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Application Analysis of Similarity Principle in the Design of the Underwater Receiving Antenna

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Abstract—To reduce the cost and blindness of antenna design, the application of electromagnetic field similarity principle in the working environment of the underwater receiving antenna was studied and verified. The field distribution and electrical parameters of the underwater receiving antenna and its reduced-scale model were calculated and proved to be following the similarity principle. The simulation analysis of the receiving antenna and its reduced-scale model for receiving the airborne electromagnetic wave signal in the seawater shows that the underwater receiving antennas before and after the scale-down are similar. The simulation is verified by measuring the receiving signal amplitude of the underwater receiving antenna and its reduced-scale model. The results of theoretical derivation and simulation analysis show that the electromagnetic field similarity principle can be applied to the underwater receiving antenna system.

1. INTRODUCTION

Underwater receiving antenna is mainly responsible for the radio communication task of the underwater vehicle in the deep submergence state [1]. Because of the high cost and risk of the underwater antenna test, we hope to take various methods to reduce the risk and blindness of the test before the test. It is a method to test the performance of the underwater antenna by using a scale model similar to the original system, but whether the method is feasible needs to be verified and analyzed. The principle of electromagnetic field similarity is usually applied to the opening problems such as radiation or scattering, and its derivation is based on the passive problem [2]. Because seawater is a good conductor, it remains to be seen whether the same principle applies to underwater antennas that pick up airborne signals in seawater.

When the antenna is submerged in seawater, the received electromagnetic wave needs to span two media, air and seawater. At present, there is no published literature to introduce the antenna reduced-scale model of receiving electromagnetic waves from the air in seawater.

To illustrate the applicability of the similarity principle in the underwater antenna system, it is demonstrated from three aspects of theoretical derivation, simulation analysis, and experimental verification to prove the consistency between the performance of the underwater antenna and its reduced-scale model.

2. THEORETICAL DERIVATION

Firstly, the feasibility of the application of the similarity principle in the design of the underwater receiving antenna is illustrated from three aspects: the distribution of electromagnetic field, electromagnetic wave propagation across the air to seawater interface, and the analysis of antenna parameters.

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2.1. Electromagnetic Distributions

The similarity principle is a theory to ensure that the model experiment is similar to the real phenomenon, and to obtain the properties of the object according to the experimental results [2]. Electrical characteristics are the inherent properties of the antenna system and electromagnetic field, which are not affected by the coordinate system and unit system [3]. The reduced-scale model is similar to the field force line structure of the actual antenna system, and their electrical parameters maintain a certain proportion relationship [4].

Let the coordinates of any observation point in the antenna system be $p(x, y, z)$. In Equations (1), (2), and (3), m, γ, α, β are respectively the scaling factors describing the physical quantities of space, time, electric field, and magnetic field of the scale model system and the actual antenna system.

$$x = mx', \quad y = my', \quad z = mz', \quad t = \gamma t' \tag{1}$$

$$E(x, y, z, t) = \alpha E'(x', y', z', t') \tag{2}$$

$$H(x, y, z, t) = \beta H'(x', y', z', t') \tag{3}$$

The field distribution in the target scale model is the same as that in the original system, that is to say, the scale factor describing the electric and magnetic fields is 1:

$$\alpha = \beta = 1 \tag{4}$$

Equations (5), (6), and (7) are the conversion relations between the scaled model system and the dielectric permeability, dielectric constant, and conductivity in the actual antenna system [3].

$$\mu'\left(x', y', z'\right) = \frac{m}{\gamma}\mu(x, y, z) \tag{5}$$

$$\varepsilon'\left(x', y', z'\right) = \frac{m}{\gamma}\varepsilon(x, y, z) \tag{6}$$

$$\delta'\left(x', y', z'\right) = m\delta(x, y, z) \tag{7}$$

Since the permeability of most natural media is the same as that of free space, the coefficient value in Equation (5) should be 1 [5]:

$$\frac{m}{\gamma} = 1 \tag{8}$$

Seawater is a kind of good conductor, which can be used as a representative of the study of the general loss medium. Equation (9) is the Debye formula for calculating the dielectric constant of saltwater [6]. T is the temperature, and X is the concentration of saltwater. In the range of room temperature, the dielectric constant of brine is little affected by the concentration

$$\begin{aligned}\varepsilon &= (87.137 - 0.1949T - 0.01276T^2 + 0.0002491T^3)\\ &\quad (1 + 1.613 \times 10^{-5}TX - 0.003656X + 3.21 \times 10^{-5}X^2 - 4.232 \times 10^{-7}X^3)\\ &\approx 87.137 - 0.1949T\end{aligned} \tag{9}$$

