TRANSMISSION PROPERTIES OF A SHALLOW HYDROACOUSTIC CHANNEL

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Multiple acoustic wave reflections on environment boundaries significantly reduce transmission capacity of shallow hydroacoustic channels. The use of BNM channel model being among the results of the international research project PROSIM developed within the framework of the MAST-III initiative, allowed to calculate the channel impulse response functions and perform a simulation of a digital signal transmission. This article presents the results of test transmission of binary FSK and PSK signals in a sample channel.

INTRODUCTION

A shallow reservoir is a very complex channel, as far as communication is concerned. This is caused by the physical properties of the aqueous environment and the geometry of a particular sea region. The main problem related to the transmission of signals in a shallow underwater channel is the occurrence of acoustic wave reflections on the bottom and water surface. Such reflections represent a significant part of the signal reaching the receiver. One of the methods employed to analyze the propagation of sound waves in shallow water channels is the normal modes method. It takes account of the depth of the sea region and bottom properties as well as the changes of sound propagation velocity with depth.

In order to examine the influence of the hydroacoustic channel on broadband communication signals, the BNM (Broadband Normal Modes) module of the PROSIM (Propagation Simulator) software was used, operating in the Matlab environment. This software is a product of three year efforts (1996-1999) of a group of scientists related to five European science centers: TNO-FEL Physics and Electronics Laboratory, TMS Thomson-Marconi Sonar, the University of Wales Marine Science Laboratories, NATO Saclantcen Undersea Research Centre and the Heriot-Watt University Ocean System Laboratory. The authors made the results available to the public. The BNM module allows to take account of the changes of the physical properties and the geometry of the sea region where the wave propagates [4].

1. BROADBAND NORMAL MODES IN PROSIM SIMULATOR

The amplitude of the direct wave decreases rapidly with increasing range in a channel whose depth is much smaller than its length, and the totally reflected signals become the most important components of the sound pressure [1]. Broadband normal modes method resolves cylindrical wave equation using separations of variables technique and boundary conditions. These lead to expressions of the sound transmission in terms of the "natural modes of vibration" [2].

The cylindrical wave equation has the following form:

$$\frac{\partial^2\varphi}{\partial r^2}+\frac{1}{r}\frac{\partial\varphi}{\partial r}+\frac{\partial^2\varphi}{\partial z^2}=\frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2} \tag{1}$$

where φ is the velocity potential.

After separating variables, i.e. substitution $\varphi \approx U(r)Z(z)T(t)$, and assuming the harmonic source $T(t)=\exp(i\omega t)$, (1) becomes:

$$\frac{U''(r)+(1/r)U'(r)}{U(r)}+\frac{Z''(z)}{Z(z)}=-\frac{\omega^2}{c^2}, \tag{2}$$

The separated equations are:

$$U''(r)+\frac{U'(r)}{r}=-\kappa^2U(r), \tag{3a}$$

$$Z''(z)=-\gamma^2Z(z), \tag{3b}$$

$$k^2\equiv\frac{\omega^2}{c^2}, \tag{3c}$$

$$\kappa^2+\gamma^2=k^2, \tag{3d}$$

where $\boldsymbol{k}$ is the wave vector, κ and γ are horizontal and vertical components of $\boldsymbol{k}$ respectively.

The solution of (3a) is acoustical pressure dependency on range. The solution of (3b) is pressure dependency on depth. After applying boundary conditions to (3b), the characteristic equations are obtained. When the surface is perfectly free and the bottom is perfectly rigid, the pressure reflection coefficient at the surface is –1 and at the bottom it is 1. In this case the characteristic equations have the form:

$$\gamma h=\left(m-\frac{1}{2}\right)\pi\ , \quad m=1,2,\ldots, \tag{4}$$

where h is the thickness (depth) of water layer.

