Theoret. Appl. Mech., Vol.34, No.3, pp. 173–195, Belgrade 2007

Study of reverberation pattern and its cancellation method in shallow water

Shiuh-Kuang Yang * **Shih-Ming Chiu** *
Ruey-Chang Wei *

Abstract

In shallow water, the primary limitation of the performance of active sonar is the reverberation that originates from volume and boundaries scattering as well as multi-path propagation. Therefore, reverberation cancelation is an important research topic for increasing the performance of active sonar in shallow water. In this research, the reverberation pattern is simulated using MATLAB software. The simulated frequency is 30-kHz in the research. There are two main aims of this work. The first is to create the signals that include the reverberation and the target. The second is to perform the reverberation cancelation for the active sonar in shallow water. The analysis of the reverberation for the spherical target is based on the propagation theory of image source, surface scattering of Rayleigh criterion of roughness, bottom scattering of Lambert's Law, and multiple scattering. The signal containing the reverberation and the target is then compressed or enhanced by AGC (Automatic Gain Control). The echo of the target is then distinguished through the method of cross correlation. The following phenomena can be found: (a) AGC can compress the signal in a specific dynamic range. (b) cross correlation can be used to locate and distinguish the echoes of the target in a high reverberation environment.

Keywords: reverberation, shallow water, AGC, cross correlation, image source

*Department of Mechanical and Electro-Mechanical Engineering, National Sun, Yat-Sen University,Kaohsiung, 804, Taiwan, R.O.C.

1 Introduction

Sonar is used to detect an underwater target. An active sonar system transmits a pulse signal of finite duration to look for a target. The reflected signal is then sensed, processed, and displayed by the same active sonar system. During propagation, the unwanted signal that originates from the volume and from the boundaries of the ocean usually determines the minimum level of the reflected signals for the detected target. Thus, a typical active sonar system always contains a receiving array, a dynamic range compressor, a signal processor, and a display for locating and classifying the target [1-7].

A simple reverberation model, in general, describes three kinds of reverberation that depend on the location of the scatters. Volume reverberation arises from volume scattering due to the presence of elementary volume elements such as fish, bubbles, thermal discontinuities and other inhomogeneities located within the ocean. Sea-surface reverberation and bottom reverberation arise from scatters located on the boundary area of the ocean. In shallow water, the possibility of several reflections from the boundaries increases the complexity of detecting targets. To predict the effects of reverberation, a number of theoretical and experimental studies have been made in the field [8-18]. Ray theory, normal mode theory, multi-path expression, fast field and parabolic equation are all frequently used in the study of the underwater transmission of acoustic waves. Also, the transmission of acoustic waves in shallow water is very similar to the transmission of acoustic waves in a wave-guide, as both involve the problem of multi-path transmission [19].

To understand the physical nature of the echo structure of elastic targets, the use of simple shapes is an important step towards the understanding of reflected echoes from complex and irregular elastic targets [20]. The acoustic scattering from elastic targets has been studied extensively in the last three decades. Rayleigh [21] was the first person to analyze the wave field of the target theoretically. He considered the condition that the wavelength is much longer than the radius of the scattered object. In 1948, Morse [22] indicated an equation that is adaptable to any wavelength. Hackman [19] modulated the scattered field of the target with multi-path propagation and studied the feature of a scattered field in a wave-guide.

If the output of the receiver, such as a digital analyzer, is connected to the data processor for signal analysis, it is necessary to prevent relatively large interference from exceeding the capacity of signal to noise ratio (S/N ratio) for the analyzer. Therefore, dynamic range compression is used to adapt to the specific dynamic range of the display for a constant spatial and temporal variance background. The common technologies related to signal compression include time varied gain (TVG), automatic gain control (AGC), and reverberation controlled gain (RCG), etc. [5]. In deep water, reverberation has a continuous decay, so RCG may be more desirable since it does not distort the echo envelope. However, AGC is seen to be superior to RCG for compressing reverberation in shallow water due to the wave propagation characterized by multiple surface and bottom reflections. Recently, attempts have been made to improve the ability of AGC so that reverberation is compressed without affecting the echoes of the target. However, reverberation must contain certain features [23]. The effectiveness of the method is in the extraction of the echoes from the target without the phenomenon of distortion.

In this paper, we build a high-frequency model to describe the signals of reverberation and target in shallow water. The model is developed with the propagation theory of image source, the bottom and surface scattering method of Lambert's Law, and the multi-path reflection method. When the reverberation is simulated, the modified AGC technique will be used to compress the simulated signal into a specific dynamic range. Then cross correlation [24] is used to detect time delays between two signals, as well as to extract a common signal from the noise.

2 Fundamental theory

The highlights of this research are found mainly in the technology of the reverberation cancelation and target location, with the frequency ranges of the model lying between 20 and 30kHz. The theories of this paper involve ray theory, image source, target scattering, AGC, and cross correction.

