Hindawi
International Journal of Antennas and Propagation
Volume 2024, Article ID 2023687, 13 pages
https://doi.org/10.1155/2024/2023687

Research Article

Propagation Characteristics and Magnetic Field Distribution of Rotating Magnet-Based Mechanical Antenna in the Air-Seawater-Seabed Three-Layer Medium

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Received 21 October 2023; Revised 31 January 2024; Accepted 14 February 2024; Published 14 March 2024

Academic Editor: Trushit Upadhyaya

Aiming at the application requirements of underwater cross-domain communication, based on the equivalent relationship between the rotating permanent magnet and the orthogonal time-varying current loop, this paper establishes an air-seawater-seabed three-layer medium model and analyzes the magnetic field distribution and propagation characteristics of the rotating permanent magnet-based mechanical antenna (RMBMA). Based on the electromagnetic field simulation software FEKO, the influence of vertical rotation and horizontal rotation of RMBMA on the radiation magnetic field is analyzed. The magnetic field distribution and magnetic field attenuation characteristics of RMBMA at different depths are obtained by simulation. The influence of RMBMA operating frequency and magnetic moment on the propagation characteristics is studied. The research shows that the horizontal rotation of the magnetic source is better than the vertical rotation in the long-distance underwater communication. When the magnetic source and the receiving point are close to the interface of the medium, the magnetic field strength and the propagation distance can be relatively increased. With appropriate frequency and magnetic moment, the magnetic field strength and communication distance can be further increased.

1. Introduction

Low-frequency electromagnetic wave has the characteristics of good seawater penetration and long propagation distance [1–4], which can be used to realize cross-media wireless communication. The existing low-frequency transmission system has problems such as large antenna volume, low radiation efficiency, and high energy consumption, which restricts its application and development in related fields. The mechanical antenna and the traditional antenna adopt different emission methods. Through the mechanical rotation or vibration motion of the electret or permanent magnet material, the alternating electromagnetic field is emitted to convert the mechanical energy into electromagnetic energy. The mechanical antenna can realize information loading by changing the mechanical motion characteristics. According to the different excitation materials and motion modes, mechanical antennas can be divided into vibrating electret, rotating electret, rotating permanent magnet, vibrating permanent magnet, and magnetoelectric composite [5–7]. Thanks to the development and wide application of rotating servo drive technology and rare earth permanent magnet materials, rotating permanent magnet mechanical antenna is a research hotspot in the industry. The mechanical rotation of a permanent magnet can directly generate a static strong magnetic field, which is expected to realize low power consumption and miniaturization of low-frequency electromagnetic emission systems. The Sixty-Third Institute of the National University of Defense Technology has carried out systematic modeling analysis and theoretical research on the radiation mechanism of rotating permanent magnet mechanical antennas and analyzed the radiation distribution characteristics of RMBMA and the general analytical expression of electromagnetic field distribution [8]. The University of California, Los Angeles, has realized the array of

RMBMA, so that the antenna can have a large frequency adjustment range, which brings great convenience to signal modulation [9].

Scholars in related fields have conducted a lot of research on cross-sea medium communication [10, 11]. However, the actual marine environment is complex and changeable, and there are still many technical problems to be solved in underwater wireless communication. For the underwater communication of RMBMA, [8] equivalents RMBMA to two orthogonally placed magnetic dipoles with a phase difference of 90°, which is used to study the near-field, far-field, and attenuation characteristics of RMBMA in infinite air and seawater space. In [12], the equivalent relationship between the rotating permanent magnet and the orthogonal current loop was given. The cross-domain propagation of RMBMA in the air-seawater two-layer medium and the magnetic field distribution near the sea surface were analyzed by using the orthogonal magnetic current element decomposition method and Sommerfeld integral. The authors in [13] analyzed the magnetic field radiation attenuation characteristics of horizontal rotation and vertical rotation of magnetic sources in two-layer media. The authors in [14] preliminarily analyzed the propagation characteristics of RMBMA in an air-seawater-seabed three-layer medium when the magnetic source and the receiving point are located at different depths. The influence of frequency, magnetic moment, and other factors on the propagation characteristics has not been studied and analyzed.