The conditions are satisfied for a discrete set of values γ called the eigenvalues. For the ideal water layer the eigenvalues are:

$$\gamma_m\equiv\frac{(m-1/2)\pi}{h}, \tag{5}$$

and the eigenfunctions have the form:

$$Z_m(z)\equiv A_m\sin\gamma_m z \tag{6}$$

for *m=1,2,3,...*, where the subscripts refer to discrete solutions. The depth eigenfunctions *Z(z)* are orthogonal in the mathematical sense and, a particular dependence of pressure on z can be expanded as a sum of the eigenfunctions. Constants of addition are:

$$A_m = \frac{\rho_0 Z_m(z_0)}{\nu_m}, \tag{7}$$

where ρ_0 is the water density, $Z_m(z_0)$ is the eigenfunction at the source depth and ν_m is the orthogonality integral:

$$\nu_m = \int_0^h \rho_0 Z_m^2(z)dz \tag{8}$$

The solution of the wave equation with boundary conditions is the product of depth eigenfunctions $Z_m(z)$, range eigenfunctions $U_m(r)$, source function $T(t)$ and addition coefficients A_m:

$$p(z,r,\omega,t) = T(t)\sum_m A_m \cdot Z_m(z)\cdot U_m(r) = a_0 \exp\left[i\left(\omega t + \frac{\pi}{4}\right)\right]\sum_m \frac{\rho_0 Z_m(z_0)Z_m(z)\exp(-i\kappa_m r)}{\nu_m(2\pi\kappa_m r)^{1/2}} \tag{9}$$

where a_0 is a constant that depends on the source power. [2]

As it is shown in (9), the normal mode expression of the sound pressure is a function of depth, range, frequency and time. The solution is obtained for particular two-dimensional coordinates (depth and range) of the transmitter and the receiver, and particular frequency of source harmonic function.

Applying normal mode method for obtaining solutions of sound pressure function, when the source function is a broadband signal, is possible. Resolving (9) for many single-frequency sources and calculating the sum of the results should be done. The set of source frequencies should cover the frequency range of the broadband signal.

A fast and efficient algorithm of the normal mode method for simulating broadband signals transmission in underwater channel is applied in PROSIM simulator [4]- [7]. PROSIM utilizes a layered model approach for broadband range-dependent sound propagation in the frequency range of 100 Hz to 10 kHz. The computational speed of PROSIM depends on the number of layers describing the environment in depth, the maximum frequency and the bandwidth. The Broadband Normal Modes model assumes that the inverse of the sound speed squared varies linearly with depth in each layer. Only real eigenvalues are included in the calculations, and the model only handle fluid sediment layers. The program requires only an accurate determination of eigenvalues and mode functions for a subset of frequencies in the frequency band of interest. The eigenvalues and mode functions are then interpolated in frequency between this subset of calculated frequencies in order to obtain a specific sample of the transfer function.

The model is able to handle range-dependent environments within the adiabatic approximation, i.e. coupling energy between modes caused by the range-dependency is neglected. The range-dependent environment is divided into a sequence of range-independent segments. The eigenvalues and mode functions are evaluated for each segment and for a frequency sub-band of the total frequency band of interest. Hereafter the frequency sub-band is changed, and the calculations start at the first segment and proceed out to the last segment. The procedure continues until all the frequency sub-bands have been analyzed.

2. TEST CONDITIONS

The broadband normal modes simulator was used for testing the transmission properties of the channel. The physical situation, for which the test was made, is sketched in Fig. 1. The waveguide consists of three layers: a water layer and two sediment layers, which are treated as fluid layers. The source of communication system is at depth $z_0 = 40\,m$ and the receiver is at horizontal range $r = 6\,km$ and depth $z = 55\,m$. All the input parameters of BNM simulator are listed in tab. 1.