Formula (9) can verify the correctness of Equation (8) under the premise of keeping the ambient temperature unchanged. It can be seen from Eq. (1) and Eq. (8) that the premise of the constant electromagnetic field distribution in the underwater receiving antenna system and the medium of the reduced-scale model is that the conversion ratio of the physical dimension and the time measurement is the same, and the product of the physical dimension and the frequency remains the same, that is, the electrical dimension remains the same.

By controlling the concentration of brine, a seawater model with conductivity proportional to the original system can be made. The conductivity of the medium in the model is amplified according to the scaling factor of physical size. The conductivity of air is 0. According to Equation (7), the air in the scale model is not scaled. From the calculation of the field distribution, it is feasible to apply the similarity principle in each medium independently.

2.2. Electromagnetic Wave Propagation across the Air to Seawater Interface

The boundary value relation is satisfied when the electromagnetic wave propagates at the interface of any two kinds of media. Therefore, the propagation characteristics of the electromagnetic wave across the water surface in the original system and the scale model system can be deduced. The following figure is the reflection and refraction diagram of electromagnetic wave incident across the medium.

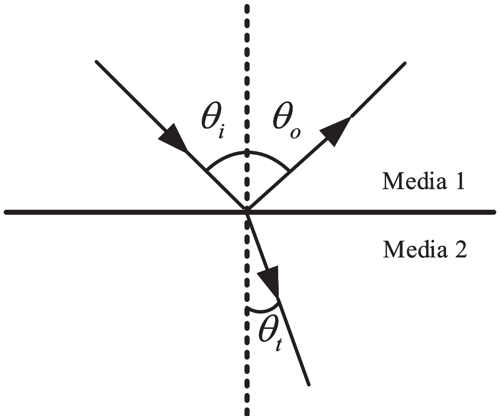

Figure 1. Reflection and refraction of the electromagnetic wave across medium.

According to the law of reflection and refraction of the electromagnetic wave, the angle relations in Figure 1 are as follows:

$$\theta_i = \theta_o \tag{10}$$

$$\omega\sqrt{\mu_1\varepsilon_1}\sin\theta_i = \omega\sqrt{\mu_2\varepsilon_2}\sin\theta_t \tag{11}$$

From Equation (11), the relationship between the incident angle and refraction angle of the electromagnetic wave across the water surface can be deduced as follows:

$$\sin\theta_i = \sqrt{\frac{\varepsilon_1}{\varepsilon_2}}\sin\theta_t \tag{12}$$

In Equation (12), ε_1 and ε_2 are the dielectric constants of air and seawater and their scaled models. Because the seawater and its scale model are good conductors, $|\sqrt{\frac{\varepsilon_1}{\varepsilon_2}}| \gg 1$. It shows that the propagation direction of the electromagnetic wave is the same in the original antenna system and the scaled model system after crossing the dielectric interface. According to Fresnel formula, the energy loss of electromagnetic waves across the interface between the air and good conductor is the same [3]. From propagation direction and energy, the change of propagation characteristics of the electromagnetic wave when it penetrates the water surface in the actual environment is consistent with that in the reduced-scale model.