2.1 Ray theory — image source [1]

The image source theory can be illustrated in figure 1. In figure 1, a homogeneous layer is bounded by the free surface of $z = 0$ above and by the bottom of $z = h$ below. A point source, O_{01}, is located at the point

$r = 0$, $z = z_0$. The reflected wave may be considered to emit from the image source O_{02} obtained by specular reflection of the source O_{01} at the lower boundary of the bottom. The acoustic pressure must then satisfy the boundary condition at the bottom ($z = h$), since O_{01} and O_{02} are symmetrical with respect to the boundary $z = h$. Similarly, in order to satisfy the boundary condition at the surface ($z = 0$), it is assumed that the other image sources O_{03} and O_{04} are obtained by specular reflection of the first two sources O_{01} and O_{02} above the water surface, continuing this construction of the image sources by alternately satisfying the conditions at one or the other boundary. Consequently, the acoustic pressure at point (r, z) can be obtained as follows:

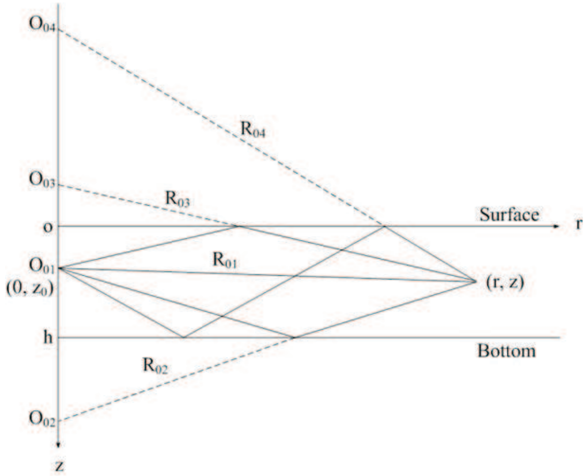

Figure 1: Wave propagation in image source [1]

$$\psi(r,z) = \sum_{m=0}^{\infty}(V_1V_2)^m[\frac{\exp(ikR_{m1})}{R_{m1}} + V_2\frac{\exp(ikR_{m2})}{R_{m2}} + V_1\frac{\exp(ikR_{m3})}{R_{m3}} + V_1V_2\frac{\exp(ikR_{m4})}{R_{m4}}] \quad (1)$$

where

$$R_{m1} = \sqrt{[r^2 + (2mh + z_0 - z)^2]},$$

$$R_{m2} = \sqrt{\{r^2 + [2(m+1)h - z_0 - z]^2\}},$$

$$R_{m3} = \sqrt{[r^2 + (2mh + z_0 + z)^2]}$$

and

$$R_{m4} = \sqrt{\{r^2 + [2(m+1)h - z_0 + z]^2\}}.$$

Also, $k = \omega/c$ is the wave number, ω the circular frequency, c the sound velocity, R indicates the distance between the point source and the receiving point, and V_1 and V_2 stand for the reflection coefficient of the sea-surface and bottom, respectively.

The acoustic pressure of the sea-bottom reverberation can be calculated in terms of the image sources method similar to the formulation shown in Eq. (1). When the effect of Lambert's law [2] is taken into consideration, the acoustic pressure of the bottom reverberation, $P_r(r)$, at a distance r from the source O_{01} can be expressed as

$$P_r(r) = \frac{exp(ikR_{01})}{R_{01}} + \sum_{(m=0)}^{\infty} (V_1V_2)^m \left[V_1 \frac{exp(ikR_{m3})}{R_{m3}} + V_1V_2 \frac{exp(ikR_{m4})}{R_{m4}} \right]$$
$$\times \alpha\left(\theta_m, \varphi_n\right) \times \sum_{(n=0)}^{\infty} (V_1V_2)^n \left[\frac{exp(ikR_{n1})}{R_{n1}} + V_1 \frac{exp(ikR_{n3})}{R_{n3}} \right] \tag{2}$$

Where $\alpha(\theta_m, \varphi_n)$ is the scattering pattern of sea-bottom, θ_m is the incident angle, and ϕ_n is the scattering angle. The received time (t) of the active sonar due to the multi-path reflection can be obtained by the trace distance (R) divided by the sound velocity of water (c), i.e.

$$t = R/c \tag{3}$$

2.2 Target scattering

A spherical ball is used in the research to estimate the echoes of the target detected by an active sonar. Assume that plane waves with one unit amplitude in water are impinging on a spherical ball of radius a, as shown in Figure 2. The incident waves are represented by [25]

$$P_i = \exp(-ikx) = \exp(-ikr\cos\theta) = \sum_{n=0}^{\infty} (2n+1)(-i)^n j_n(kr) P_n(\cos\theta) \tag{4}$$

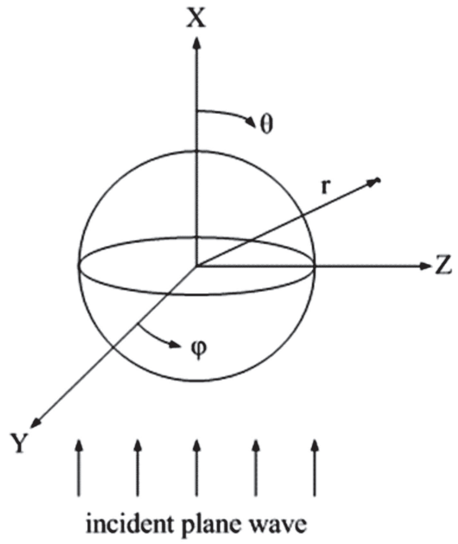

Figure 2: Plane harmonic compressional wave incident to a spherical ball.

