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NUMERICAL MODELING AND SIMULATION OF ACOUSTIC PROPAGATION IN SHALLOW WATER

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Abstract. The sound has been extensively used in active and passive detection of ships and submarines, seismic studies, communications and acoustic tomography. The high sensitivity to the propagation of acoustic signals with frequencies between 1 Hz and 20 kHz is one of the most important properties of the oceans and unlike all types of electromagnetic radiation, can gather a significant amount of information on large-and small-scale marine. The main objective of the underwater acoustic models is to simulate the propagation of acoustic wave, for a wide variety of cases, thus providing the most important features of this phenomenon. When it comes to the environment of "shallow water", which limits some models, the acoustic propagation becomes extremely complex due to several mechanisms to mitigate present and the intense interaction of the acoustic signal at the top and bottom. This paper aims to present a model of acoustic propagation in shallow water, and the simulation using a Toolbox from MatLab software of a particular case of propagation.

1 INTRODUCTION

The ocean acoustics is the science of sound in the sea and covers not only the study of sound propagation, but also its masking by the phenomena of acoustic interference (Maia, 2010).

One of the most important properties of the oceans lies in their high sensitivity to the propagation of acoustic signals with frequencies in the range of 1Hz to 20kHz that, different types of electromagnetic radiation, bring together a significant amount of information on the marine environment (Rodríguez, 1995). Another reason for the practical interest in acoustic propagation in the ocean is the distance the sound can spread, reaching several hundred kilometers.

Some properties of the seabed, such as the propagation speed and compressional attenuation, density, among others, contribute to the spread in shallow waters significantly, making it interesting to perform a quantitative estimation of their values.

The underwater acoustic models are designed to simulate critical in a variety of cases, the acoustic wave propagation, thus enabling the prediction of the characteristics of this phenomenon. A number of limitations are inherent in these models and may have to do with the description the medium in question (depth variation, means of two or three dimensions, etc.). As to the description of the dispersion, which can be caused by various reasons (surface irregularities, presence of substances derived from natural or artificial, and so on).

2 THEORY OF WAVE PROPAGATION

2.1 The Wave Equation

The wave equation can be deduced from the principles of the mechanics of using the state equations of continuity and motion (Kinsler, et al., 1982). For fluid media, the equation of state relates physical quantities that describe the thermodynamic behavior of the fluid

$$P - P_0 = \beta \frac{(\rho - \rho_0)}{\rho_0} \tag{1}$$

where P is the instantaneous pressure at a point, P_0 is the equilibrium pressure in the fluid, β is the adiabatic modulus (coefficient of thermal expansion of fluid), ρ is the density instantaneously at one point and ρ_0 is the density of the fluid balance.

In terms of sound pressure *p* and condensation *s*, the Eq. (1) can be expressed as

$$p \approx \beta\, s \tag{2}$$

where $p = P - P_0$ is the sound pressure and $s = \dfrac{\rho - \rho_0}{\rho_0}$ is a condensation point.

The restriction is essential for the condensation *s* must be very small, $|s| << 1$ (Kinsler, et al., 1982).

To relate the motion of fluid with its compression or expansion, we need a function that relates the velocity $\vec{u}$ of the fluid particle with its instantaneous density ρ.

It is considered an infinitesimal element of fluid volume, fixed in space. The continuity equation relates the growth rate of mass in that volume element with the mass flow through the closed surface surrounding that volume. Since the flow must be equal to the rate of growth, we obtain the continuity equation.

$$\frac{\partial s}{\partial t} + \nabla \vec{u} = 0 \tag{3}$$

The equation of motion relates the acoustic pressure p with the velocity $\vec{u}$ instantaneous particle, for a viscous fluid and not adiabatic, ie the effects of viscosity of a fluid despised. That way lies the Euler equation (force equation) for small-amplitude acoustic phenomena.

$$\rho_0 \frac{\partial \vec{u}}{\partial t} = -\nabla p \tag{4}$$

From the above equations, rearranging the terms gives the linear wave equation:

$$\rho_0 \nabla \cdot \left[\frac{1}{\rho_0} \nabla p \right] - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0, \tag{5}$$

This equation is the starting point for developing the physical theory of sound propagation from the implementation of methods with which the sound pressure is calculated if the initial distribution thereof, in the middle is set and if conditions are imposed contour, determined by the geometry of the environment (surface and bottom of the sea and obstacles). The initial conditions are essential in all problems, refer to specific disorders that cause the soud propagation.

2.2 Harmonics Waves

Wave whose time variation is harmonic function (sine, cosine or linear combinations) are produced by many sound sources. Thus, the solution of Eq. (5) can be represented as follows:

$$p = Pe^{i\omega t}, \tag{6}$$

where ω is the angular frequency of the source.

