TIME DOMAIN SIGNAL ANALYSIS OF DIVER ATTACK
SCENARIOS FOR HARBOR SECURITY

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In today’s world, the threats through the harbor areas are becoming more and more important topic due to national security demands. In this concern, an effective protection against the different diver attacks through the harbor areas needs to be well understood the phenomena of the acoustic wave propagation and the sensor detection capability in the investigated region. In this work, three different diver attacks are considered through a maritime area. Three paths are defined for the different attacks and the diver is located at three different positions along each of the paths. Frequency modulated acoustic signal is used to excite acoustic waves along the maritime area. First, a two dimensional acoustic waveguide problem in time domain is solved by Finite Difference Time Domain method (FDTD), numerically. Second, the acoustic signals are evaluated at a receiver location and in the sense of the Receiver Operating Characteristics (ROCs), i.e., the probability of the detection for a definite false alarm rate.

1 Introduction

One of the important issues for the harbor security is to well understand the behavior of the underwater acoustic wave propagation affecting the detection of the different diver attacks through the harbor region. The detection of the diver will be successful especially if the high frequency sonar diver detection system is used [1]. Because the geometry of the seabed along the maritime area is so complex and is not generally smooth in nature, the diver can hide himself behind some taper or clefts on the seabed. These make more difficult to detect the diver attacks with different diving paths through the maritime areas.

There may be some realistic scenarios in which the diver can follow the different diving paths. In order to understand the underwater acoustic wave propagation properties in the case of the different diver attacks along the complex seabed geometries, it is necessary to solve the underwater acoustic wave propagation problem with the complex seabed structures for each diver attack scenarios.

The complexity of the seabed geometry generally leads to a non-separable coordinate system, and therefore the analytical solution of the underwater acoustic wave...
propagation problems in complex seabed geometries (specifically for the different attack scenarios) is a difficult task or is not possible in general. However, the numerical techniques give rise to solve the acoustic wave propagation problems in the case of the different diver attack scenarios in relatively complex environment. In this work, the Finite Difference Time Domain (FDTD) method is used to solve this problem in the time domain, numerically. The received acoustic time domain signals are evaluated in the sense of the probability of detection, the probability of false alarm that are all expected for a range of Signal-to-Noise-Ratio at a receiving point.

2 Methods

2.1 The Geometry of the Problem

The underwater acoustic problem space can be modeled as a kind of acoustic waveguide. The three different diver attack scenarios (Path I, Path II and Path III) with the nine different diver positions are considered in two dimensional (range-depth) problem space. The sea surface is considered as a smooth region but the seabed region has a slope and a cleft. It is assumed that no acoustic wave propagation is allowed through the sea bottom. The diver can hide himself in the seabed cleft or pit. The considered diver attacks and the positions of the transmitter and the receiver in the harbor area are shown in Fig. 1.

![Figure 1. The three different diver attack scenarios through the harbor area.](image)

The transmitter emits the frequency modulated acoustic signal to the maritime area and the receiver collects the reflected acoustic signals from the sea surface, from the seabed structures and from the diver situated at one of the nine different positions along the three different paths. First, the acoustic time domain signal reflected from the sea surface and the seabed boundaries is obtained by the FDTD method when the diver is not in the scene. Second, the reflected acoustic time domain signal is obtained when the diver is in
the scene. The pure acoustic signal reflected only from diver is obtained by subtracting one signal from the other. The resulted signal is evaluated in terms of the probability of detection. To check the linearity of the noise propagation in the waveguide, the noise source is considered at the right side of the problem space as a vertical line source. The propagation of the noise along the region is taken into account. Additionally, it is assumed that there is no interaction between the diver and the propagated noise field.

2.2 The Finite Difference Time Domain Method

The Finite Difference Time Domain (FDTD) is one of the widely used numerical methods in time domain for the wave propagation analysis for both acoustic and electromagnetic problems [2]. The FDTD is based on the time and the spatial discretization of the acoustic field with the central finite differencing of the time and the spatial derivatives in the time domain wave equation. The time domain wave equation in the two dimensional space (range-depth) can be solved for the different diver attack scenarios in the harbor security problems. In this case the two dimensional time domain wave equation can be written in Cartesian coordinates as

\[
\frac{\partial^2 u}{\partial x^2} u(x,y,t) + \frac{\partial^2 u}{\partial y^2} u(x,y,t) - \frac{1}{v^2} \frac{\partial^2 u}{\partial t^2} u(x,y,t) = 0 \quad (1.1)
\]