The scattered waves will be of the form

$$P_s = \sum_{n=0}^{\infty} c_n [j_n(kr) - i y_n(kr)] P_n(\cos\theta) \tag{5}$$

A time factor $exp(i\omega t)$ is suppressed; where j_n is the spherical Bessel function of the first kind, y_n is the spherical Bessel function of the second kind and $P_n(cos\theta)$ are Legendre polynomials. The boundary conditions, the continuity of the displacement and the stress at the interface, are applied to surface of the spherical ball. We find that

$$c_n = -(2n+1)(-i)^{n+1} \sin\eta_n \exp(i\eta_n) \tag{6}$$

where η_n, the phase-shift angle of the n-th scattered wave, is defined by [25]. The pressure in the scattered wave at large distances from the sphere is found from Eqs. (5) and (6) by means of the asymptotic expressions for the spherical Bessel functions for large arguments:

$$|p_s| \underset{r\to\infty}{\longrightarrow} \frac{1}{k\,r} \left| \sum_{n=0}^{\infty} (2n+1) \sin\eta_n \exp(i\eta_n) P_n(\cos\theta) \right| \tag{7}$$

The scattering pattern for a steel sphere of 14 m in diameter at 30 kHz, i.e. $ka = \frac{2\pi f}{c}a = 875$, is plotted in Figure 3. In the figure, the angle represents scattering angle θ, and the radius corresponds to the scattering coefficient. The maximum scattering coefficient is at $\theta = 0^o$ and $\theta = 180^o$.

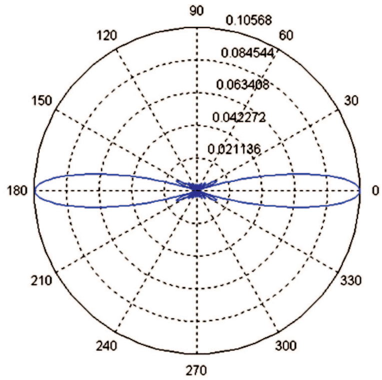

Figure 3: Beam-pattern of a spherical steel ball for $ka = 877$.

In Figure 4, the target echo is demonstrated; the distance between the sonar and the target is 750 m. The received acoustic pressure is calculated by image source method. In the figure, the horizontal axis represents the received time while the vertical axis corresponds to the received acoustical pressure. Hence, the shortest trace distance that reflects directly from the target without touching sea-surface and bottom is 1500 m, so the earliest received time is about 1 sec.

2.3 The target location and reverberation cancelation technology

a. AGC [23]

The AGC is an amplifier of amplitude modulation. The average signals (root mean square) of the received signal are calculated by the circuits. These processed signals could be a fixed signal power level in the received signals. AGC is achieved by using an amplifier whose gain can be controlled by an external current or voltage. For example, the circuit shown in figure 5. can be used as the gain-controlling element in an AGC system. In

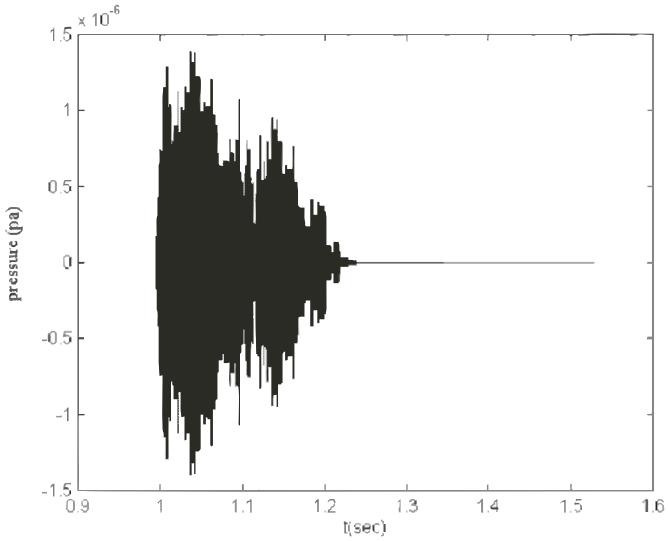

Figure 4: Signal of the target echo for the CW point source. The target is 750 m away from the source.

order to avoid saturation upon receiving the reverberation and the largest expected echo, the sonar receiver must have sufficient dynamic range so that it can detect the weakest signal. For this reason, the research will use AGC to compress the signals to a specific dynamic range and to obtain a constant spatial and temporal variance background in our simulation.