For the underwater communication application of RMBMA, based on the equivalent relationship between the rotating permanent magnet and the orthogonal current loop, an air-seawater-seabed three-layer medium model is established. Based on the superposition principle of electromagnetic field, the analytical expression of RMBMA in the three-layer medium is obtained. Based on the electromagnetic field full-wave simulation software FEKO, the effects of the depth of the magnetic source and the receiving point, the rotation direction of the magnetic source, the frequency, and the magnetic moment of the permanent magnet on the propagation characteristics are analyzed. Through the comparative analysis of the propagation characteristics and magnetic field distribution of RMBMA under different conditions, it was found that the horizontal rotation of RMBMA is better than the vertical rotation at a longer communication distance. In cross-media communication, the link loss can be reduced by the side wave. When the magnetic source and the receiving point are located at the seabed or sea level, with the appropriate frequency and magnetic moment, the communication distance and magnetic field strength can be further expanded.

2. The System Architecture of RMBMA

Figure 1 shows the system architecture of RMBMA [8], which consists of a rotating magnetic source (permanent magnet) and a rotating servo system (drive motor and controller). The information loading of RMBMA is realized by mechanical driving, and the symbol data are loaded into the mechanical motion state of the magnetic source. At present, the modulation of RMBMA mostly adopts a frequency modulation scheme. The widely used signal modulation method is frequency-shift keying (FSK). The radiation frequency corresponds to the rotation frequency. By changing the rotation frequency of the motor, the data signals "0" and "1" can be switched by switching the high and low speeds of the motor. It can also represent multibit data with multiple different frequencies to achieve multibit FSK modulation, so only the energy of the magnetic source motion state needs to be maintained or changed.

3. Propagation Characteristics in Infinite Lossy Media

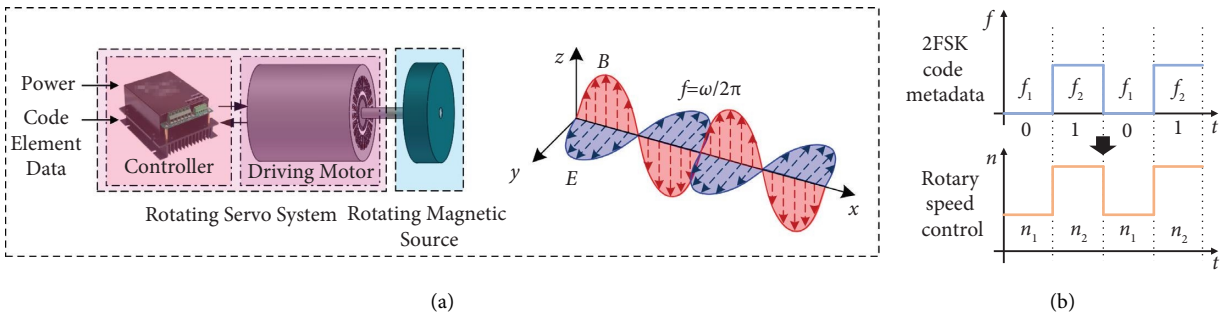
Figure 2 shows the equivalent relationship between the rotating magnetic source and the orthogonal current loop. When the cylindrical permanent magnet moves uniformly around the center of the circle, it can be equivalent to two orthogonally placed time-varying current loops with a phase difference of 90°.

The external static magnetic field of the permanent magnet is equivalent to a constant current loop [15], which satisfies the following relationship: $B_r \times V/\mu_0 = N \times I \times S$, where N is the number of turns of the current loop, μ_0 is the permeability in vacuum, I is the current, S is the area of the current loop, B_r is the remanence of the permanent magnet, and V is the volume of the permanent magnet. For NdFeB permanent magnet materials, the remanence can reach 1.4 T. If the magnetic moment is 1000 Am^2, the volume of the corresponding cylindrical permanent magnet is 902.75 cm^3. From the equivalent relationship between the rotating permanent magnet and the orthogonal current loop, it can be obtained that the magnetic field component B_M of the magnetic dipole moment m_0 in an infinitely large conductive medium is [16]