Substituting this expression in (5), we obtain:

$$\rho_0 \nabla \cdot \left[\frac{1}{\rho_0} \nabla (Pe^{i\omega t}) \right] - \frac{1}{c^2} (\omega^2 Pe^{i\omega t}) = 0. \tag{7}$$

Replacing ω^2/c^2 for K^2 , K being the wave number, and simplifying this equation, we obtain the Helmholtz equation, or of the acoustic wave equation in frequency domain:

$$\rho_0 \nabla \cdot \left[\frac{1}{\rho_0} \nabla P \right] - K^2 P = 0. \tag{8}$$

For convenience, in order to keep the same symbols used until now, this equation is written as:

$$\rho_0 \nabla \cdot \left[\frac{1}{\rho_0} \nabla p \right] - K^2 p = 0. \tag{9}$$

2.3 Physical and Chemical Properties

The underwater acoustics is influenced by physical and chemical properties of the ocean, primarily by temperature, salinity and density.

The greatness that is more important, with respect to the propagation of sound at sea is the temperature, which influences the density field and their stratification in the distribution of nutrients and biological mass.

The salinity expresses the amount of dissolved salts in the water, affecting the compressibility and hence the propagation speed of sound, refractive index, freezing point and the temperature of maximum density.

The density of sea water is responsible for the hydrostatic stability of the oceans. It is important to study the dynamics of the oceans, as small horizontal variations can produce very strong currents.

Related to this property is the compressibility, which expresses the changes in volume, depending on the variations of pressure. Through it, determine accurately the density and the propagation speed of sound, which is given by the following equation (Etter, 2002):

$$c = \sqrt{\frac{\tau}{\mu\rho}} \tag{10}$$

where c is the speed of sound, μ is the coefficient of compressibility, τ the specific heat of water and the density ρ.

2.4 Speed of sound

The main quantity considered in sound propagation is the speed of sound, depending on the compressibility and density of the medium. Therefore, it varies at each point of the ocean, every instant of time, because the dynamics of the marine environment. It is obtained by empirical models that describe a function of the parameters of temperature, salinity and pressure (depth). The stratification of these parameters leads to stratification of speed, which entails the existence of typical profiles. One of the formulations applied in science is developed by (Mackenzie, 1981):

$$\begin{aligned} c = {} & 1448.96 + 4.591T - 5.304*10^{-2}T^2 + 2.374*10^{-4}T^3 + 1.304(S-35) + \\ & 1.630*10^{-2}D + 1.675*10^{-7}D^2 - 1.025*10^{-2}T(S-35) - 7.139*10^{-13}TD^3 \end{aligned} \tag{11}$$

where c is the speed of sound *(m/s)*, T temperature (°*C*), salinity S (*psu*) and D the depth (*m*).

According to expression (11), we observe that the speed of sound increases with the increase of any of the three parameters, and temperature, the determining factor. Because the operation of sonar equipment to give, usually in "shallow water", the effect of pressure variation is very small. As for salinity, due to variations in the open ocean are small, the influence of this parameter is also small, except for areas near river mouths, where the salinity becomes a factor.

The distribution of velocity profiles varies from ocean to ocean and for different seasons. Basically, a sound speed profile (Figure 1-b) is extremely dependent on temperature profile (Figure 1-a), which can be divided into three arbitrary tiers, each with distinct characteristics.

Just below the surface lies the mixed layer, approximately isothermal region, where the speed is influenced by variations in surface heating and sea by the wind and the base is called the depth of the mixed layer. As this layer is characterized by a temperature profile approximately constant, the velocity increases with depth due to increased pressure. The second layer is called the main thermocline. In this region the temperature decreases rapidly with depth, causing a strong negative gradient. Finally, below the thermocline and extending to the bottom, lies the deep layer, characterized by the constancy of temperature and increase the speed of sound due to the increase of pressure. In this layer, the velocity profile is nearly linear with a positive slope.

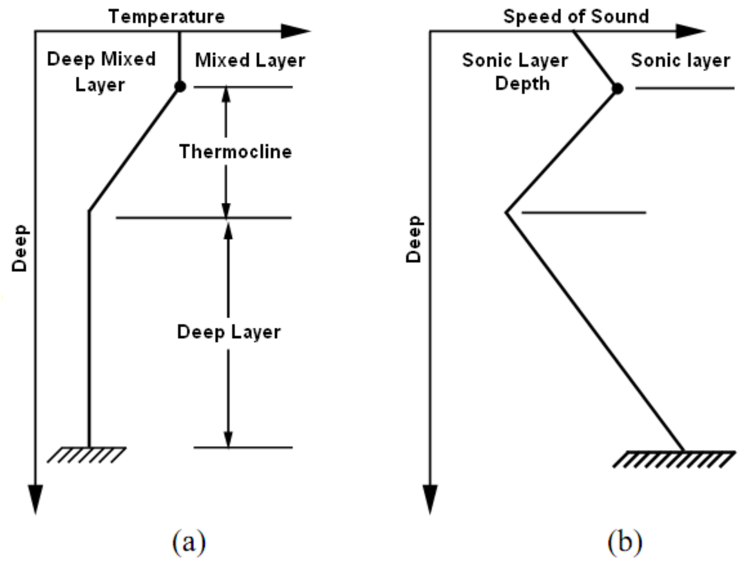

Figure 1 (a e b) – Relationship between the profiles of temperature and speed of sound for deep water.