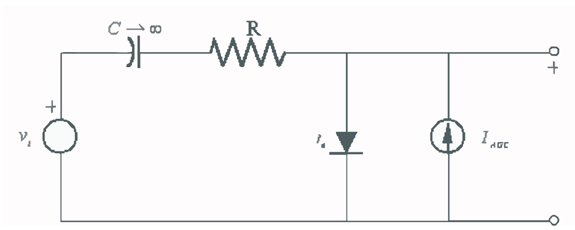

Figure 5: The circuit of a simple AGC

b. Cross Correlation [24]

Cross correlation indicates the similarity between two signals as a function of time shift (τ). The most useful application for the cross correlation function is to determine time delays between signals. Let $a(t)$ and $b(t)$ be two signals; the cross correlation function in time shift $R_{ab}(\tau)$ is defined as [24]

$$R_{ab}(\tau) = \int_{-\infty}^{\infty} a(t)\, b(t+\tau)\, d\tau \tag{8}$$

This gives a measurement of the extent to which two signals, $a(t)$ and $b(t)$, correlate with each other as a function of the time delay, τ, between them. These signals, $a(t)$ and $b(t)$, can be impulsive signals as encountered in radar and sonar applications. The cross correlation function will indicate delay time and the degree of correlation between $a(t)$ and $b(t)$ even where the reflected signal $b(t)$ is attenuated and/or contains additive noise when the signal $a(t)$ is excited in a propagating field. Thus, the major applications of the cross correlation function are to detect time delay between two signals, and to identify a considered signal from the boundaries reflected. When the wave speed is constant, such as with acoustic signals, the delay time directly represents path lengths; thus, the cross correlation function can be used to determine the relative distance of the various paths by which a signal reaches a particular measurement point. Another application occurs in practice when the considered signal $a(t)$ is launched along the waveguide to the boundary. The cross correlation function will in principle identify the considered signal $a(t)$ from the reflected signal $b(t)$ which contains the contaminating noise.

3 Results and discussion

The research uses the MATLAB software as a tool to simulate the shallow water reverberation in a personal computer. The results of the reverberation simulated with the method of image source at 30 kHz are based on the following assumptions.

1. The boundaries of the sea surface and the sea bottom are parallel to each other as well as the speed of the acoustic wave is constant simplify the shallow water environment.

2. The travel distance of acoustic waves is calculated by the ideal spreading law, $\alpha\, r = 10\ dB$, where α is the volumetric absorption in sea water and r is the limit range.

3. The scattered coefficients of the sea surface are calculated using the Rayleigh criterion of roughness theory. The wind speed is assumed to be a constant, 0.3 m/sec.

4. The sea bottom is a rough plane, and the scattered coefficients of the sea bottom obey the rules of Lambert's law.

5. The parameters of the shallow water environments are shown in Table 1.

Enactment of the shallow water environment	
Speed of the acoustic wave in sea water c_0	1508 m/sec
Density of the sea water ρ_0	1033 kg/m^3
Depth of the shallow water h	22.6 m
Salinity of the sea water S	35 ppt
Temperature of the sea water T	15 ?C
Speed of the acoustic wave in sea-floor c_1	1689 m/sec
Density of the sea-floor ρ_1	2066 Kg/m^3
Wind-speed W	0.3 m/sec
Source	
Depth of the source	10 m
Length of the array	0.1 m
duration of the CW	0.1 sec
duration of the pulse	0.0012375 sec

Table 1: Enactment of the shallow water environment and the source.

According to the basic theory of image source and previous assumptions, the signal of reverberation in shallow water could be simulated and shown in Figures 6 and 7. Figure 6 plots the profile of sound pressure as a function of received time, which is simulated by the model of image source with a pulse transmission. In this figure, the attenuation of received acoustic pressure decays exponentially by the distance traveled. Similarly, Figure 7 shows the profile of pressure as a function of received time, which is simulated by the model of image source with a CW (continuous wave) transmission. In the figure, the received pressures also decay by the distance traveled. However, there are some additional wave packets in the

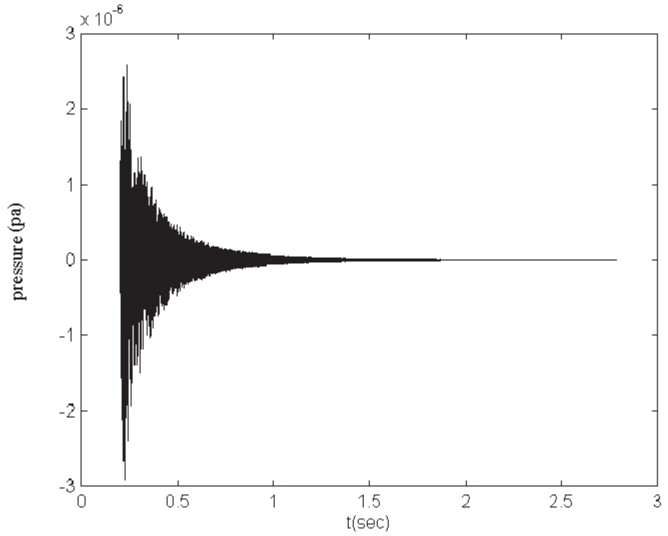

Figure 6: Signal of reverberation which is simulated by the model of image source with a pulse transmission.