2.3. Parameter Analysis of Antenna

The physical parameters of a complete underwater receiving antenna system are described, including physical length, frequency, wavelength, permeability, dielectric constant, conductivity, input power, and antenna gain. Equation (7) is the scaling relationship between the scale model system and the conductivity in the original antenna system. The antenna length and electromagnetic wavelength are physical quantities in the sense of space; the frequency is wavelength physical quantities in the sense of time, so from formula (1), we can get:

$$l' = l/m \tag{13}$$

$$f' = \frac{1}{t'} = \frac{m}{t} = mf \tag{14}$$

By substituting Equations (2) and (3) into the calculation formula of the Poynting vector, the relationship between the model and the input power of the antenna in the actual system, power density, and gain in the specified direction is obtained as follows. S represents the unit area in the radiation direction, and r represents the distance from the observation point to the origin of the system:

$$P' = E' \times H' = E \times H = P \tag{15}$$

$$W' = \int_{S'} P' dS' = \frac{\int_S P dS}{m^2} = \frac{W}{m^2} \tag{16}$$

$$G' = \frac{4\pi' \left(r'\right)^2 W'}{P'} = \frac{4\pi(r)^2 W}{P} = G \tag{17}$$

The wavelength of the electromagnetic wave is an important factor affecting the antenna size design. From the Maxwell equations and their auxiliary equations, the formula for calculating the wavelength in any medium can be deduced as follows [7]:

$$\lambda = \frac{2\pi}{\sqrt{\pi f \mu_0 \delta}} \tag{18}$$

By substituting Equations (5), (7), and (14) into Equation (18), Equation (19) is obtained. It is shown that the scaling of physical dimensions in seawater is consistent with the scaling of physical dimensions in the general sense of Equation (13).

$$\lambda' = \lambda / m \tag{19}$$

To sum up, the parameters describing the length, frequency, and gain of the underwater receiving antenna system have a quantitative relationship with the corresponding physical quantities in the reduced-scale model, which satisfies the similarity principle. To explore the influence of approximate value on the result in the derivation process, the simulation software is used to verify whether a similar principle applies to the underwater receiving antenna system.

3. SIMULATION ANALYSIS

To verify the applicability of the similarity principle in the underwater receiving antenna and its scaling model, a typical half-wave dipole antenna is taken as an example before the experiment, and the gain of the antenna and its scaling model is simulated and analyzed from two aspects of frequency and physical length. The central frequency of the receiving antenna is 347.50 MHz, and the working frequency band is 344 MHz $\sim$ 351 MHz. Formula (20) is the calculation formula of antenna length, electromagnetic frequency, and light speed in free space.

$$l = c/f \tag{20}$$

According to Equation (20), the design length of the antenna is 4 cm, and the conductivity of seawater is 4 S/M. If the scaling factor is 4; the length of the antenna scaling model is 1 cm; the center frequency is 1.39 GHz; and the conductivity of the scaled brine is 16 S/m. The position of the antenna in the coordinate system is shown in Figure 2. The XOZ plane pattern and YOZ plane pattern of the underwater receiving antenna and its scale model at 8 cm underwater are simulated and compared. XOZ plane pattern and YOZ plane pattern can describe the electromagnetic wave receiving ability of the antenna at the angle above the horizontal plane [9]. Theta is the inclination of Z-axis positive direction to X-axis positive direction; phi is the inclination of X-axis positive direction to Y-axis positive direction; a represents the underwater receiving antenna; b represents the scale model of the antenna.

The pattern curves in Figure 3 and Figure 4 show that the simulation results and the scale model of the receiving antenna pattern at 8 cm underwater can be compared, which shows that the receiving antenna system in seawater meets a similar principle to its scale model. Table 1 shows the simulation results of the maximum gain of the antenna and the scaling model at different corresponding depths. The results show that the gain variation trend of the receiving antenna is the same as that of the scaling model, and the gain difference between the receiving antenna and the corresponding depth scaling model is stable.

According to the corresponding relationship between the underwater receiving antenna and the scaled model, eight frequency points were selected to calculate the frequency point in the frequency

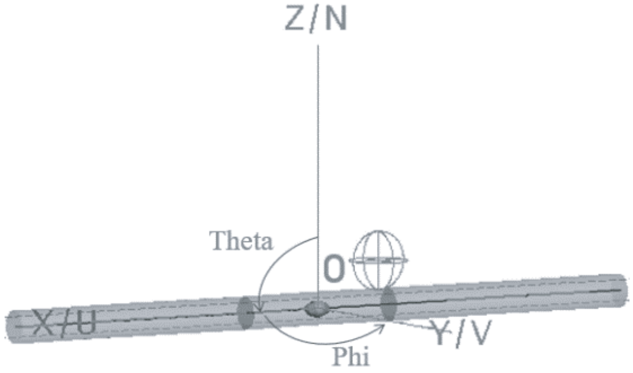

Figure 2. Position of the antenna in the coordinate system.