$$B_M = B_0 e^{-j\gamma r}\left\{2\left[j\left(\frac{1}{\gamma r}\right)^2 + \left(\frac{1}{\gamma r}\right)^3\right](\cos\theta + j\sin\theta\sin\varphi)\hat{r} - \left[\left(\frac{1}{\gamma r}\right) - j\left(\frac{1}{\gamma r}\right)^2 - \left(\frac{1}{\gamma r}\right)^3\right]\left[(\sin\theta - j\cos\theta\sin\varphi)\hat{\theta} - j\cos\varphi\hat{\varphi}\right]\right\}, \quad (1)$$

where $B_0 = -\mu_0\gamma^3 m_0/4\pi$, $m_0 = B_r V/\mu_0$, r is the propagation distance, θ and φ are the direction angles, γ is the wave number in the medium, which can be expressed as $\gamma = \beta\text{-}j\alpha$, and α and β are the attenuation factor and phase shift factor, respectively.

Figure 3 illustrates the magnetic field attenuation characteristics of RMBMA in a uniform infinite lossy medium. The magnetic moment is 1000 Am^2. In this scenario, the relative dielectric constant (ε_r) and conductivity (σ) values for air, seawater, and seabed are 1, 4 S/m, 81, 10 S/m,



(a) (b)

Figure 1: (a) The system architecture and (b) frequency modulation of RMBMA.

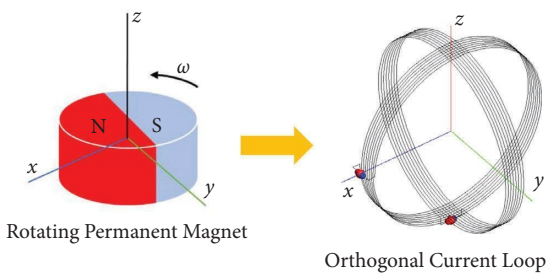


Figure 2: Rotating permanent magnet and orthogonal current ring.

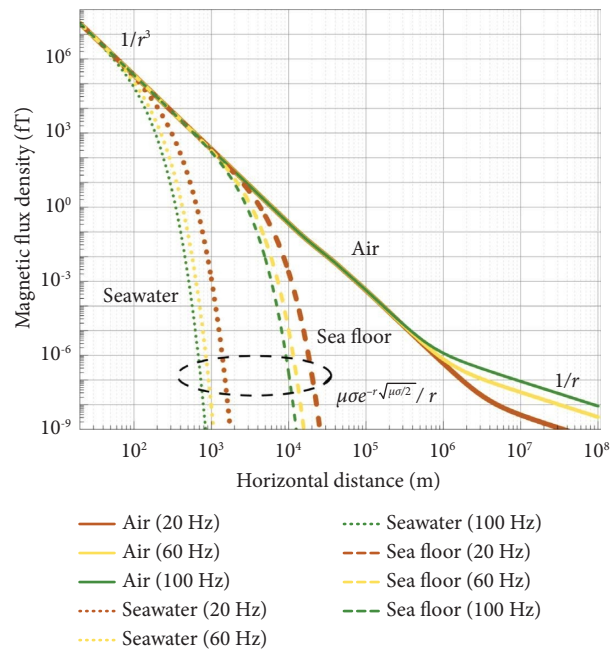


Figure 3: Simulation comparison of magnetic field attenuation characteristics of RMBMA.

and 0, 0.01 S/m, respectively. The magnetic source is located at the origin, and the measured field point is located in the horizontal distance of $20-10^8$ m in the x direction. In different media, with the increase of frequency and horizontal distance, the near-field magnetic field has the same attenuation rate, and the far-field magnetic field exhibits different attenuation characteristics. In the near region, the magnetic field strength is proportional to m_0/r^3 and has nothing to do with the propagation medium. For the far-field magnetic field, the air is approximately a lossless medium, and the far-field field strength is proportional to m_0/r. The conductivity of seawater and seabed rock is not 0 S/m, and the wavelength is compressed when the electromagnetic wave propagates in it, and the near-field range becomes smaller. The attenuation rate of the magnetic field in the far field is $\mu\sigma e^{-r\sqrt{\mu\sigma/2}}/r$, the magnetic field strength will decay rapidly as the distance increases, and the greater the conductivity, the faster the attenuation.