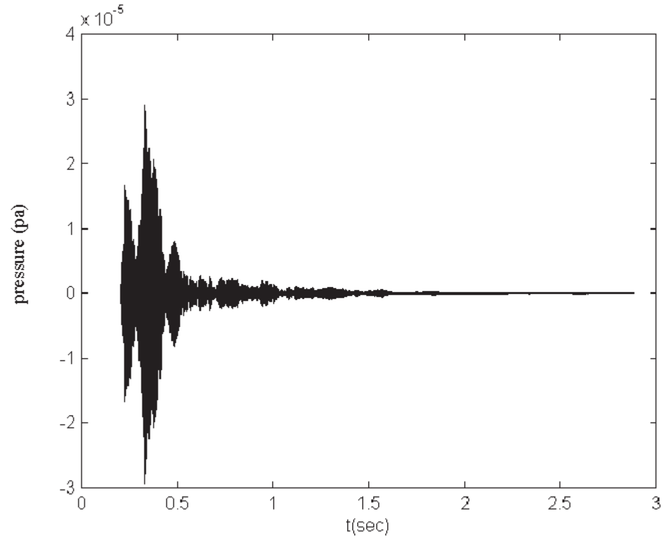

Figure 7: Signal of reverberation which is simulated by the model of image source with a CW transmission.

received time domain, since the reverberation signals are reflected from various boundaries.

A. The signal of reverberation that includes the echoes of the target

Figure 4 plots only the echo of the target while Figure 7 shows the signal of reverberation simulated by the image source with a CW transmission. We combine with the profile of the target's echo (see Figure 4) and unwanted reverberation (see Figure 7) as the characteristic of the signals in a shallow water environment. Thus, the total modeled reverberation will consist of the sum of target echo and environmental reverberation in the study. The profile of the acoustic pressure as a function of received time can be obtained (see Figures 8 to 10). In these figures, the distance between the target and the source in each figure is 600 m, 750 m, and 900 m, respectively. When a target is near the active sonar, the influence of reverberation by the target echo is great. Hence, a distance between 500 m to 1000 m is used to simulate the signals that include the reverberation and the target. The received acoustic pressure is low as the trace distance becomes longer. When the target is 1000 m away from the source, the received echo will arrive after 1.33 sec. When the distance of the target is located 600 m away from the source, the received echo will arrive after 0.8 sec as marked by an arrow in figure 8. Similarly, when the distances of the target are at 750 m and 900 m away from the source, the echo will arrive after 1.0 sec and 1.2 sec as marked by an arrow in Figures 9 and 10, respectively. In the three figures, the target echoes have relatively low pressure in comparison with the reverberation signal.

B. The signal compression

In the model that combines the multi-path propagation and the image source, the reverberation signal and the echo of the target will lie within a larger dynamic range. In this research, a signal compression method is adapted to compress the signal to a specific dynamic range. Figure 11 is a figure of the AGC control line. The horizontal axis represents the time series (in sec), and the vertical axis corresponds to the compressed rate. The control line is developed by the average pressure of reverberation from the pulse transmission. Figures 12 to 14 are the result that the original signals (Figures 8 to 10) are compressed by the control line of AGC plotted

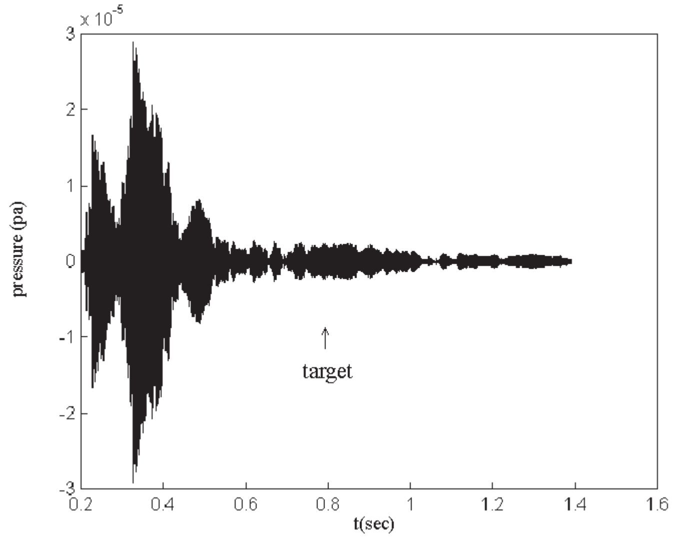

Figure 8: Signals of the reverberation and the target. The target is 600 m away from the source.

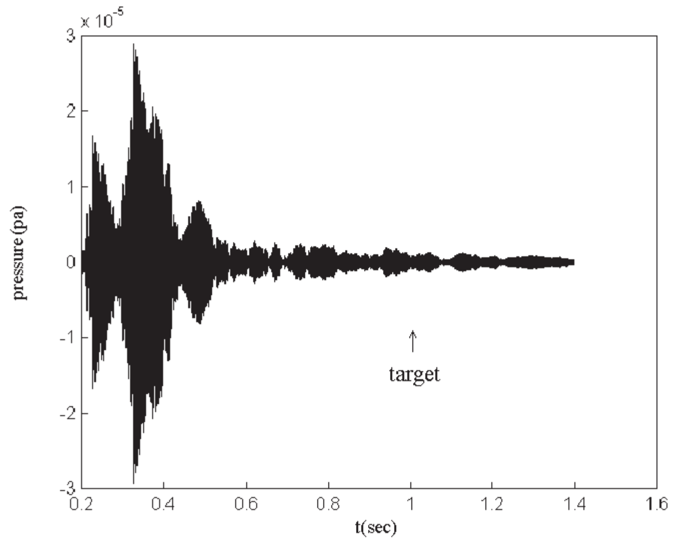

Figure 9: Signals of the reverberation and the target. The target is 750 m away from the source.