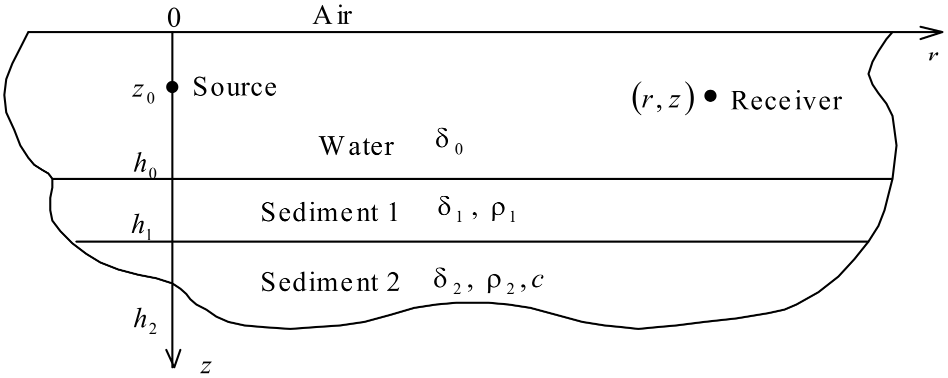

Fig. 1. Diagram of the situation simulated by PROSIM simulator.

Tab.1 Environment and communication system parameters input to the PROSIM program.

Parameter	**symbol**	**Values**
Water layer depth	h_0	120 m
Attenuation in water layer	δ_0	0.25 dB/L
Depth of sediment 1 layer	h_1	40 m
Density of sediment 1 relative to water density	ρ_1	1.2
Attenuation in sediment 1 layer	δ_1	0.25 dB/L
Depth of sediment 2 layer	h	40 m
Density of sediment 2 relative to water density	ρ_2	2
Attenuation in sediment 2 layer	δ_2	0.5 dB/L
Sound velocity in sediment 2 layer	c	1800 m/s
Number of receivers	---	1
Receiver depth	z	55m
Range	r	6 km
Source depth	z_0	40m
Response examinations band	---	5000Hz-10000Hz
Observation time	---	1s

For the above system configuration, the program has calculated the transfer function (fig.2) of the channel.

The Inverse Fourier Transform of the transfer function has been computed to obtain the impulse response of the channel (fig. 3). This impulse response has been used for testing the effect of the channel on a transmitted signal. A gaussian pulse shown on fig. 4, has been transmitted through the channel.

Fig. 5 shows the pulse at the receiver. The multiple reflection effect is evident. It has a significant impact on the possibility of a correct detection of the transmitted signal. The received pulse has time width three times that of the original pulse. Fig.5 and fig.6 show the normalized amplitude spectra of both the transmitted and received pulses. The effect of comb filtering is noticeable in the spectrum of the received signal, characteristic for communication channels with multiple reflections [1].

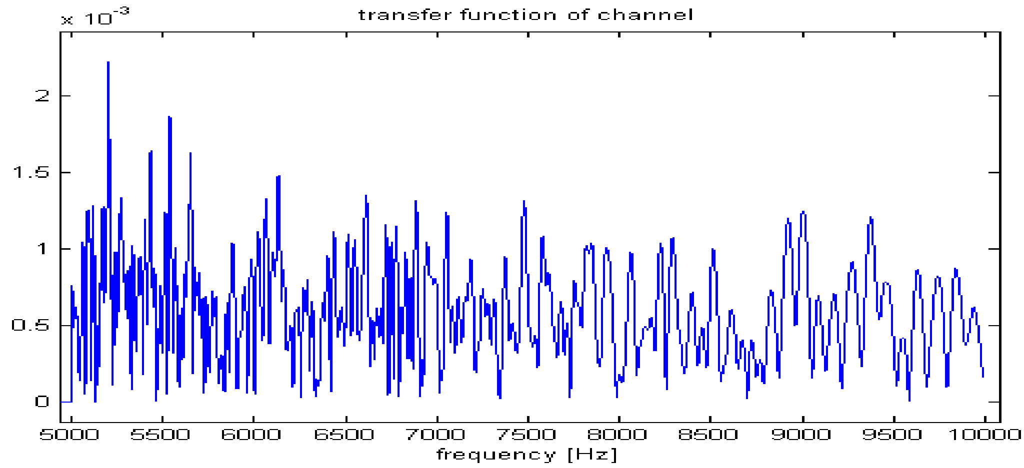

Fig. 2. BNM transfer function of the channel (tab.1)