4. Propagation Model Based on Air-Seawater-Seabed Three-Layer Medium

Figure 4 shows the propagation model of RMBMA in the air-seawater-seabed three-layer medium. The isotropic air-seawater-seabed three-layer medium is considered. The upper half space is air (insulating medium), the middle layer is seawater (lossy medium), and the lowest layer is seabed (lossy medium). In the cylindrical coordinate system, d is the distance from the magnetic source to the sea level, z is the distance from the receiving point to the sea level, h is the depth of the seawater, and r is the horizontal distance from the magnetic source to the receiving point, and the seawater-air interface is located at the horizontal plane at $z=0$. The air layer and the seabed layer are semi-infinite spaces. According to the different rotation axes, the permanent magnet has different rotation modes in space. Due to the existence of the medium interface, it is mainly divided into side wave, direct wave, and reflected wave propagation paths. The field strength at the receiving point is a combination of multiple propagation paths.

Since the rotating permanent magnet can be equivalent to two orthogonally placed magnetic dipoles, the magnetic field of RMBMA in the three-layer medium can be synthesized by the magnetic field of two orthogonal magnetic dipoles in the three-layer medium. In the cylindrical coordinate system, the total field is written as the sum of the transverse electric field and the transverse magnetic field [17–20], and the boundary conditions are satisfied on the interface. The magnetic field of the horizontal magnetic dipole in the three-layer medium is shown in formula (2), where γ_z is the z-direction wave number in seawater and γ_r is the radial wave number. $H_1(\gamma_r r)$ is the first-order Hankel

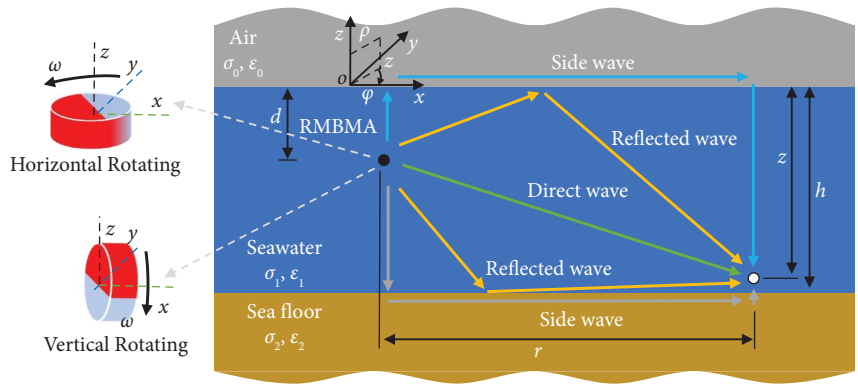


Figure 4: Underwater propagation model of the air-seawater-seabed three-layer medium.

function of the first kind, $H_1'(\gamma_r r)$ is the derivative of $H_1(\gamma_r r)$, φ is the horizontal angle of the magnetic dipole, and $C_1(\varphi)$ and $S_1(\varphi)$ are the coefficients associated with the first-order sine and cosine functions. Z is the vertical propagation distance of different propagation paths. A and B are the amplitude of the TM wave and C and D are the amplitude of the TE wave [21–23].

