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Analysis of the Detectability of Sonar Under the Virtual Battlefield

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Abstract: Due to the high propagation speed and the low attenuation in the water, the sonar has played a crucial role in developing the ocean resources and the marine target detection. Therefore, simulation of the sonar detectability is indispensable to the virtual battlefield. This paper will combine the background noise model of the ocean, the reverberation model, the target strength model and the transmission loss to build the sonar performance model, and realize the calculation of the sonar detectability. Ultimately, the parameters' effect in the sonar equation on the performance of the sonar detection is analyzed, and the validity of this model is verified by two serving sonars parameters. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Virtual battlefield, Sonar detectability, Background noise, Sonar equation, Model and simulation.

1. Introduction

After the 1990s, as the rapid development of virtual simulation and computer technology, the virtual reality technology has entered a rapid development period. The virtual battlefield is a successful case of virtual reality technology in the military field and it is also the development trend of the modern military technology. The virtual battlefield technology can break through some constraints of the military training, and plays an important role in the tactical exercises, the system demonstration, the military training and so on.

The acoustic warfare is an important method to the modern underwater warfare. In recent years, with the enlargement of the underwater target threat, more and more countries have begun to apply the virtual battlefield technology into the underwater acoustic confrontation [1]. For example, German has developed an anti-mine warfare simulation system called ATCM [2]. And British has studied a system named TDSmos to evaluate the acoustic countermeasures [3]. Tsinghua University in China has established an underwater acoustic countermeasure optimization model [4]. Southeast University in China has studied how to assess the performance of the underwater acoustic awarding system [5]. But the simulation of the sonar, which is one of the most important underwater weapons, is rarely reported. Therefore, this paper will build the sonar performance model based on the ocean background noise model, the reverberation model, the target model and the propagation model. Finally two kinds of serving sonar parameters are used to verify the validity of the model.

2. Sonar Environmental Noise

The environmental factors which affect the sonar performance are mainly divided into two types: the ocean background noise and reverberation. For the former, we will use the Wenz curve to obtain the noise level with the given working frequency, shipping and sea-state. For the latter, we will study three types of reverberation. They are the volume reverberation, the surface and bottom reverberation.

2.1. Ocean Background Noise

The background noise is the noise of the acoustic background, which exists commonly and must be overcome for the active and passive sonar detection. Fig. 1 shows the background noise level with the different shipping and sea state. These curves in Fig. 1 are called Wenz curves.

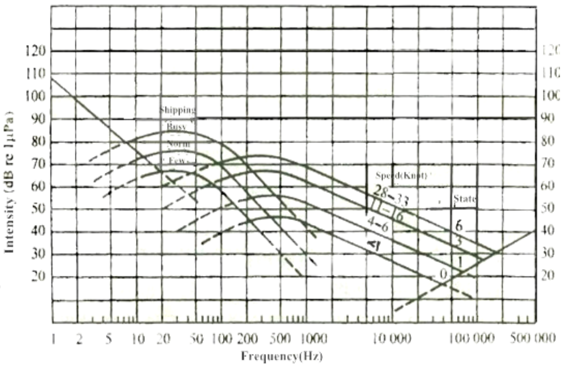


Fig. 1. The average ocean noise level [6].

Can be found from Fig. 1, within the band (20 Hz~1 kHz), the noise source may be more than one. So the operator of the summation of power is defined as:

$$\oplus = 10\lg \sum_{i=1}^{n} 10^{L_i/10}, \tag{1}$$

where L_i is the i^{th} source of noise level (dB), n is the total number of the noise sources considered.

In order to get the noise level with the given condition, we use the method of the piecewise polynomial fitting to fit the Wenz curves. According to the characteristics of the Wenz curves, the frequency range is divided into three parts:

1) When the frequency is less than 20 Hz, the Wenz curves are expressed as:

$$y = 14.29x + 108 \tag{2}$$

2) In the range of 20 Hz to 100 kHz, the noise level can be seen as a quadratic curve:

$$y = a_2 x^2 + a_1 x + a_0, \tag{3}$$

where a_2, a_1, a_0 are the curve binomial fitting coefficients which can be obtained by the typical values read from Fig. 1 and polynomial fitting.