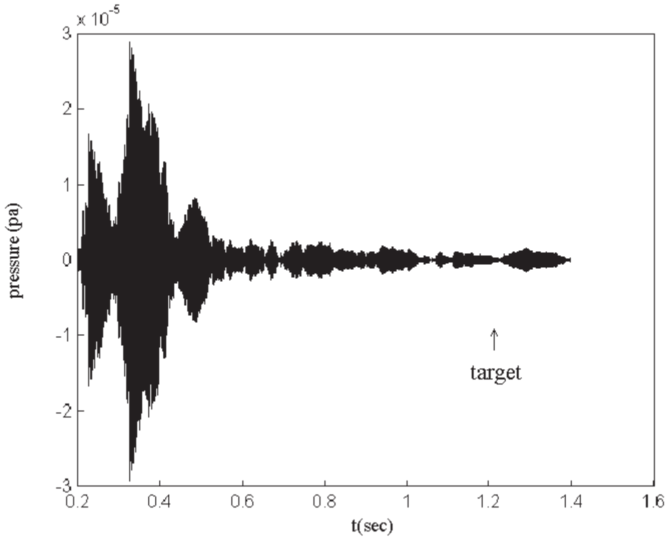

Figure 10: Signals of the reverberation and the target. The target is 900 m away from the source.

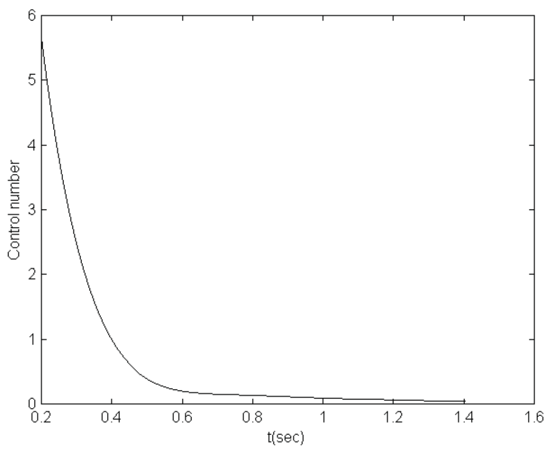

Figure 11: Control line of the AGC.

in Figure 11. Hence, the echo will be also received at 0.8 sec, 1.0 sec and 1.2 sec later in Figures 12, 13 and 14, respectively. It is shown that the signals are compressed to a specific dynamic range in these figures.

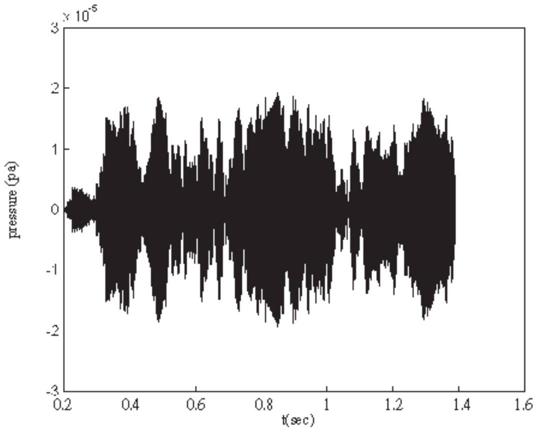

Figure 12: Signals that include the reverberation and the target at 600 m are processed with AGC.

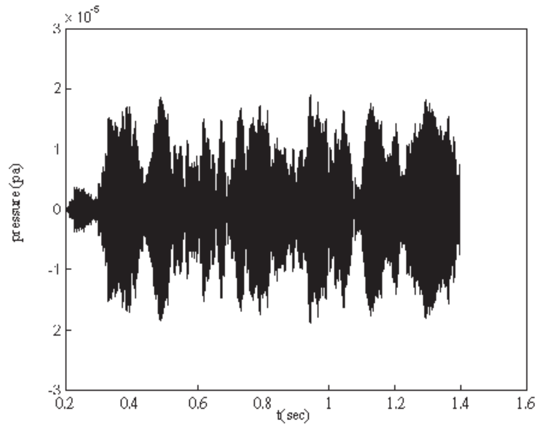

Figure 13: Signals that include the reverberation and the target at 750 m are processed with AGC.

C. Modified AGC technique

In general, the use of the AGC will encounter a problem related to the fact that the control line is not smooth. Consequently, the signal compression will make the dynamic range larger. One method to mitigate this problem involves increasing the point number of the control line. However this also makes the calculation more complex and time-consuming. To offer

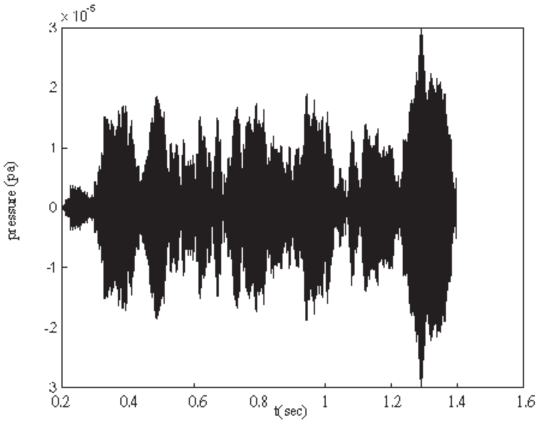

Figure 14: Signals that include the reverberation and the target at 900 m are processed with AGC.