$$\begin{aligned}
H_{\text{rhmd}} &= \int_{-\infty}^{\infty} \frac{i\gamma_z}{\gamma_r}\left(\mathrm{C}e^{i\gamma_z Z} - \mathrm{D}e^{-i\gamma_z Z}\right)H_1'(\gamma_r r)S_1(\varphi)\mathrm{d}\gamma_r + \int_{-\infty}^{\infty} \frac{-i\omega\varepsilon}{\gamma_r^2 r}\left(\mathrm{A}e^{i\gamma_z Z} + \mathrm{B}e^{-i\gamma_z Z}\right)H_1(\gamma_r r)C_1'(\varphi)\mathrm{d}\gamma_r,\\
H_{\varphi\text{hmd}} &= \int_{-\infty}^{\infty} \frac{i\gamma_z}{\gamma_r^2 r}\left(\mathrm{C}e^{i\gamma_z Z} - \mathrm{D}e^{-i\gamma_z Z}\right)H_1(\gamma_r r)S_1'(\varphi)\mathrm{d}\gamma_r + \int_{-\infty}^{\infty} \frac{i\omega\mu}{\gamma_r}\left(\mathrm{A}e^{i\gamma_z Z} + \mathrm{B}e^{-i\gamma_z Z}\right)H_1'(\gamma_r r)C_1(\varphi)\mathrm{d}\gamma_r,\\
H_{\text{zhmd}} &= \int_{-\infty}^{\infty} \frac{IS\gamma_r^2}{8\pi}\left(\mathrm{C}e^{i\gamma_z Z} + \mathrm{D}e^{-i\gamma_z Z}\right)H_1(\gamma_r r)S_1(\varphi)\mathrm{d}\gamma_r.
\end{aligned} \tag{2}$$

Equation (3) is the magnetic field expression of the vertical magnetic dipole in the three-layer medium [21], where $H_0(\gamma_r r)$ is the zero-order Hankel function of the first kind, and $H_0'(\gamma_r r)$ is the derivative of $H_0(\gamma_r r)$. C' and D' are the amplitude of the TE wave produced by the vertical magnetic dipole, and the vertical magnetic dipole only produces the TE wave, and the magnetic field component in the φ direction is 0.

$$\begin{aligned}
H_{\text{rvmd}} &= \int_{-\infty}^{\infty} \frac{i\gamma_z}{\gamma_r}\left(C'e^{i\gamma_z Z} - D'e^{-i\gamma_z Z}\right)H_0'(\gamma_r r)\mathrm{d}\gamma_r,\\
H_{\varphi\text{vmd}} &= 0,\\
H_{\text{zvmd}} &= \int_{-\infty}^{\infty} -i\frac{IS\gamma_r^3}{8\pi\gamma_z}\left(C'e^{i\gamma_z Z} + D'e^{-i\gamma_z Z}\right)H_0(\gamma_r r)\mathrm{d}\gamma_r.
\end{aligned} \tag{3}$$

Since the rotating magnetic source can be equivalent to an orthogonal magnetic dipole, the magnetic field distribution of the horizontal and vertical rotating magnetic sources in the three-layer medium can be expressed as

$$\begin{aligned}
H_r &= H_{\text{rhmd}} - \mathrm{j}H_{\text{rhmd}}\left(\varphi + \frac{\pi}{2}\right),\\
H_\varphi &= H_{\varphi\text{hmd}} - \mathrm{j}H_{\varphi\text{hmd}}\left(\varphi + \frac{\pi}{2}\right),\\
H_z &= H_{\text{zhmd}} - \mathrm{j}H_{\text{zhmd}}\left(\varphi + \frac{\pi}{2}\right),
\end{aligned} \tag{4}$$

$$\begin{aligned}
H_r' &= H_{\text{rhmd}} - \mathrm{j}H_{\text{rvmd}},\\
H_\varphi' &= H_{\varphi\text{hmd}} - \mathrm{j}H_{\varphi\text{vmd}},\\
H_z' &= H_{\text{zhmd}} - \mathrm{j}H_{\text{zvmd}}.
\end{aligned} \tag{5}$$

5. Magnetic Field Distribution and Propagation Characteristics in the Three-Layer Medium

In Figure 4, in addition to the direct wave and the interface reflected wave transmission path, the radiation magnetic field of the magnetic source in seawater also has the propagation path of vertical sea level upward propagation to the sea-air medium interface, then forward propagation in the air in the form of side waves, and finally downward

propagation to the receiving point, and the propagation path that the vertical seabed interface propagates downward to the seabed interface, then propagates forward in the form of side waves in the seabed layer, and finally propagates upward to the receiving point. The actual propagation path of the radiated electromagnetic field should be a combination of multiple paths. Because the magnetic field expression of RMBMA in a three-layer medium has Hankel integral, this kind of integral does not have an analytical solution, and the calculation is more complicated. In this paper, the electromagnetic field full-wave simulation software FEKO is used to establish a three-layer medium model for simulation analysis. The simulation model is shown in Figure 5. The space of air and seabed medium is infinite space. Two orthogonally placed red arrows represent the magnetic dipoles with a phase difference of 90°, which are used to simulate rotating permanent magnets. The field strength at any position can be calculated in the model.