2.5 The Surface and the Deep Blue Sea

The surface of the sea, in addition to being reflective, it is also spread from one interface sound, because as the surface roughness (specified in terms of wave height) is increasing with the wind, the reverberation and reflection losses, the attenuation bubbles and the turbulence and the generation of high-frequency noise due to sea conditions begin to influence the acoustic propagation (Etter, 2002).

If the ripples on the surface are very small, this interface is flat and behave as a free surface (pressure release), responding as an ideal or perfect reflector (Xavier, 2005).

Similarly to the surface, the interaction of sound with the background affects the propagation and reverberation due to losses in reflection, the attenuation due to the porosity of the sediment and the generation of low frequency noise due to seismic activity.

These effects, however, are more complicated to be calculated due to varying composition and laminated to the bottom, which ranges from hard rock to soft mud. They are also included abrupt changes in density and speed of sound (Etter, 2002).

The bottom topography can also be very variable and rugged, which in certain cases, blocks the sound propagation, causing the appearance of shadow areas. In general, the higher the frequency, greater sensitivity to the roughness of the signal.

The modeling of the interaction of sound with the background depends on the availability of techniques to estimate the geoacoustic profile, which can be characterized by the effective depth of penetration of sound and its speed, density and the coefficients of compressional and shear attenuation for each of these layers. These geophysical parameters can be obtained precisely by means of inversion techniques based on the propagation losses obtained by acoustic propagation models (Etter, 2002).

In practice, due to high costs of experimental tests and lack of environmental data acquired in a controlled manner, proceeds to the calibration of numerical models, which consists of estimated values of the parameters of the fund by comparing the signal intensity measured at direct path and the result obtained computationally through the numerical model.

3 SHALLOW WATER

The ocean environment limited by the surface and lower the seabed is known by the term "shallow". An important feature of this configuration is to allow the trapping of sound energy between these two interfaces and also enables the propagation of sound over long distances.

The existing criteria for defining the regions of "shallow" is based not only on the properties of sound propagation in the medium, but mainly in the frequency of the sound source and the interactions of sound with the background, resulting in a ratio linking the wavelength with the dimensions of the waveguide.

Second (Katsnelson, 2002) under the acoustic point of view, a region can be classified as being shallow if the ratio below is met:

$$r^2 >> \frac{H^2}{\lambda}, \quad (12)$$

where r is the distance between the source and receiver, H the depth of the channel and λ the wavelength. If the relation (12) is not met, the region is said to be "deep water".

This relationship comes from comparing the number of modes present in an ideal waveguide, which is given by $M \approx \frac{2H}{\lambda}$, provided by the Theory of Normal Modes and the maximum number of rays to the same channel $M' = \frac{2r}{H}$, given by the Theory of Rays. If the relation (12) is confirmed, the number of rays exceeds the number of modes and the energy associated with each mode exceeds the energy of each beam. This condition occurs in regions of shallow waters of the ocean to sound signals with frequencies lower than 500Hz.

Moreover, according to the hypsometric criterion (Etter 2002), related to the depths, we define "shallow" as the waters of the continental shelf. Due to the depth of the platform along the slope, to be approximately 200m, the regions of "shallow" are defined as having depths less than 200m.

Moreover, ocean areas beyond the continental shelf can be considered "shallow" when the propagation of a signal with very low frequencies is given by numerous interactions with the surface of the signal and background.

In practical terms, for a given frequency, are considered "shallow" regions in which the boundaries and reflective paver great influence on the propagation and the energy is distributed in the form of a cylindrical divergence, getting trapped between the surface and bottom. It is valid the relation: r > 10*H*.

3.1 Sound Propagation in Shallow Water

The main characteristic of sound propagation in "shallow" is the profile setting the speed of sound, which usually has a negative gradient or approximately constant along the depth. This means that the spread over long distances due almost exclusively to the interactions of sound with the bottom and surface.

Because each reflection at the bottom there is a large attenuation, spread over long distances is associated with large losses of acoustic energy (Etter, 2002).