3) When the frequency is more than 100 kHz, the main noise sources are the sea wind and waves, which can be written as a linear expressions:

$$y = 10.09x - 91.25 \tag{4}$$

By the process above, the fitting results are shown in Fig. 2. Comparison with Fig. 1, it illustrates the effectiveness of the method of the background noise fitting.

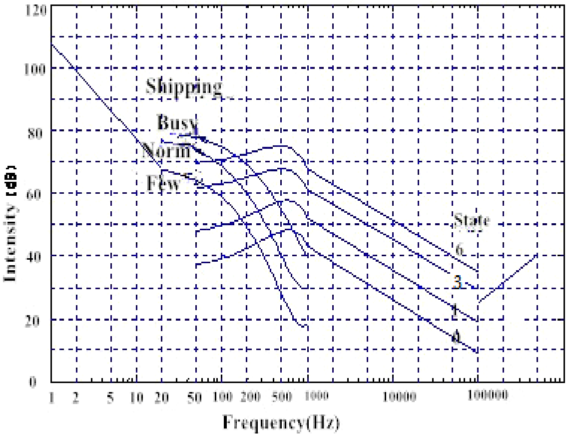


Fig. 2. The fitting results of the Wenz curves.

2.2. Reverberation

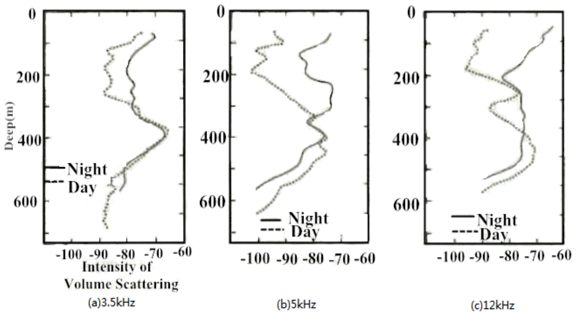
In many instances, the reverberation can be a major component of the environmental noise. The source of the reverberation can be divided into three types. The first one is the volume reverberation, which is reduced by the scatterers distributed in the ocean. The second one is the surface reverberation produced by the scatterers on the ocean surface. The last one is the bottom reverberation derived from the seafloor scatters.

2.2.1. Calculation of the Volume Scattering Intensity

The distribution of volume scatterer is not uniform in the ocean. The scattering intensity changes with the depth, the frequency, location and time. Fig. 3 shows the volume scattering intensity with three typical frequency and the depth. As seen from the figure, the intensity curves change irregularly. So we use curve fitting by means of spline interpolation within the same frequency. And a linear interpolation processing is applied to get the intensity with given frequency by the three typical frequency (3.5 kHz, 5 kHz and 12 kHz).

2.2.2. Calculation of the Surface Scattering Intensity

Surface roughness and the bubble make the surface be an effective and complex scatterer. The surface scattering intensity changes with the grazing angle, the frequency and the surface roughness. The surface roughness is usually related with the sea wind or waves. When the frequency is low and the grazing angle is small, the scattering intensity changes a lot with the frequency. While in the high frequency and large grazing angle, the scattering intensity changes little with the frequency.



(a)3.5kHz (b)5kHz (c)12kHz

Fig. 3. Volume scattering intensity with three frequencies [7].

Chapman - Harris did a series of measurements, and got a empirical formula:

$$S_S = 3.3\beta\lg\frac{\theta}{30} - 42.2\lg\beta + 2.6,\qquad \beta = 158\left[v f^{1/3}\right]^{-0.58}, \tag{5}$$

Here S_s is the surface scattering intensity (dB), θ is the grazing Angle (degrees), v is the wind speed (knots), f is the frequency (Hz). This empirical formula is appropriate for the frequency band 1 to 10 kHz.