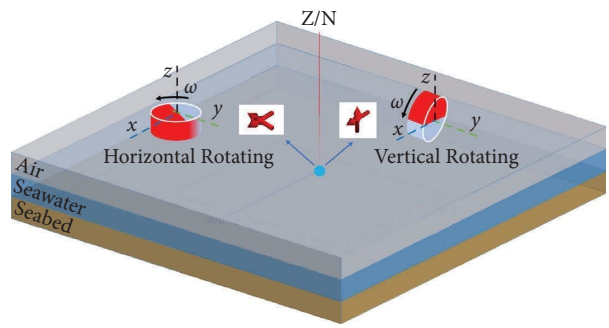


Figure 5: Simulation model of RMBMA in three-layer medium.

5.1. The Influence of Magnetic Source Placement on Propagation Characteristics. Figure 4 illustrates the horizontal and vertical rotation of the magnetic source. In the rectangular coordinate system, the horizontal rotation of the magnetic source takes the z-axis as the rotation axis, and vertical rotation takes the y-axis as the rotation axis. The frequency is 60 Hz, the magnetic moment is 1000 Am^2, and the seawater depth is 100 m. Figure 6 shows the magnetic field intensity of the magnetic source located at 1 m above the water. The horizontal distances from the receiving point to the magnetic source are 100 m and 1000 m, respectively, and the receiving points are located at 1 m, 50 m, and 99 m underwater, respectively. In the figure, the solid line represents the horizontal rotation of the magnetic source and the dotted line represents the vertical rotation. From the figure, we can see that the horizontal rotation shows omnidirectionality on the horizontal plane, and the vertical rotation shows directionality. At a horizontal distance of 100 m, the magnetic field strength of the vertical rotation is the largest in the 180° direction. At different receiving depths, the magnetic field strength is 1.1 times, 1.5 times, and 1.7 times the horizontal rotation, respectively. With the increase in receiving depth, the multiple gradually increases. At a horizontal distance of 1000 m, the magnetic field of the vertical rotation is nearly omnidirectional, and as the receiving point is located on the seabed, the direction of the maximum magnetic field changes from 180° to 0°. In addition to the magnetic field strength, the vertical rotation of the magnetic source is greater than the horizontal rotation in a certain direction as the receiving point is located on the seabed, and in other cases, the magnetic field strength is smaller than the horizontal rotation of the magnetic source.

Figure 7 shows the magnetic field intensity as the magnetic source is located at 99 m underwater. From the figure, we can see that at a horizontal distance of 100 m, the rotation direction does not change when the magnetic source is placed on the seabed and rotates vertically, while the relative position of the magnetic source and the interface changes, so the direction of the maximum magnetic field becomes 0°. At different receiving depths, the maximum magnetic field strength of the vertical rotation of the magnetic source is 1.7 times, 1.5 times, and 1.1 times that of the horizontal rotation, respectively. With the increase in the receiving depth, the multiple gradually decreases. At the horizontal distance of 1000 m, the magnetic field intensity of the horizontal rotation is greater than that of the vertical rotation. In summary, the vertical rotation field strength is larger at a small communication distance, and there is a greater field strength at the receiving point. The omnidirectionality of the magnetic field is more advantageous when the magnetic source rotates horizontally at an underwater long-distance communication, and the magnetic field intensity of the horizontal rotation is greater than that of the vertical rotation at a long distance.