The emission frequency of the source is also an important parameter. As in most regions of the ocean bottom is made of acoustic energy absorbing material, this will become more transparent to the energy in waves of low frequencies, which reduces the energy trapped in the waveguide. Thus, the lower the frequency, greater penetration of sound in the background and therefore, the greater the dependence of propagation in relation to the geoacoustics parameters. At high frequencies (> 1kHz), sensitivity to the roughness of the interfaces and the marine life is greater, resulting in a greater spread, a lower penetration of the bottom and a larger volume attenuation (Xavier, 2005).

So, spread over long distances occurs in the range of intermediate frequencies (100 Hz to about 1 kHz) and is strongly dependent on the depth and the mechanisms of attenuation. Figure 2 shows the attenuation of sound absorption in seawater as a function of frequency. According to (Etter, 2002), the dependence with frequency can be categorized into four major regions, in increasing order of frequency: absorption in the background, the boric acid relaxation, relaxation of magnesium sulfate and viscosity.

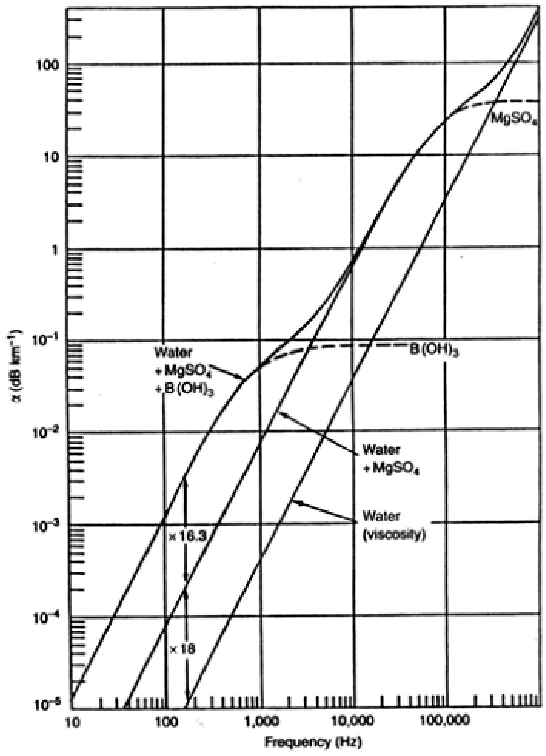

Figure 2 – Absorption Coefficients for sea water (Etter, 2002).

4 ACOUSTICS MODELS

The development of modeling techniques in underwater acoustics began in the 40s as a way to achieve the improvement of sonar systems and their evaluations, during the Second World War, in support of naval operations.

According to (Etter, 2002), an acoustic model is called physical or analytical when it represents the theoretical conceptualization of the physical phenomena that occur in the ocean. The mathematical models include both empirical models, those based on experimental observations, the numerical models, those built from the mathematical representation of physical ruler. It also defines a third type, called the reduced models (analog models), defined as controlled trials acoustic test tank with the use of appropriate scale factors.

The acoustic models can be classified into three broad categories: Environmental Models, Acoustic Models Core, Sonar Performance Models. This paper focuses on case study of a Basic Acoustic Model: The Method of Normal Modes.

4.1 The Method of Normal Modes

The study of the Normal Modes Method begins by applying the concept of vibrations in an idealized ocean model, where the medium is homogeneous, bounded above by a surface free (pressure release) and below by a perfectly flat disk, where the reflections are specular, the propagation speed of sound is constant and sound waves are considered flat. Figure 3.2 shows an excerpt of this model and the propagation of only one pulse of sound. In it, the red wave front, high pressure, it focuses on the free surface, reflects and reverses the phase, returning as a front of low pressure (green line) on the environment. The reflectance at the surface is then -1. At the bottom hard, because this resist compression, the wavefront incident reflects without reversing the phase, if the wave front cover as high pressure, as it reflects a high pressure front. The reflectance of this interface is 1. The direction of propagation defined by the sound beam is normal to the wavefront and the apparent horizontal velocity is given by c $\sin\theta$, c being the speed of sound propagation and the incidence angle θ, measured between the normal to the interfaces and the radius sound

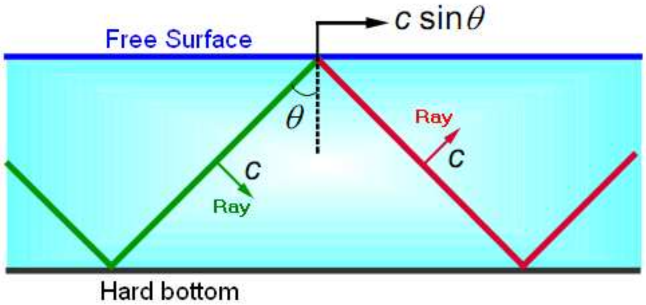

Figure 3 – Reflection of plane waves in an ideal waveguide

The pressure field is confined between the free surface and rigid bottom and its establishment is the depth of the channel conditions allow for adequate reflection of the rays with incident angles items related to the frequency of the excitation source. Figure 4 presents four waveguides with different depths, which satisfy the conditions for confinement in discrete ways. All other parameters such as speed of sound, the frequency of the source, the density of water and the surface characteristics and background are constant and equal for all channels. Highlights are shown variations of the amplitude of sinusoidal pressure with depth. The nodal points, pressure points are located in the zero crossing of the pressure curve with the axis of depth (z) and antinodes correspond to those points where pressure is high or low.