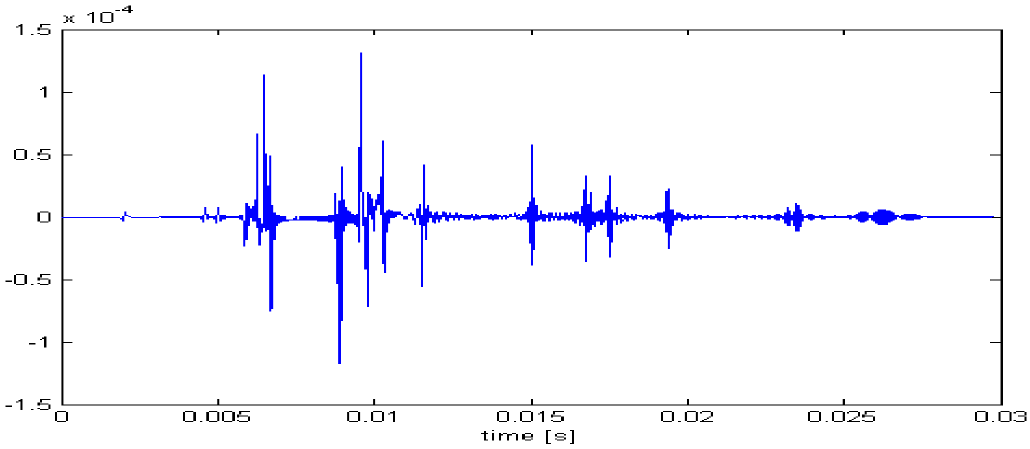

Fig. 3. Impulse response of the channel

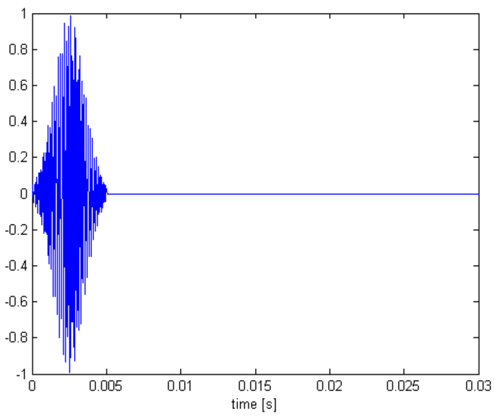

Fig. 4. Gaussian pulse of 7500 Hz carrier frequency and 5 ms duration

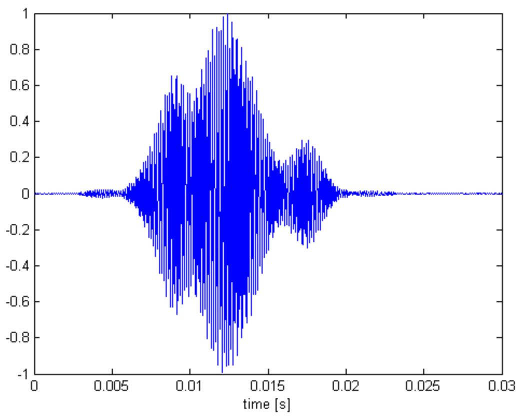

Fig. 5. Gaussian pulse shown in figure.4 after passing through the channel with impulse response shown in Fig. 3

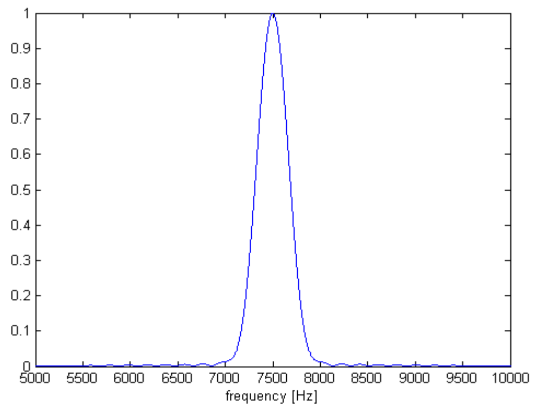

Fig. 6. Normalized spectrum of the Gaussian pulse of 7500 Hz carrier frequency and 5 ms duration