a more comfortable method to compress the signals in a specific dynamic range, an attempt may be adapted to transform the sound pressure into sound energy by the following equation [1-2].

$$E = 10 \cdot \log(P^2/P_{ref}^2) \quad (dB) \tag{9}$$

Where E is the sound energy level, $P$is the sound pressure, and P_{ref} is the reference sound pressure. Shown in figure 15 is the energy of the reverberation with the pulse source listed in Table 1, where the horizontal axis represents the received time and the vertical axis represents the energy. It is found in figure 15 that the maximum energy profile of the considered time interval is almost normalized as the constant energy. Therefore, the larger dynamic range are improved upon through this energy method. After obtaining the curve of the maximum sound energy, the sound energy (Equation 9) can be inverted to obtain the sound pressure as follows:

$$P = P_{ref} \cdot 10^{(\frac{E}{20})} \quad (Pa)(10) \tag{10}$$

Using the calculation of Eq. (10), one can compress the signal of reverberation. Figure 16 is the acoustic pressure of the reverberation versus the received time for the CW source listed in Table 1, where the curve in the figure is transformed from sound energy based on Eq. (10). Signals of reverberation are compressed by the modified AGC control line. The

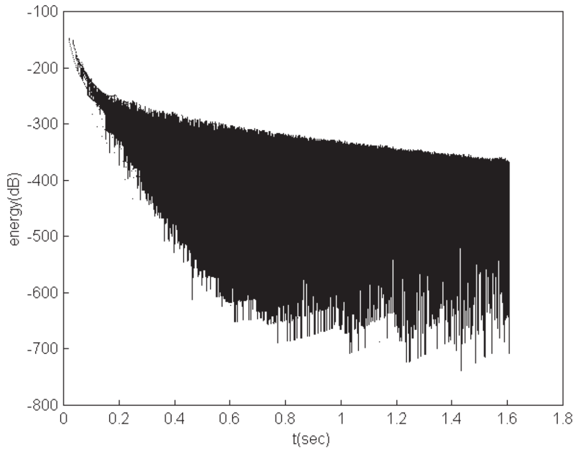

Figure 15: Energy of the reverberation with a pulse source.

results are shown in Figure 17. It is evident that the signal is compressed to a specific dynamic range.

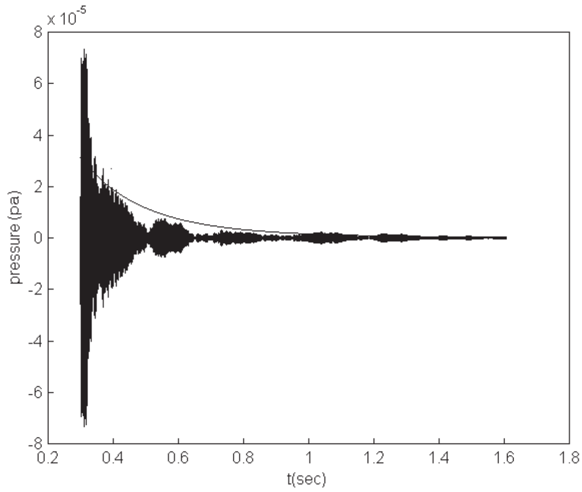

Figure 16: Sound pressure of the reverberation is shown in a CW source,where the control line is transformed from the curve of the sound energy.

D. Cross correlation

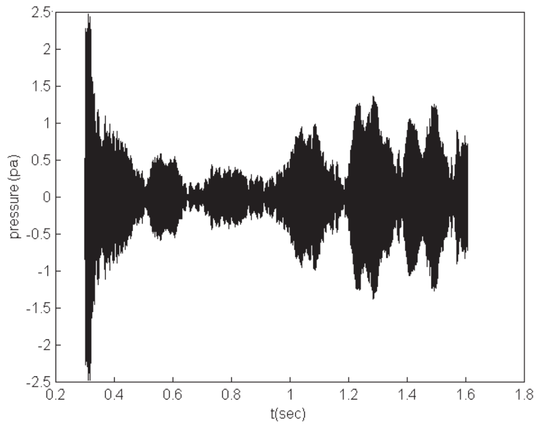

Figure 17: Signal of the reverberation that the original signal is compressed by the control line shown in figure 16.

Figures 18 to 20 show that the original signal is processed with modified AGC and cross correlation with source. These figures plot the cross correlation of the signals, in Figures 8 to 10, and a single period of the source wave as a function of received time. In these figures, the amplitude of the maximum peak indicates the location of the echo of the target, but the time of the largest echo shifts to 0.1 sec. The reason for the time shift is due to the duration of the source.

4 Conclusion

We construct a model to describe the signals of reverberation and target. They are based on the propagation theory of image source, bottom and surface scattering of Lambert's Law, and multi-path reflections. A technique of the modified AGC is adapted to compress the signal in a specific dynamic range. Then a tryout for signal processing technique, called cross correlation, is used to locate and distinguish the echoes of the target. The conclusions obtained in this research can be summarized as follows:

1. Signal compression: AGC can compress the signals to a specific dynamic range, but the computation process is very complex and time-consuming. However, using the control line of modified AGC based on the energy domain is simpler and time-saving in the paper.