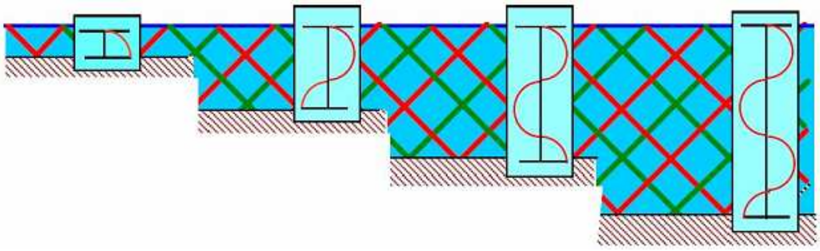

Figure 4 – Trapping modes for waveguides of variable depth, excited by a harmonic source. The graphs show the highlighted horizontal pressures due to depth (Xavier, 2005).

Each normal mode of vibration is formed only for a given frequency at a particular angle of incidence. For the analysis of Figure 5 can be seen that the angle of incidence, θ, is given by θ = arccos $(\lambda/4h)$ for the first mode and

$$\theta_m = \arccos\left[\frac{\lambda}{2h}\left(m - \frac{1}{2}\right)\right],\ m = 1, 2, 3, ... \tag{13}$$

for other modes.

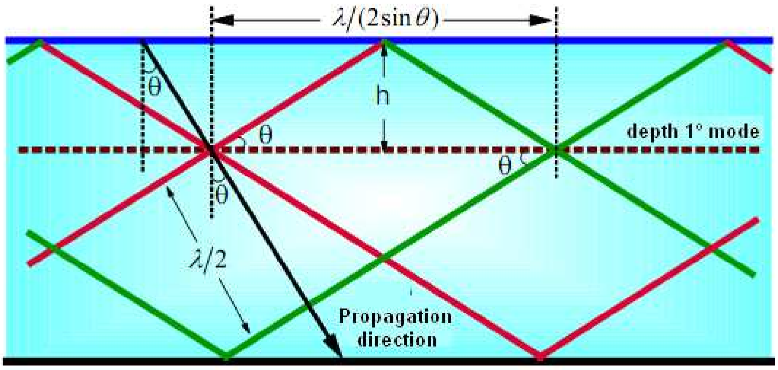

Figure 5 – Geometry to obtain the relationship between the incidence angleθ, the. Wavelength λ and depth h for the mode number (Xavier, 2005).

It is important to note that due to the orientation of wave fronts in relation to the borders of the channel, the speed of propagation of the interference pattern of pressure for each mode, known as group velocity (apparent) will be given by the expression:

$$u_m = c\, sin\theta_m, \tag{14}$$

known as dispersion relation, where *c* is the speed of sound propagation or phase velocity.

If θ_m tend to 90º, the wave fronts will have a virtually vertical alignment and be propagated to the next phase velocity, *c*. This only happens when the frequency of excitation is very high. On the other hand, if the excitation frequency drop dramatically, so that the depth of the channel is approximately $\lambda/4$, θ_m tend to 0° and the wave fronts will have an alignment almost horizontally forming standing waves that are reflected continuously in the background and surface. The group velocity in this case is void. This frequency is known as the cutoff frequency for the nth mode, because for a frequency below it, the mode ceases to exist. For frequencies above the cutoff frequency, the propagation occurs for a specific angle of incidence (θ_m) and their respective group velocity, (u_m).

How many ways are spreading, each with its group velocity, the pressure field will consist of the superposition of the sound pressure due to each mode. It is worth mentioning that the source depth also plays an important role in establishing the magnitude of the pressure field and even in existence in certain ways, because if the source is positioned at a nodal point, the way they have this point will not exist. To obtain an excitation maximum for a particular mode, the source must be placed in one of the antinodes. The dispersive character of the spread can be determined experimentally by analysis of the sound produced by an explosive source, which contains a very broad spectral band (20 Hz to 2 kHz). In the vicinity of the detonation, the sound heard is quite serious. In regions distant from the sound you hear is a sine pulse duration of about 1s, initially acute, with a frequency of 2 kHz and serious at the end, often a few hundred Hz This is because at high frequencies, the group velocities of the modes are grouped near the phase velocity, while the low frequencies sustain fewer *c* modes and group velocities for *c* decrease. Thus, the high frequency components will arrive before the low frequency components.

