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SHALLOW WATER PROPAGATION MODELLING FROM 5HZ TO 25 KHZ.

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ABSTRACT.

To accurately predict sound propagation in shallow water (12-60m) over a wide frequency band (5Hz-25 Khz) and at ranges up to 2000 m using a single acoustic propagation model is a difficult task. Probably the only model that claims to come near to fulfilling this requirement is OASES although the maximum range achieved drops to only ~100 m at the higher frequencies. There are however a number of other models available, each of which has a "domain of applicability". This paper compares two of these models, a ray model (ISO-RAY) and a normal mode model (STOKES) , and assesses their useability over the frequency band stated above. In addition it also investigates the operational limitations of OAST (the transmission loss module of OASES), since this model is generally considered a benchmark in underwater acoustics. By combining the ray and normal mode model it was possible to nearly fulfil the above requirement.

1.INTRODUCTION.

The accurate prediction of sound propagation in shallow water (12 -60 m) over a wide frequency band (5Hz to 25 KHz) and at ranges up to 2 Km using a single acoustic propagation model is a difficult task. There are however a number of acoustic propagation models available all of which have regions of applicability. In this paper we investigate the feasibility of combining two such models in order to achieve the above requirement. The two models chosen for this work are a normal mode model called STOKES [1] and a ray model called ISO-RAY [2]. STOKES was designed as a shallow water model capable of handling a two layer seabed. ISO-RAY is based on ray theory specifically for iso-velocity water and uniform liquid seabed. The suitability of both models is assessed over the frequency band stated above and the results are compared to those of OAST the transmission loss module of OASES [3] which is generally considered a benchmark in underwater acoustics.

2.THEORY.

All acoustic propagation models are derived from the 3D time-dependant wave equation,

$$\nabla^2 P = \frac{1}{c^2}\frac{\partial^2 P}{\partial t^2} \qquad (1)$$

where P ($\underline{r}$, t) is the acoustic pressure at position $\underline{r}$ and time t, c ($\underline{r}$) is the speed of sound and ∇^2 is the Laplacian operator. For a single frequency (ω) source, Eq(1) transforms into a spatial Helmholtz equation:

$$\nabla^2 P + (\omega/c)^2 P = 0$$

In shallow water environments a cylindrical coordinate system is used, the two distance axes of which are horizontal range (r) and depth (z). Variation of azimuthal angle is neglected. If c is a function of depth only (the environment is said to be "stratified"), the pressure can be expressed as the product of separate range- and depth- dependent functions. If the source is a point (as is usually the case), the pressure can be expressed as (Ref [4], p.110):

$$P(r,z)=\int_0^{\infty} G(z,\xi)J_0(\xi r)\xi d\xi \qquad (2)$$

This can also be written as (Ref [5], p.110):

$$P(r,z)=\frac{1}{2}\int_{-\infty}^{\infty} G(z,\xi)H_o^{(1)}(\xi r)\xi d\xi \qquad (3)$$

where G is the Greens function, J_o is the zero order Bessel function, $H_o^{(1)}$ the zero order Hankel function of the first kind and ξ, which was introduced as a separation variable, is the horizontal wavenumber . A detailed description of the theory involved can be found in Ref [4]. Mathematics of various models begins to diverge when evaluating the integral in eq (2). The three models in question can be classified as follows,

(1) *OAST*:

This is an example of a model that uses the wavenumber integration technique [4] to evaluate Eq (2). However, for OAST, in order to evaluate the integral in equation (2) with an FFT technique the Bessel function is replaced by the appropriate Hankel function. Using the Hankel function means that zero range calculations are not possible. In addition, in order to perform the Fourier integration it is necessary to replace the Hankel function with its asymptotic approximation (far field approximation), thus constraining calculations to ranges >> wavelength (λ). This can be quite drastic for low frequency calculations, for example, for f=5Hz, λ~300 m and consequently inaccurate results will be obtained for ranges <~600 m!. One solution would be to use the Bessel function in the integral. If this was used it would inherently include the 'negative' wavenumber portion of the spectrum, the contribution of which should vanish at long ranges. According to Ref [4] (p.232), the exponential (asymptotic) function is more suitable for numerical integration than the Bessel function, particularly in terms of computational time. Consequently the Bessel function is not convenient, especially for longer ranges. OAST's neglect of the negative portion of the ξ spectrum in Eq (3) means that it is liable to be inaccurate at very low frequencies.

(2) *STOKES*:

This uses contour integration to evaluate Eq (3) together with the inclusion of the branch line integral to account for a head wave. In order to do the contour integration it is necessary to use the Hankel function version(Eq (3)) and consequently the results at zero range cannot be calculated. .

(3) *ISO-RAY*:

This uses the method of stationary phase to evaluate the integral in equation (2). This method however only gives valid results at high frequencies (d(water depth) /λ >>1) and is consequently referred to as the high frequency approximation. It should be noted however that at close ranges this method will give correct results for all frequencies (the maximum range for valid results will decrease with decreasing frequency), and it is possible to calculate results at zero range, unlike the other two models.

3. METHOD.

Using the above information it was decided to calculate the transmission loss using STOKES provided $d/\lambda \leq 10$ and ISO-RAY for $d/\lambda > 10$. By doing this it was possible to predict the transmission loss (TL) versus range for the frequency band required. Errors however will still occur at low frequencies and short ranges due to the far field approximation used in both OAST and STOKES. This problem could however be eliminated by using ISO-RAY for the close ranges and work is currently under way to assess the maximum close-range capability of ISO-RAY as a function of frequency.