where \( u(x,y) \) is the acoustic field distribution along \( x-y \) coordinates and \( v \) is the velocity of the sound in the sea. If the two dimensional problem space is discretized for the FDTD method as \( u^t(i,j)=u(i\Delta x,j\Delta y,n\Delta t) \), then the FDTD update equation for the acoustic field can be arranged as the following

\[
u^{n+1}(i,j) = \left[ 1 - \left( \frac{V_N}{\Delta x} \right)^2 - \left( \frac{V_N}{\Delta y} \right)^2 \right] + 2u^n(i,j) - u^{n-1}(i,j) + \frac{V_N}{\Delta x} \left[ u^n(i+1,j) + u^n(i-1,j) \right] + \frac{V_N}{\Delta y} \left[ u^n(i,j+1) + u^n(i,j-1) \right]. \quad (1.2)
\]

The problem space is supported with a pressure-release boundary (Dirichlet boundary condition, \( u=0 \)) along the sea surface and a hard bottom boundary (Neumann boundary condition, \( \partial u/\partial n=0 \)) along the sea bottom. The Neumann boundary condition means that no acoustic wave penetration is considered through the sea bottom. MUR absorbing boundary condition (ABC) at the beginning section and at the end section of the waveguide is used for the termination of the problem space. The MUR ABC can absorb the acoustic waves and no reflection from MUR ABC region is occurred regarding the limitation of the MUR ABC success. The MUR ABC condition requires the following acoustic field update equation in the ABC region.

\[
u^n(i,j) = \nu^{n-1}(i+1,j) + \frac{c\Delta t - \delta}{c\Delta t + \delta} (\nu^n(i+1,j) - \nu^{n-1}(i,j)). \quad (1.3)
\]
where $\delta$ shows the spatial unit cell. The discretization of the two dimensional problem space with the boundaries and MUR absorbing boundary condition are shown in Fig 2.

Figure 2. The discretization of the two dimensional problem space with the boundaries and MUR Absorbing Boundary Condition.

An acoustic point source is used to excite the underwater acoustic waves along the waveguide structure. The time dependence of the acoustic point source is chosen as a frequency modulated (FM) signal due to its wideband characteristic which may be more efficient to detect the diver as a small target. The definition and location of the FM signal source can be formulated as the following

$$u(x, y, t) = A_m \sin(2\pi f_m t + A_p \sin(2\pi f_p t)) \delta(x - x_s)\delta(y - y_s)$$

where $A_m$ is the signal amplitude and $A_p$ is the modulation index, $f_m$ and $f_p$ are the carrier and the modulation frequencies, respectively. $\delta(.)$ is Dirac function, $x_s$ and $y_s$ show the location of the acoustic point source. The reflected acoustic signals relating to the diver positions are obtained in the time domain. The different path effects including three diver attack scenarios are compared with each other and the results are evaluated in the sense of possibility of the diver detection for the high frequency sonar detection systems.

2.3 Detection Algorithm

The detection of the diver is assessed over the FDTD simulation data obtained through the three different paths. We assumed that the reverberation signals are effectively removed from the sensor system (observation point) and therefore the receiver
performance is only limited by the noise on the sensor. The Signal-to-Noise-Ratio (SNR) may also be defined using the average signal power and the average noise power as

$$SNR = \frac{\bar{P}^2}{\sigma^2}.$$  \hspace{1cm} (1.5)

The reverberation free signals are achieved by subtracting the received signal at the receiver estimated when the diver is not in the simulation scenario. We also obtained the reference (typical) noise power values on the system using the reverberation free signal of the Path-II at the Position-I, and changing the SNR in between 0 to 30 in dB. Accordingly, the reference noise values serviced to a comparison among the Paths are obtained from the Eq. (1.5). Assuming the noise power on the receiver has Gaussian probability density function, the probabilities of the correct detection at a given false alarm rate may be calculated using these reference noise powers and the following equation

$$P_d = \frac{1}{2} - \Phi(k - \sqrt{SNR})$$  \hspace{1cm} (1.6)

where

$$\Phi(t) = \frac{1}{\sqrt{2\pi}} \int_0^t \exp(-x^2/2) \, dx$$  \hspace{1cm} (1.7)

where \(k\) is the constant for a false alarm rate and also known as the multiplication margin of the noise power for a threshold value [3]. For a certain probability of the false alarm, \(k\) can be determined from the tables in [3] or from the inverse function of the equation

$$P_{fa} = \frac{1}{2} - \Phi(k).$$  \hspace{1cm} (1.8)