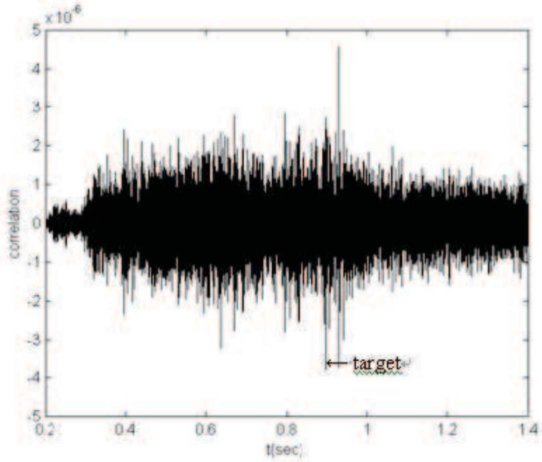

Figure 18: Signal that include the reverberation and the target at 600 m is processed with modified AGC and cross correlation.

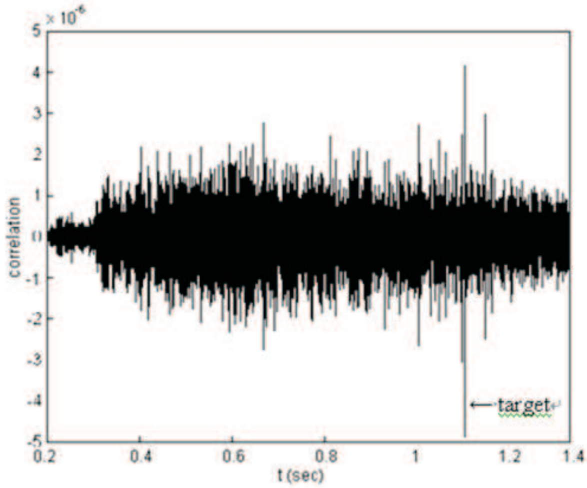

Figure 19: Signal that include the reverberation and the target at 750 m is processed with modified AGC and cross correlation.

2. Cross correlation: The signals of the target located at different distances are processed by modified AGC and cross correlation. When the target is near the sonar, 600 m, 750 m, and 1000 m, the result of identification is obvious. However, the simulation also finds

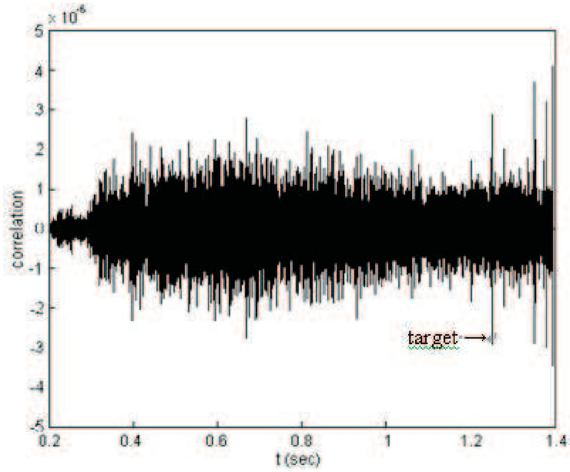

Figure 20: Signal that include the reverberation and the target at 900 m is processed with modified AGC and cross correlation.

the phenomenon of time shift that is caused by the duration of the source.

3. In the model of image source, the signals that include the reverberation and target echoes are processed by the signal compression of AGC and cross correlation. This method is suitable to locate the target and identify the target echoes.

Acknowledgments

This research is supported by the National Science Council (NSC), ROC, under the grant No. NSC88-2623-D-110-002.

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Submitted on May 2007.

Studija reverberacije i njeno poništenje u plitkoj vodi

Za performanse aktivnog sonara u plitkoj vodi prevashodno ograničenje je reverberacija koja potiče od raspršivanja po zapremini i granicama kao i prostiranje po višetrukim putevima. Zbog toga je poništenje reverberacije značajan istraživački zadatak. Ovde je mreža reverberacije simulirana softverom MATLAB. Simulirana učestanost je $30[kHz]$. Postavljena su dva osnovna cilja.

(1) Prvi je stvaranje signala koji uključuju reverberaciju i metu.

(2) Drugi je poništenje reverberacije za aktivni sonar u plitkoj vodi. Analiza reverberacije za sfernu metu se zasniva na teoriji prostiranja izvorne slike, površinskog raspršivanja Rejlijevog kriterijuma hrapavosti, donjeg raspršivanja Lambertovog zakona i višestrukog raspršivanja. Signal koji sadrži reverberaciju i metu je zatim sabijen i poboljšan pomoću AGC (automatske kontrole postizanja). Eho mete se tada izdvaja metodom unakrsne korelacije. Sledeće pojave mogu se naći:

(a) AGC može da sabije signal u posebni dinamički opseg i

(b) unakrsna korelacija može da se koristi za odredjivanje položaja i razlikovanje ehoa meta u okolini visoke reverberacije.

doi:10.2298/TAM0703173Y Math.Subj.Class.: 76B15, 62H35