For the higher frequency, the perturbation theory can be used to express the scattering intensity. And the expression is:

$$S_{pert} = 10\lg[1.61\times10^{-4}\tan^4\theta\exp(-\frac{1.01\times10^6}{f^2v^4\cos^2\theta})] \tag{6}$$

where v is the wind speed (m/s) and the other parameters are same with Eq. (5).

However, when the frequency is 10 kHz, the values calculated by Eq. (5) and (6) are different. So we set 8~12 kHz as a transition band for compromise with the two equations. In the transition band, a linear processing is used. The surface scattering intensity with the transition band is shown in Fig. 4.

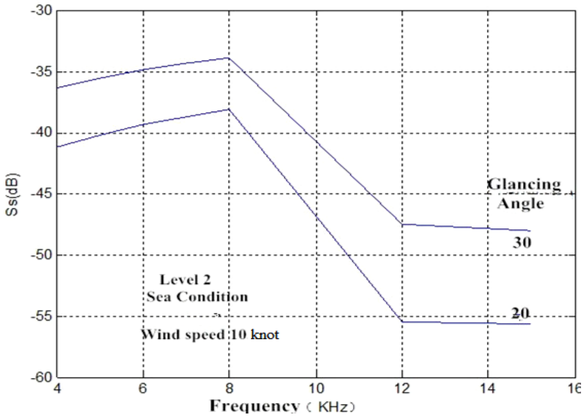


Fig. 4. The surface scattering intensity curve with a transition band.

2.2.3. Calculation of the Seafloor Scattering Intensity

The floor of the sea, like the sea surface, is also the sound emitter and scatterer. When the grazing angle is less than 45°, the Lambert's law is a good approximation to the observation data. Then the seafloor scattering intensity is:

$$S_b = 10\lg\mu + 10\lg\sin^2\theta \tag{7}$$

where S_b is the seafloor scattering intensity (dB), μ is the seafloor scattering constant, μ=$10^{-2.7}$. θ is the grazing angle. Then the seafloor scattering intensity with θ is shown in Fig. 5.

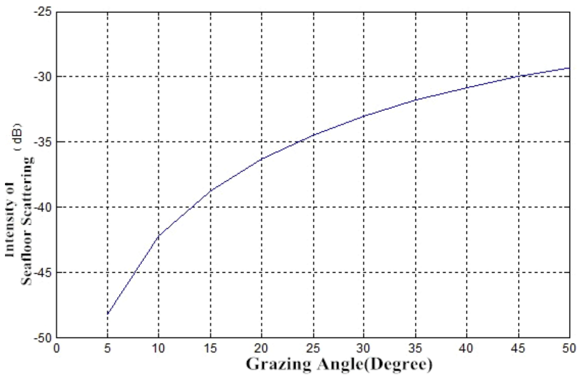


Fig. 5. The scattering intensity of the seafloor.

Usually, the seafloor scattering intensity is bigger than the surface scattering intensity, so when the sonar beam intersects with the seabed, the bottom reverberation is the main background of target detection and recognition.

3. Models of Target Strength

3.1. Strength of Marine Mine

The mine is often regarded as a sphere or a cylinder with a hemispheric end, then the strength is:

$$T_S = 10\lg\left[\frac{aL^2}{2\lambda}\left(\frac{\sin x}{x}\right)^2 \cos^2\theta\right] \tag{8}$$

where a is the radius, L is the length and

$$x = \frac{2\pi L}{\lambda}\sin\theta \tag{9}$$

When the beam is perpendicular to the cylinder axis, the target strength can be simplified as:

$$T_S = 10\lg\left(\frac{aL^2}{2\lambda}\right) \tag{10}$$

Assume the mine is a 2 m long cylinder with a hemispheric end and the radius of sphere is 0.15 m. Let the wavelength of sound waves λ=0.15 m. Then T_S=3 dB when the beam is perpendicular to the cylinder axis, and T_S=-22.5 dB when the end of mine is detected.

3.2. Strength of Torpedo

The torpedo is basically a cylinder with a flat or arc head. Let the length of torpedo is 5 m and the diameter is 0.5 m. When the acoustic frequency is 10 kHz, the target strength of torpedo body is 13 dB, and target intensity of the head is -18 dB.

