{1/2} \end{cases}$ whichever is smaller

Cylindrical spreading region:

$$L = 10 \log \left[(RH/2\phi)/R_o^2 \right] + \alpha_w R$$

valid for $H/2\phi < R < 6.8H/\alpha\phi^2$ where $\phi = \begin{cases} \phi_c \\ \phi_{1/2} \end{cases}$ whichever is smaller

Mode stripping region:

$$L = 10 \log \left[R^{3/2} H^{1/2} \alpha^{1/2} / 5.2 R_o^2 \right] + \alpha_w R$$

valid for $6.8H/\alpha\phi^2 < R < \begin{cases} 27H^3/\alpha\lambda^2 & \text{for } \phi_{1/2} > \phi_1 \\ H/2\phi_{1/2} & \text{for } \phi_{1/2} \gtrsim \phi_1 \end{cases}$ where $\phi = \begin{cases} \phi_c \\ \phi_{1/2} \end{cases}$ whichever is smaller

Some Simple Propagation Models for Linear and Parametric Sources in Shallow Water

Single mode region:

$$L = 10 \log RH^2/\lambda R_o^2 + R\lambda^2\alpha/8H^3 + \alpha_w R$$

$$\text{valid for } R > \begin{cases} 27H^3/\alpha\lambda^2 & \text{for } \phi_{1/2} > \phi_1 \\ H/2\phi_{1/2} & \text{for } \phi_{1/2} \gtrsim \phi_1 \end{cases}$$

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