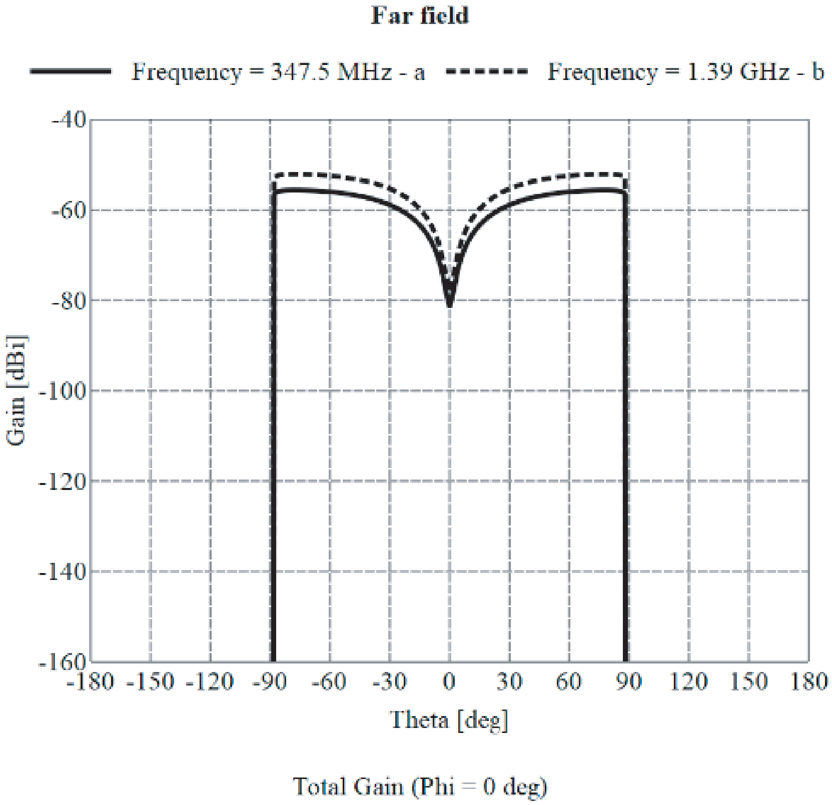

Figure 3. The XOZ plane pattern of receiving antenna and its scale model at corresponding depth underwater.

Table 1. Simulation results of the maximum gain of the electromagnetic wave of the central frequency received by the half-wave dipole antenna and the scaled model at different corresponding depths.

Underwater receiving antenna		Scale model	
Depth (cm)	Gain (dBi)	Depth (cm)	Gain (dBi)
−4	−53.3	−1	−49.7
−8	−55.6	−2	−52.0
−16	−60.4	−4	−56.8