4.2 Mathematical model for a True Channel

In the theoretical model of Pekeris, representing features often found in nature, composed of sedimentary layers laminated, roughly parallel, the interfaces are considered flat and parallel and act as a reflection horizons.

4.3 Characteristic Equation in Stratified Media

Initially, it presents the characteristic equation for a generic stratified media for later presentation of the characteristic equation applied to the theoretical model of Pekeris.

Represents a stratified media is so generic, for a physical model consisting of a homogeneous fluid layer, bounded above by a horizontally stratified medium with a coefficient of reflection $\Re_s$ and bounded below by a half, also horizontally stratified, with the coefficient reflection $\Re_f$, as shown in Figure 6.

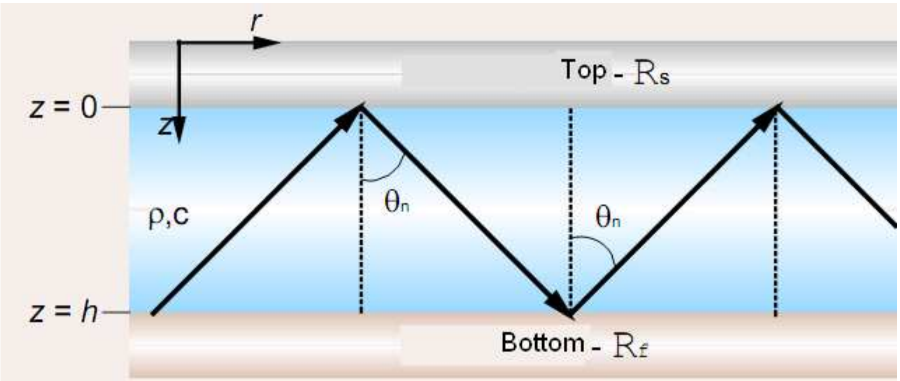

Figure 6 – Stratified generic media

Knowing that the solution of wave equation consists of the product of two factors, one dependent only on the depth and horizontal distance from the other, the first factor can be described as resulting from the interference of two plane waves, one propagating upward and the other down according to the equation below:

$$S(z) = Ae^{i\gamma z} + Be^{-i\gamma z}, \tag{15}$$

where A and B are constants to be determined by boundary conditions and initial.

Umpiring is the positive direction of *z* axis down, the first term of the right corresponds to a wave propagating upward and the second term a wave propagating down.
As the reflection coefficient at the surface $\Re_s$ is defined as the ratio between the incident and reflected waves on the surface (z = 0), it is expressed by:

$$\Re_s = \left.\frac{Be^{-i\gamma z}}{Ae^{i\gamma z}}\right|_{z=0} = \frac{B}{A}, \tag{16}$$

Similarly, at the bottom (*z* = *h*), $\Re_f$ is given by:

$$\Re_f = \left.\frac{Ae^{i\gamma z}}{Be^{-i\gamma z}}\right|_{z=0} = \frac{A}{B}e^{i2\gamma z} \quad (17)$$

Relating Eq. (16) and (17) gives:

$$\Re_f = \frac{1}{\Re_s}e^{i2\gamma h} \Rightarrow \Re_s\Re_f e^{-2i\gamma h} = 1 \therefore 1 - \Re_s\Re_f e^{-2i\gamma h} = 0 \quad (18)$$

In the case of an ideal channel, we have that $\Re_s = -1$ and $\Re_f = 1$. Substituting these values in Eq. (18) arrives in the expression:

$$1 + e^{i2\gamma h} = 0 \quad (19)$$

Transforming the exponential in its trigonometric form, Eq. (19) becomes:

$$\cos(-2\gamma h) + i sin(-2\gamma h) = -1 \quad (20)$$

By the equality of complex numbers, we have that:

$$\cos(-2\gamma h) = -1 \text{ and } i sin(-2\gamma h) = 0 \quad (21)$$

From Eq. (21) gives:

$$\gamma_m = \frac{(m - 0,5)\pi}{h}, \text{ for } m = 1,2,3,\ldots \quad (22)$$

4.4 Pekeris' Model

Once defined the characteristic equation for general stratified media, the same applies to the physical model of Pekeris, composed of a homogeneous liquid overlying an unconsolidated sediment layer (absorber) and stratified, with flat and parallel interfaces. Knowledge of the solution to this model, illustrated in Figure 7, is the basis for modeling more complex environments.