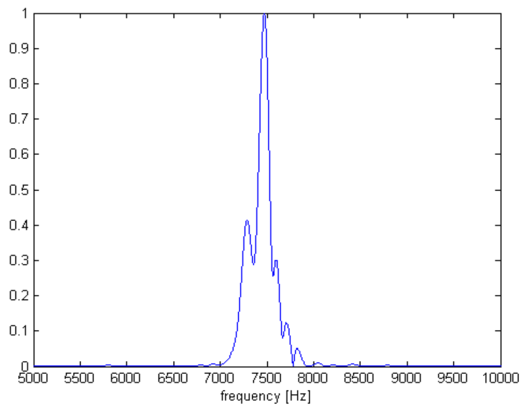

Fig. 7. Normalized spectrum of the channel response to the frequency pulse shown in Fig. 4

3. TESTING THE CHANNEL PROPERTIES

Influence of the modeled channel on the transmission possibilities of binary signals has been examined. Two modulation schemes of continuous carrying wave has been used, namely frequency shift keying (FSK) and phase shift keying (PSK). The simulation of digital signal transmission has been performed in the Simulink computing environment of The Mathworks. The input signal was a pseudorandom binary series with a specified frequency (transmission rate). Models of modulator and demodulator has been taken from Communications Blockset. Channel was implemented as a user functional block [9]. The result of the simulation was binary error rate (BER) of transmission. The diagram of the transmission simulator is presented in Fig. 8.

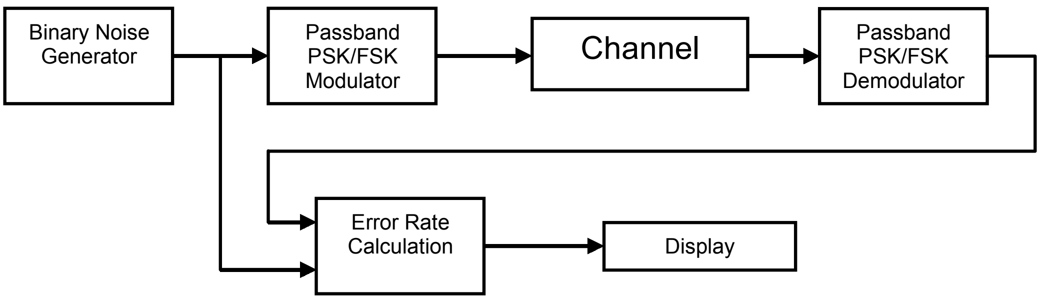

Fig. 8. Transmission simulator block diagram

The simulation parameters used in the simulation are listed in tab.2.

Tab.2 Parameters of simulation

parameter	value
modulating signal	pseudorandom binary signal
distance between transmitter and receiver	1000 m (667 ms)
sampling frequency	16 kHz
carrier frequency	5 kHz
frequency separation for FSK modulation	800 Hz

The Binary Noise Generator block generates random binary numbers. The PSK/FSK Modulator Passband Block modulates the input signal using the phase/ frequency shift keying method. The output is a passband representation of the modulated signal. The PSK/FSK Demodulator Passband Block demodulates the signal transmitted through the channel. Error Rate Calculation Block computes the BER (Bit Error Rate) of the received signal by dividing the total number of unequal pairs of data elements by the total number of input data elements from the source. Display Block shows the value of the BER [8]

Tab.3 Simulation results

Transmission rate [b/s]	150	160	195	200	210
BER [%] - FSK modulation	<0.1	15	24	32	32
BER [%] - PSK modulation	<0.1	<0.1	< 0.1	7	21

Examples of simulation results are presented in tab. 3. It can be seen, that for low transmission rates the bit error rate is close to zero. Similar situation has place in the case of stationary channel described in [1]. For transmission rates above the limit value, reduction of the bit error rate requires application of matched filtering techniques.

4. CONCLUSION

The BNM model has been used for calculating the transfer function and impulse response of a hydroacoustic channel. Transmission properties of such a channel has been tested. The model being stationary, it is mere fist step in building more realistic nonstationary model of hydroacoustic communication channel [1].

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