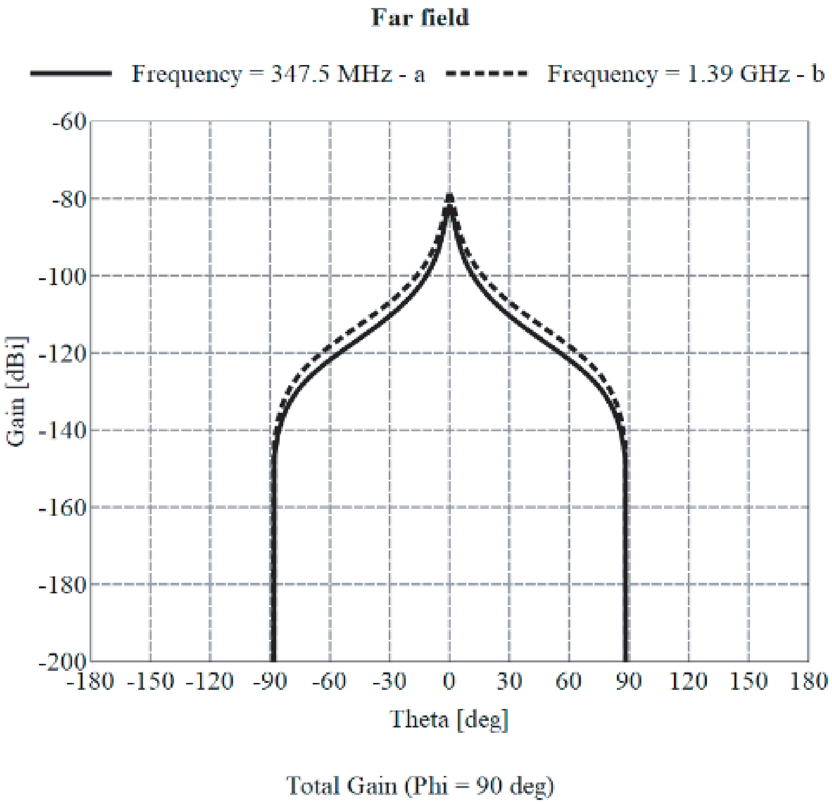

Figure 4. The YOZ plane pattern of the receiving antenna and its scale model at the corresponding depth underwater.

band of this type of receiving antenna. The maximum gain of the simulated antenna prototype was obtained at the depth of 4 cm by stepping at 1 MHz. The scaling model is the eight frequency points of the corresponding proportion, and the step is 4 MHz. The simulation gain is 1 cm underwater. The results in Table 2 show that the changing the relationship between frequency and gain of the receiving antenna at 4 cm underwater and the corresponding relationship between frequency and gain in the scaling model is the same, with a small difference in value.

To sum up, the prototype antenna satisfies the similarity principle with its scaled model. The

Table 2. Simulation results of 344 MHz $\sim$ 351 MHz electromagnetic wave gain received by prototype antenna and scale model at the same corresponding depth.

Prototype antenna		Scale model	
Frequency (MHz)	Gain (dBi)	Frequency (MHz)	Gain (dBi)
344	−53.4	1376	−53.4
345	−53.4	1380	−53.4
346	−53.3	1384	−53.3
347	−53.3	1388	−53.3
348	−53.2	1392	−53.2
349	−53.2	1396	−53.2
350	−53.2	1400	−53.2
351	−53.1	1404	−53.1

simulation results show that the electrical parameters between the underwater receiving antenna and the scaling model are basically the same, and the influence of the change of propagation characteristics on the gain is minimal, which verifies the feasibility of using the scaling model to design the underwater receiving antenna.

4. EXPERIMENTAL VERIFICATION OF SIMULATION METHOD

To verify the correctness of the simulation analysis method, the half-wave dipole antenna is tested on the scale model test platform of the underwater receiving antenna. The concentration of brine is proportional to conductivity [8]. According to the relationship between brine concentration and conductivity in Table 3, adjust the conductivity of the medium in the platform.

Table 3. The conductivity of a partial concentration of saltwater.

Conductivity (S/m)	Brine concentration (%)
0.4	0.21
0.8	0.43
2	1.15
4	2.38
8	5.08
16	10.23

When building the experimental test platform, the environment of the antenna in the simulation software is strictly restored. Set up the experimental test platform according to the working environment of the antenna. Figure 5 shows the structure of the test platform.

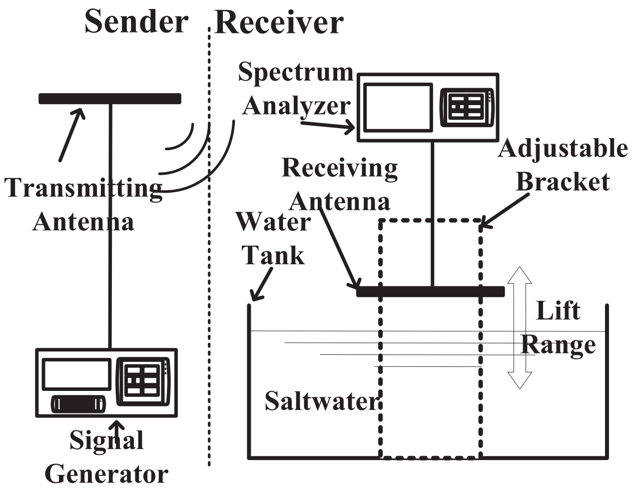

Figure 5. The structure of the test platform.