5.2. The Influence of Transmitting Point Depth and Receiving Point Depth on Propagation Characteristics. According to the above analysis, the horizontal rotation of the magnetic source is more advantageous in long-distance underwater communication. Therefore, only the propagation characteristics and magnetic field distribution of the horizontal rotation are analyzed. Figure 8 shows the magnetic field distribution of RMBMA in the vertical plane at different positions in the infinite uniform seawater medium and the air-seawater-seabed three-layer medium. The black dotted line is the range of the magnetic field reaching 100 fT in the infinite uniform seawater medium, and the red dotted line is the range of the magnetic field reaching 100 fT in the three-layer medium. The depth of seawater is 100 m, the air and the seabed are semi-infinite spaces, the magnetic source rotates horizontally, the frequency is 60 Hz, and the magnetic moment is 1000 Am^2. Due to the different electromagnetic parameters of the medium, the magnetic field distribution is different as the position of the magnetic source changes. And for different emission points and receiving points, there are multiple magnetic field propagation paths. At the receiving field strength of 100 fT, the magnetic field can propagate 200–300 m in uniform seawater. In the three-layer medium, due to the presence of side waves, the propagation distance can be extended, and the magnetic field propagation can be increased to more than 1000 m. The magnetic field generated by RMBMA propagates in the air for a certain distance and

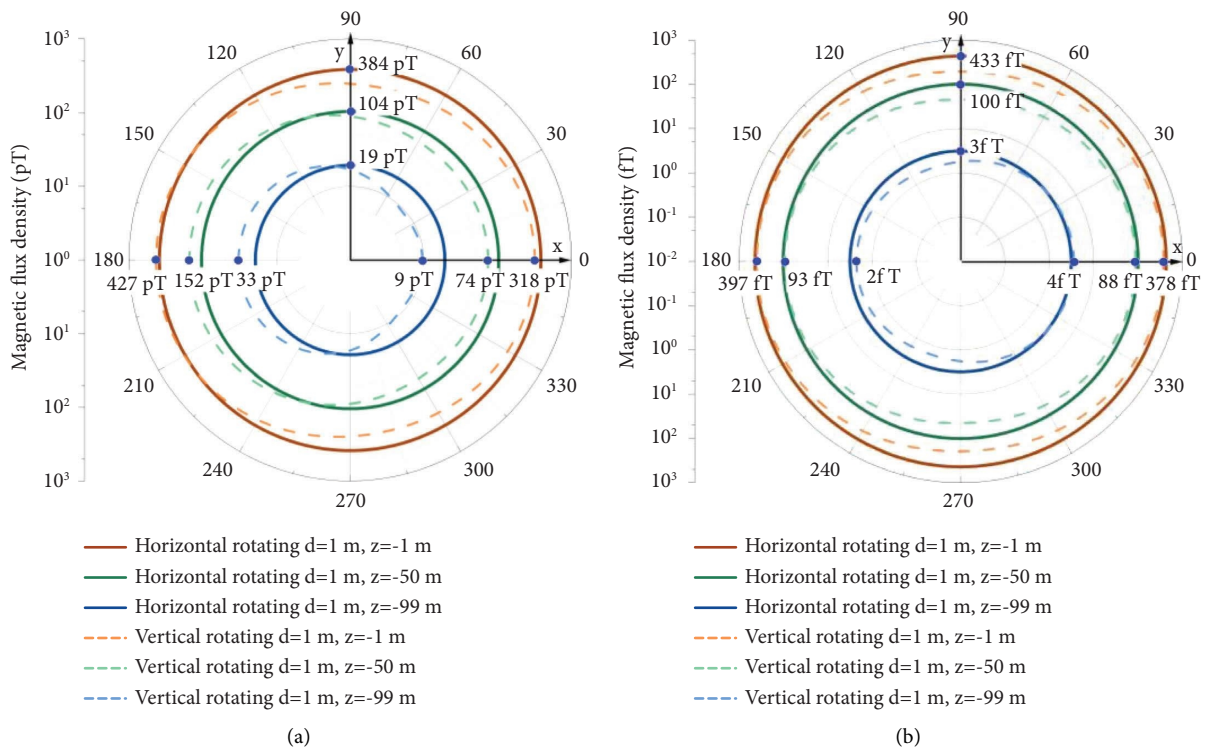


Figure 6: Directional pattern in the horizontal plane (the magnetic source is located 1m above water). (a) $r = 100$ m. (b) $r = 1000$ m.