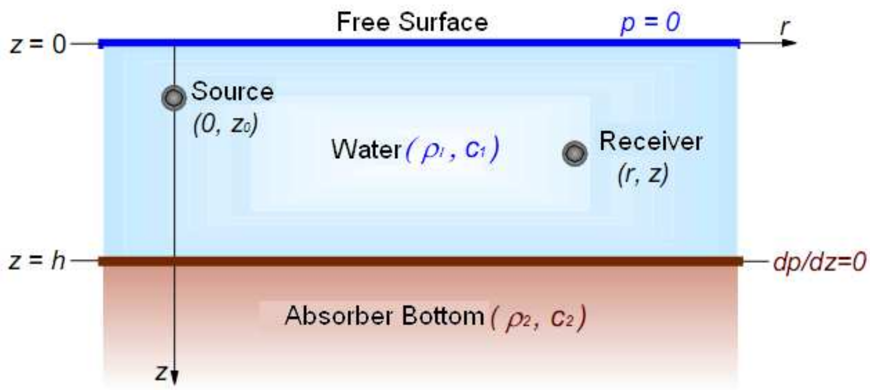

Figure 7 – Physical Model of Pekeris

In this model, the final equation for the pressure field is then given by the following equation (Xavier, 2005):

$$p = \rho\, exp\left(i\frac{\pi}{4}\right) r^{-1/2} \sum_m q_m S_m(z_0) S_m(z)\, exp(-\delta_m r - ik_m r)\,. \qquad (23)$$

where m is the total number of modes, k is the horizontal wave number, S_m are the eigen functions, q_m is the rate of excitation modes and δ_m is the term attenuation estimated by calibration with experimental data.

5 NUMERICAL SIMULATION AND RESULTS

The propagation model based on the theory of normal mode functions used in this work was the KRAKEN program, which is part of the Toolbox AcTUP v2.2 lα - Acoustic Toolbox User-interface & Post-processor to Matlab R2006a – Mathworks, from Centre for Marine Science & Technology, University of Technology Curtin, in Australia, developed by Michael B. Porter (Maggi, 2006). In this Toolbox, the computational techniques are divided into various methods of acoustic propagation. Among these methods can be highlighted: BOUNCE & BELLHOP, KRAKEN, RAM, RAMGEO.

The program calculates the Transmission Loss (TL) due to discrete modes, those that propagate only by undergoing total reflection.

The ocean is modeled as taking a fluid layer, with a sound velocity profile on an arbitrary infinite half-plane uniform. In this simulation, we have Waveguides with Flat Bottom and Parallel and two propagation modes.

This model consists of a layer of water 23 feet deep, with constant velocity, superimposed on an infinite half-plane sedimentary also considered fluid, with speed of propagation of sound and density constant. The emitting source is punctual and continuous unitary amplitude.

The model has the following characteristics:

- Layer net: c_1=1508 m/s, ρ_1= 1033g/m^3 and width = 23 m;
- Sedimentary layer: c_2=1689 m/s, ρ_2=2066g/m^3;
- Source: 147.8 Hz, located 10 m from the surface;
- Receiver: positioned 20 m at the surface;

The following figure shows the transmission loss as a function of horizontal distance from the model described above. This first simulation was performed using the program KRAKEN.

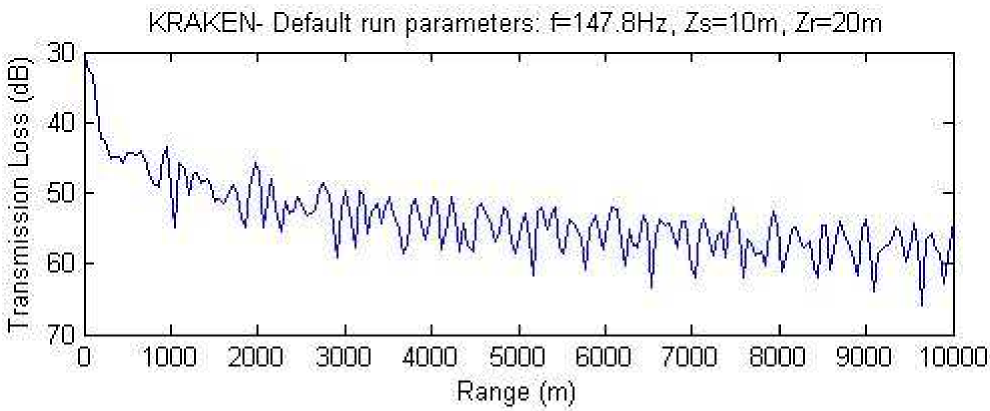

Figure 8 – TL curves for distance, obtained by the KRAKEN model.