Therefore, the strength changes a lot with the grazing angle. And the strength of torpedo is not less than -18 dB.

3.3. Strength of Submarine

In the sonar system simulation, the strength of submarine is listed in Table 1.

Table 1. The strength of submarine.

Component of Target	**T_S (dB)**		
	Small boats	**Large boats with paint**	**Large boats**
Transverse	5	10	25
Head or Tail	0	5	10
Average Value	3	8	15

From Table 1, the target strength is not only related to the type and size of the target, but also in connection with the target moving direction. To get the target strength, which component of target is scattered should be determined. But sometimes for simplification, the average value is taken as the approximation of the target intensity.

4. Transmission Loss

The transmission loss is one of the most important factors in simulation of the sonar performance. We can obtain the value in two ways. One is based on the simple model, which can calculate the loss but can't tell the propagation of the sound wave. The other is based on the wave equation, which can describe the propagation path but is with massive calculation. Which way is adopted depends on the application condition. In this section, two ways will be discussed.

4.1. Simple Calculation of Transmission Loss

In the propagation of the sound wave, the transmission loss between the sound source and the receiver can be written as:

$$P_L = 10\lg\left(\frac{I_o}{I_r}\right)(\mathrm{dB}), \tag{11}$$

where I_o is the sound intensity at one-meter distance from the center of the sound source, I_r is the sound intensity at the receiver.

The transmission loss includes the spreading loss and the absorption loss. For the spreading loss, the total sound power of any sphere around the sound source is constant. And it is equal to the total power P, which can be expressed as:

$$P = 4\pi r_1^2 I_1 = 4\pi r_2^2 I_2 = \ldots\ldots\ldots.4\pi r^2 I_r \tag{12}$$

For the absorption loss, the absorption index a is used to represent the total absorption loss, which is listed in Table 2.

Table 2. The absorption coefficient with the sound frequency.

Frequency (kHz)	**0.5**	**1**	**2**	**5**	**10**
***a* (dB/km)**	0.02	0.06	0.14	0.33	1.00
Frequency (kHz)	**20**	**50**	**100**	**200**	**500**
***a* (dB/km)**	3.80	15	30	35	120

So the transmission loss can be regarded as the sum of the spreading loss and absorption loss.

$$P_L = 20\lg r + ar \times 10^{-3} \tag{13}$$

To get the sonar detection distance, we must solve the above transcendental equation. And the dichotomy is often used to solve this problem.

4.2. Accurate Calculation of Transmission Loss

To calculate the propagation path accurately, it is necessary to solve the wave equation. There are three models to solve this equation, ray model, normal model and parabolic model. Which model is adopted depends on the sonar frequency and the location of the sonar and the target. Lack of space, we only give the simulation results with the ray model as an example. The ray model is suitable to the condition with high frequency and deep depth.

The simulation parameters are: the depth of sea is 5000 m, the depth of source is 3500 m, the depth of receiver is 2000 m, the horizontal distance is 30 km, the launch grazing Angle is from -14° to 14° and the frequencies are 50 Hz and 1 kHz. Results are shown in Fig. 6 and Fig. 7.

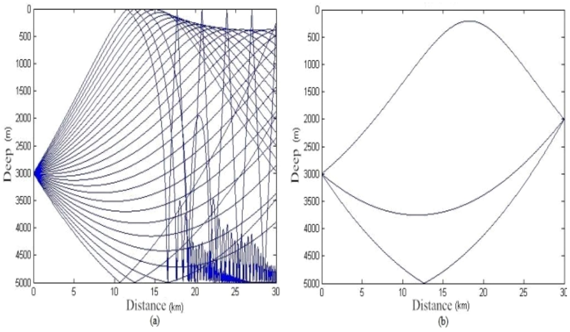


Fig. 6. (a)The sound ray diagram,
(b) The eigenray at 3000 m.