3 Numerical Example

Two dimensional problem space is 250 m in range and 35 m in depth. The slope and the cleft are also considered along the seabed surface for more realistic modeling of the harbor area. The diver is considered as 2 m tall which may not be easily detectable in low frequencies. It is assumed that the diver satisfies the soft boundary condition. The unit cell dimensions are chosen as \(\Delta x = \Delta y = \lambda/10\) in order to satisfy the stability criteria of the FDTD method. The number of time step is 11788 and the duration of unit time step is 5.6569x10^{-5} second. The acoustic FM signal parameters are chosen as \(A_w=1.41\), \(A_p=2\), \(f_w=1 \text{ kHz}\) and, \(f_p=250 \text{ Hz}\). The sound speed is taken as 1500 m/s and assumed
constant in the problem space. The acoustic field distribution for “empty” acoustic waveguide (without diver and noise) is shown in Fig. 3.

Figure 3. The acoustic field distribution for “empty” acoustic waveguide.

The point source (transmitter) is located at the depth of $x_t=3.35$ m, and the range of $y_t=0.45$ m. The observation point (receiver) is chosen at the depth of $x_o=1.7$ m, and the range of $y_o=0.45$ m. It is assumed that there is no interference between the receiver and the transmitter. The received acoustic signal in the time domain for “empty” acoustic waveguide (without diver and noise) is shown in Fig 4. As an example when the diver is present at the Position I which is important for all the paths, the received acoustic signal is shown in Fig. 4. This signal is obtained after it is subtracted from the received acoustic signal for “empty” acoustic waveguide. All the received signals for the nine different diver positions along the three paths are obtained and evaluated for the detection.
Figure 4. The time domain received acoustic signals:

a) The signal from “empty” acoustic waveguide,
b) The subtracted acoustic signal when the diver is present at the Position I.

Figure 5. The detection probabilities at the Position-I and $P_{fa} = 1e-5$ ($k = 4.26$).

Figure 6. The detection probabilities at the Position-II and $P_{fa} = 1e-5$ ($k = 4.26$).
Figure 7. The detection probabilities at the Position-III and $P_{fa} = 1e-5$ ($k = 4.26$).

Fig. 5 shows the detection probabilities of all Paths at the Position-I and at $P_{fa} = 1e-5$. The correct detection probabilities in between $P_d = 0$ and $P_d = 1$ can be achieved for three Paths given the reference noise power obtained from the signal of Path-II for a definite SNR value. Nevertheless it should be noted that each signal from the Paths has different SNR level at a given reference noise power. Fig. 6 shows the detection probabilities of all Paths at the Position-II and at $P_{fa} = 1e-5$. The correct detection probabilities in between $P_d = 0$ and $P_d = 1$ can only be achieved for the Path-II given the reference noise powers from the Position-I of the same Path. The signal from the Path-I at that position can not be detectable. The diver is in the cleft and may be relatively invisible in terms of the acoustic backscattering. The Path-III at the Position-II results in very small ($P_d < 0.05$) detection probability given the reference noise powers. Fig. 7 shows the detection probabilities of all Paths at the Position-III and at $P_{fa} = 1e-5$. The correct detection probabilities in between $P_d = 0$ and $P_d = 1$ can be achieved for the three Paths given the same reference noise powers. The Path-III at the Position-III results in the early detection rates (the higher SNR values) for the certain sensor noise levels than the other Paths give at the same noise powers. The diver at the Path-III and the Position-III shows larger profile to the sensor when he is on the way of the Path-III and Position-II.

4 Discussion

The two dimensional acoustic wave propagation problem is solved by using the Finite Difference Time Domain method, numerically. A slope, a cleft and a diver in the seabed outline a problem space for the acoustic propagation and backscattering. The sensor system is assumed as a noise limited detection system and the noise is Gaussian. The time domain sensory signals are evaluated in the sense of the probability of the detection for different diver attacks. According to the simulation results, the diver on the Path-II is fully detectable if the sensor system is designed for a high correct detection rate for the backscattering signals at Position-I of Path-II. The same system may have very low detection rates for the diver on the Path-III at the points in between Position-I and Position-II. The Path-I may result in similar detection rates as the Path-II except the Position-II of Path-I, i.e., when the diver is in the cleft or pit.

Acknowledgements

We thank Deniz BÖLÜKBAŞ, Dr. Sevgi AKGÜN and Dr. Bülent ÖRENCİK in TUBİTAK for supplying us efficient and exciting research environment.

References

1. D. Schneider and A. Corsten, Combined Performance of various Sonar Systems for Own Ship/Harbor Protection against an Asymmetric Attack, Proceedings of the Conference on