The validity of STOKES and ISO-RAY was tested against OAST which is generally considered a benchmark in underwater acoustics. In doubtful cases, an in-house model (FIELDINT) that computes the integral in Eq (2) with a NAG [6] library integration routine, was also used.

In order to test the models two environmental conditions were chosen. The first follows a method reported by Zhang [5] and is shown in figure 1a. By setting the sound speed in water equal to that of the seabed constrains the reflection coefficient to be independent of the grazing angle. Consequently, under these particular conditions the ray model will give the exact result and the other two models can be compared to this. The second test case is more realistic and is shown in figure 1b. It is very similar to case 1 except the sound speed in the sea bed has been increased to 1600 ms^{-1} and the attenuation in the seabed = 0.5 $dB\lambda^{-1}$.

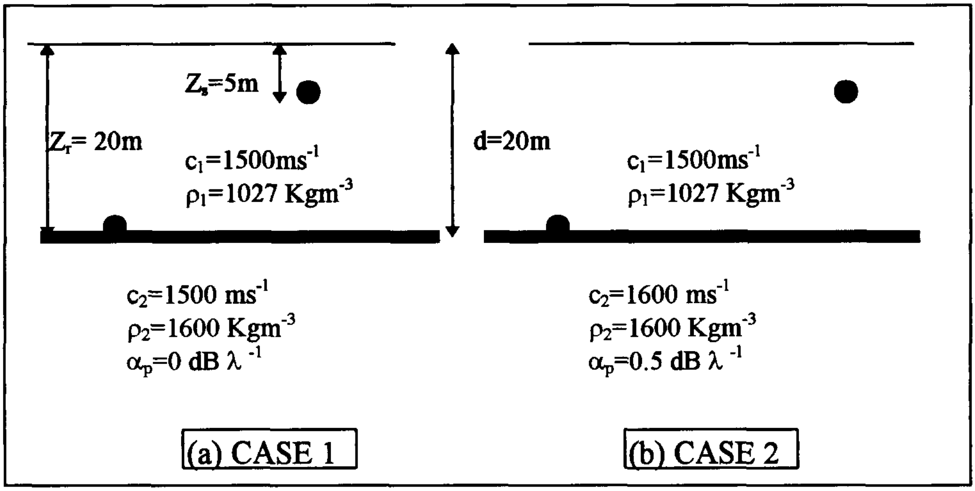

Figure 1.

For both cases the transmission loss (TL) versus range was calculated from 0 to 2000m for the frequencies 5 Hz, 500 Hz, 5000 Hz and 25 KHz.

4. RESULTS.

CASE 1 .

For f=5 Hz (d/λ=0.7) ISO-RAY, STOKES and FIELDINT are in good agreement over the entire range. OAST however shows oscillations with a period of approximately 300m. The origin of this is probably OAST's neglect of the negative portion of the ξ-spectrum.

At f=500 Hz (d/λ=6.7) OAST agrees well with ISO-RAY. STOKES however shows a progressively increasing discrepancy at ranges>750 m resulting in a maximum error of approximately 8 dB at 2000m. The overall structure however is very similar to that of ISO-RAY.

At f= 5 KHz (d/λ=66.7) ISO-RAY, STOKES and OAST are in very good agreement over the entire range. At this frequency however the maximum range of OAST is limited to ~ 750m. This is an inherent problem with OAST due to the Fourier integration which results in a trade off between frequency and range. A more detailed discussion of this can be found in ref.[4].

For f=25 KHz (d/λ=333.3) OAST once again suffers from the frequency/range problem observed for f=500 Hz (maximum range is a few hundred metres). However, over this range, OAST agrees well with ISO-RAY. At the longer ranges STOKES and ISO-RAY agree well. A difference appears at shorter ranges (<100m) due to there being more modes present in the water column than STOKES is searching for (in this case STOKES searched for only 200 modes).

CASE 2.

For this case ISO-RAY no longer gives the exact solution. As was observed for f=5 Hz in case 1, OAST gave oscillations from 0 to 2000m. At this low value of d/λ the ray model is no longer applicable and gives the incorrect result everywhere except for ranges <10 m. STOKES however agrees well with FIELDINT everywhere except at very close ranges. For f= 500, 5000 and 25 KHz all three models agree well, with the exception of STOKES at ranges <100m for the highest frequency.

5. CONCLUSION.

By using either STOKES (a normal mode model) or ISO-RAY (a ray model) in their appropriate regions of the frequency-range plane, it has been shown that it is possible to accurately predict the sound propagation for d/λ values ranging from 0.05 to 330 and out to ranges of 2000m. For $0.05 < d/\lambda < 13$ STOKES gives excellent results almost everywhere, except at zero and very close range. At these ranges however ISO-RAY can be used to calculate the TL. For $13 < d/\lambda < 330$, ISO-RAY gives very good results over the entire range.

While OAST is generally considered a benchmark in underwater acoustics, problems arise at $d/\lambda < 0.8$ where oscillations are observed over the entire TL versus range result. Another limitation arises due to the use of the Hankel function which limits OAST to ranges $>> \lambda$. This is also true for STOKES, but not ISO-RAY

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