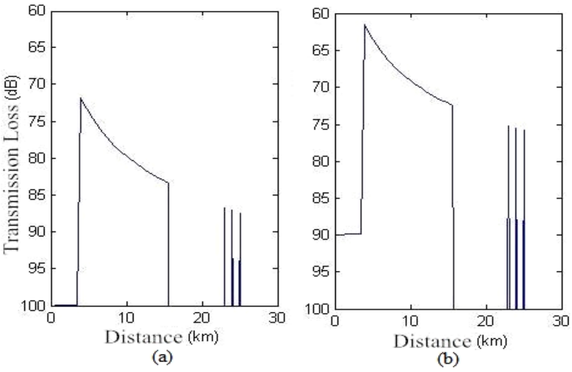


Fig. 7. (a)Transmission loss of 50 Hz, (b) Loss of 1 kHz.

5. Sonar Equation

According to the sonar working mode, the sonar equation can be divided into the passive sonar equation and the active sonar equation. And the active sonar equation is divided into the background noise equation and the reverberation equation according to the dominant environmental factor.

5.1. Passive Sonar Equation

For the passive sonar, it mainly detects the signal scattered by the target. So the equation is

$$S_E = (S_L - P_L) - N = D_T \tag{14}$$

where S_E is the receiving power, S_L refers to the source level, P_L is the transmission loss, and N is the background noise. D_T is the detection threshold, which is determined by the false-alarm probability and detection probability. As the source radiates without directivity, S_L is regarded as the intensity with one-meter distance from the sound source. The spherical area with one meter radius is 12.6 m^2. If the nondirectional power is P, then

$$S_L = 10\lg\left(\frac{P/12.6}{0.67\times10^{-18}}\right) = 10\lg P + 170.8 \tag{15}$$

If the sound source is directive, then

$$S_L = 10\lg P + 170.8 + G_t\,, \tag{16}$$

where G_t is the transmitting antenna gain in the direction of the sonar receiver.

5.2. Active Sonar Equation

Active sonar equation has two forms: one is used to determine the performance with the background noise, another is used to study the performance with the reverberation background. Although there are some equations used to estimate the performance with the two background factors, it is beneficial to consider the two factors respectively, because such doing can better understand the effects of the device parameters and the environment conditions.

The sonar equation under the noise background is:

$$S_E = S_L + T_S - 2P_L - (N + 10\lg B) - D_T\,, \tag{17}$$

where B is the band of the receiver.

The equation with the reverberation background is:

$$S_E = S_L + T_S - 2P_L - (S_L - 2P_{LR} + T_{SR}) - D_T\,, \tag{18}$$

where P_{LR} is the transmission loss between the reverberation and the receiver. T_{SR} is the intensity of the reverberation.

6. Analysis of Sonar Detectability

Analysis of the detectability is the problem to solve the detection distance. First of all, the type of the sonar must be determined. Then we should understand the environmental characteristics. According to the appropriate sonar equation, the environmental parameters, target parameters and working parameters, the detection range is calculated. The process is shown in Fig. 8.

When the sonar is with a given transmission power and f =10 kHz, the relationship between the detection distance and the target intensity is shown in Fig. 9. In the figure, the results under three conditions, the noise background, the reverberation background with S_b=-30 dB and S_b=-40 dB, are given. By comparison, we find that the detection distance is not sensitive to the change of target strength under the noise background. While the target strength changes, the detection distance in reverberation varies greatly.

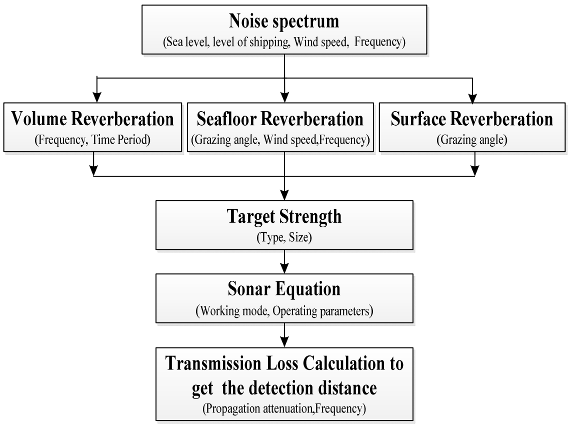


Fig. 8. Analysis of Sonar performance.