Other tests were performed using the other programs in the package ACTUP. They use the method of parabolic equations (PE), from the development of the Padé approximation, whose accuracy increases with the number of terms in the series. The next figures show the results obtained with the BELLHOP method, simulated in this work, and the results obtained by (Xavier, 2005) using the RAM method.

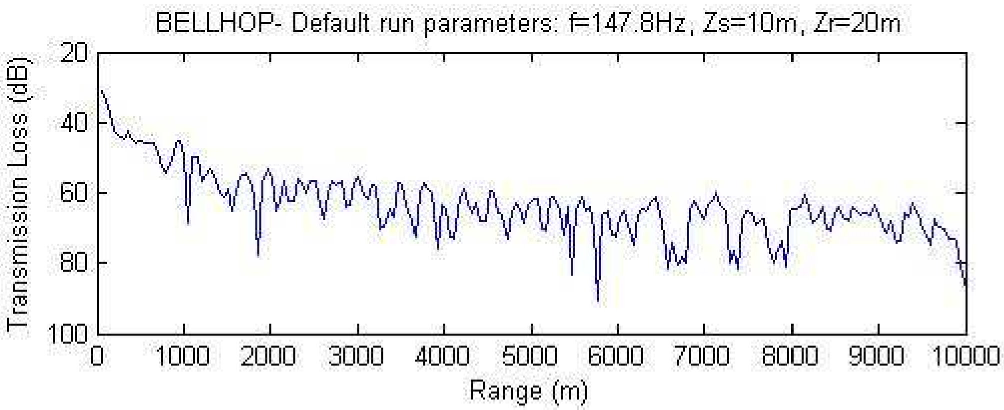

Figure 9 – TL curves for distance, obtained by the BELHOP model.

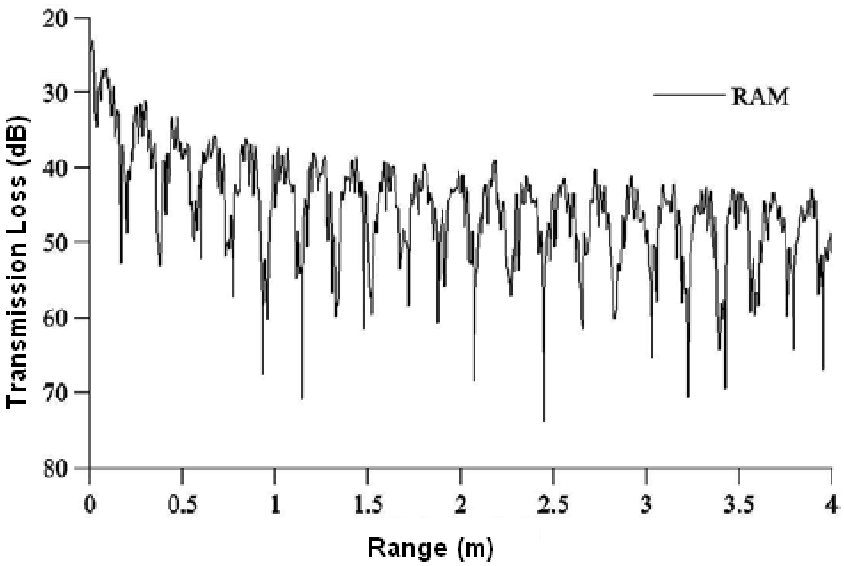

Figure 10 – TL curves for distance, obtained by the RAM model for (Xavier, 2005).

The results obtained with the KRAKEN and BELLHOP methods are very close and follow a pattern of transmission loss in accordance with the horizontal distance. The KRAKEN method uses the method of normal modes, while the BELLHOP method uses the boundary element method to obtain the transmission loss. Despite different methods, the results follow a similar pattern. The RAM method, used in (Xavier, 2005), is based on the approximation of parabolic equations (PE) and uses the approach by the terms of the Padé series. For this method the scale of the figure was increased to evaluate the behavior of transmission loss up to a distance of 4 km. It is observed that the findings of this study are close to those results obtained in the literature.

6 CONCLUSIONS

This paper presented a review on the modeling of acoustic propagation in shallow water, using the Normal Mode Method, applied to the model Pekeris. Besides this method, we used the method based on Boundary Elements and the results were compared with those obtained by the literature.

It appears that the results of transmission loss increases with the horizontal distance of propagation. There was analyzed the transmission loss with depth in this work.

The simulation results are very close to the results obtained by (Xavier, 2005) and and with that, we have that the methods are valid and can be applied to other cases.

From these results, we can expand the application of the methods to other problems such as underwater acoustic propagation, sloping bottom, three layers, among others.

All methods used in this study are suitable for seawater. As future work, we propose the modification of parameters in these methods so that they can be used for simulation of acoustic propagation in rivers. This is the subject of my doctoral program, which is being developed at the (Universidade Federal de Minas Gerais).

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