In the experiment, the transmitting section sends out electromagnetic signals of different frequencies but the same amplitude according to different antennas to be tested. Figure 6 shows the receiver in the experimental test platform. The sending end is the signal generator and the dipole antenna. The amplitude of the received signal of the prototype antenna is compared with that of the shrinkage model by using the control variable method.

The amplitude test results of the underwater receiving antenna and the scaled model at different corresponding depths are shown in Table 4.

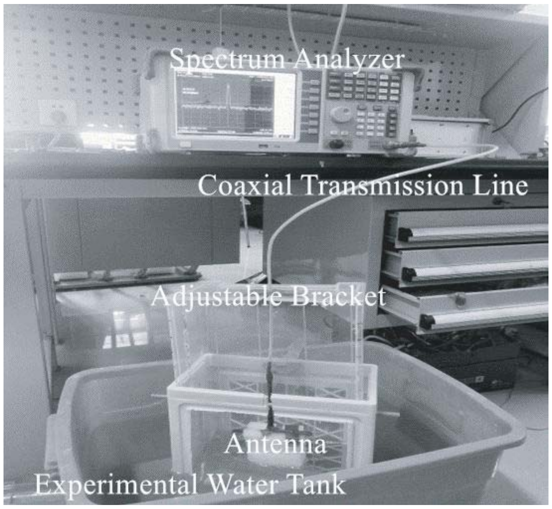

Figure 6. The receiving end of the experimental test platform.

Table 4. Signal amplitude received by the prototype antenna and scale model at different corresponding depths.

Prototype antenna		Scale model	
Depth (cm)	amplitude (dBmv)	Depth (cm)	amplitude (dBmv)
−4	5.9	−1	6.1
−8	3.1	−2	3.6
−12	0.2	−3	1.1

As can be seen from Table 4, although there are some experimental errors, the prototype antenna satisfies the similarity principle with its scaled model. The amplitude difference between the received signals of the prototype antenna and the scaled model at different corresponding depths in seawater is the same, which is consistent with the simulation results, indicating the correctness of the simulation results and the simulation analysis method.

5. CONCLUSION

The electric parameters of the underwater receiving antenna can be calculated by using the scale model to receive the electromagnetic wave from the air in the seawater. In the experiment, the smaller the size of the antenna is to be tested, the smaller the error is caused by the limitation of the volume of the experimental equipment. At the same time, it can reduce the cost of the experiment and the blindness of the design, and improve the design efficiency. According to the comparison and analysis, it can be seen that the electromagnetic parameters of the underwater receiving antenna inferred by the reduced-scale model must meet the following conditions:

1. The physical characteristics of the prototype antenna and the scaling model are following the scaling factor.
2. The electric dimensions of the underwater receiving antenna remain unchanged before and after scaling.
3. The scaling factor in the underwater receiving antenna system and the scaling model does not apply to all electrical parameters. For example, antenna gain, input power, etc. need to be derived according to the antenna design theory.

Through theoretical derivation, simulation analysis, and experimental verification, it is shown that the principle of electromagnetic field similarity can be applied to the reduced-scale model of the underwater receiving antenna system, which provides a new method for the design of the underwater receiving antenna. In the actual design process, some scaling conditions are difficult to meet the strict standards, such as the limited conductivity range of saltwater and the imperfect propagation path of the electromagnetic waves. These factors have a certain impact on the simulation and test results of the underwater receiving antenna system. However, in the design of the underwater receiving antenna, these factors should be fully considered; the limited range of conductivity should be reasonably used; and the path loss in the test environment should be minimized. The reduced scale model can strictly restore the electrical parameters of the underwater receiving antenna in the sea.

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