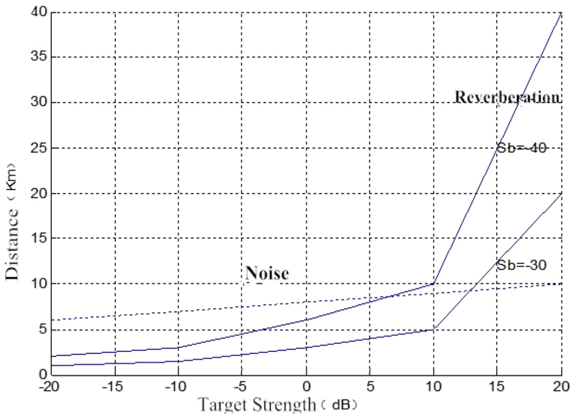


Fig. 9. Sonar detection distance with target intensity.

At the same time, in order to verify the correctness of the sonar detectability model, the parameters of two sonars are used to calculate its detectability.

Case 1: the American passive towed line array sonar AN/SQR-19. The working frequency of the sonar receiver is 10 Hz~2 kHz, and it can work under the sea state 4. We assume the working frequency is 10 Hz, the source level is 160 dB, G_t=30 dB, D_T=16 dB. These parameters are taken into Equation (16), and result of the detection distance is 113 km. It is reported that this sonar detection range is 70 nmile, about 129 km. The calculation result is similar with the actual one.

Case 2: the Canada sonar AN/SQA-505. Its working frequency is 7 kHz, the detection distance is 32 km, the transmitting power ranges from 1 w to 40 kW, the directivity index is 15 dB. By the detectability model, when the sea state is 0 and the transmitting power is 20 kW, the sonar can detect the target with the intensity 15 dB at 32 km. Therefore, some working parameters can be speculated by the model mentioned in this paper.

7. Conclusions

In this paper, the sonar detect ability model is analyzed from the environmental model, the target intensity model, the transmission loss and the sonar equation. Firstly, in the environmental model, we use the piecewise fitting and spline interpolation to realize the background noise and reverberation model. Secondly, three types of the targets intensity are given. Thirdly, the simple and accurate calculation of the transmission loss is studied respectively. Then three kinds of sonar equation are discussed. Finally, using the parameters of two kinds of the serving sonar, the effectiveness of the detection model proposed is verified.

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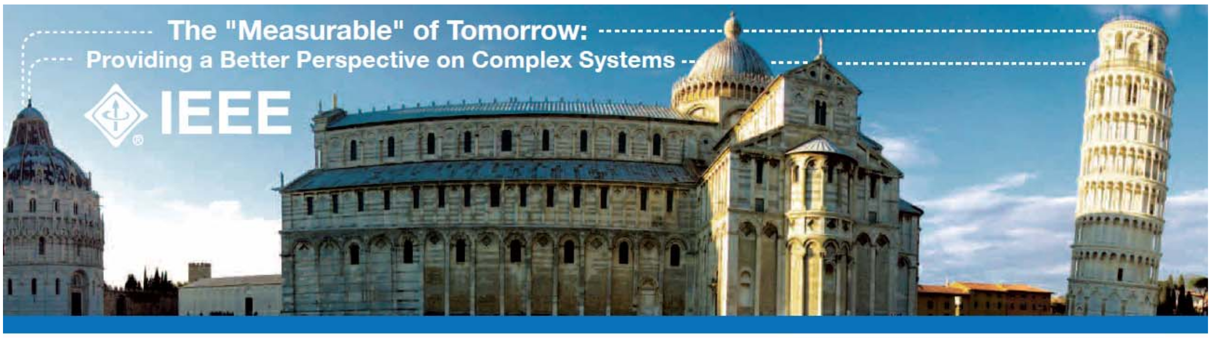

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