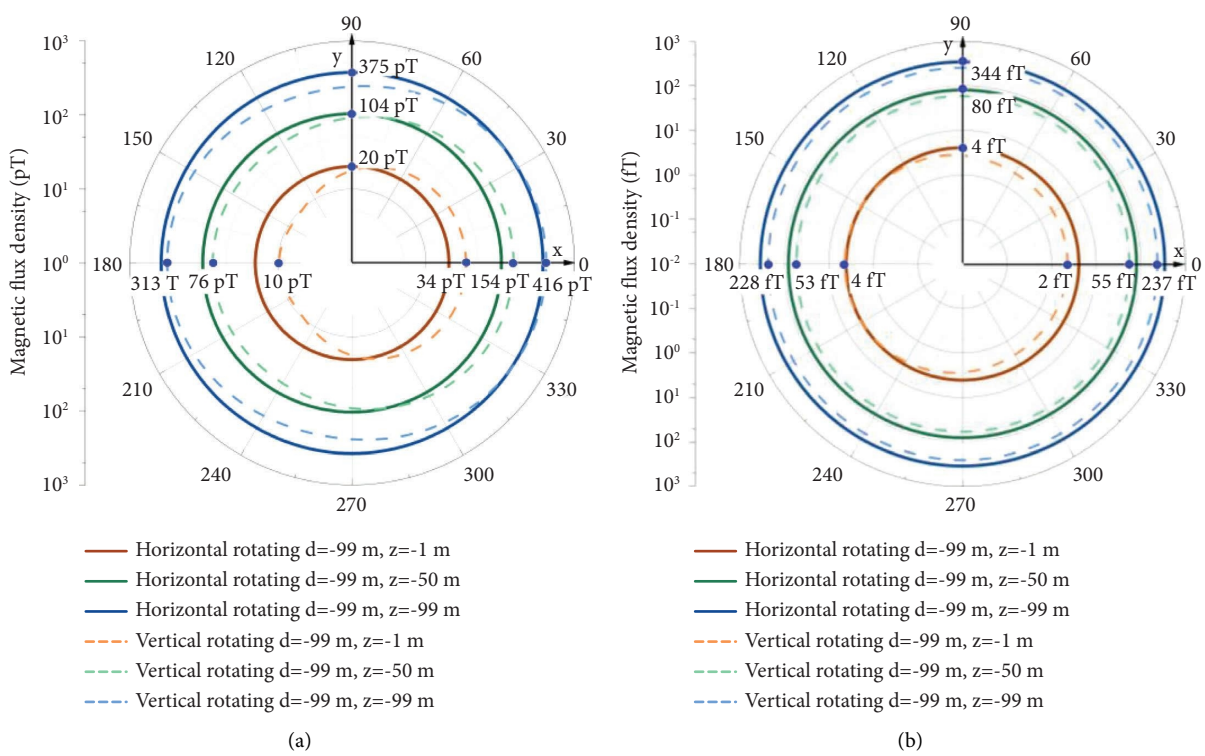


Figure 7: Directional pattern in the horizontal plane (the magnetic source is located 99 m underwater). (a) $r = 100$ m. (b) $r = 1000$ m.

then penetrates the air-seawater interface into the seawater and propagates in the seawater medium when the magnetic source is located on the sea surface. The magnetic field attenuates greatly after a certain distance of propagation in the seawater medium, but some energy still penetrates the seawater-seabed interface into the seabed medium. Compared with the magnetic field propagating in the uniform seawater medium, the magnetic field can propagate in the air for a certain distance and then enter the seawater, and the attenuation is small, which can increase the magnetic field strength in the seawater. The magnetic field can penetrate the air-seawater interface and the seawater-seabed interface into the air and seabed medium when the magnetic source is located in seawater. Due to the low conductivity of air and seabed medium, the attenuation of the magnetic field is very small. After a certain distance of propagation, the magnetic field penetrates the interface again and enters the seawater. Due to the existence of a side wave propagation path, the magnetic field in seawater can be enhanced, which is conducive to expanding the underwater communication distance.

Figure 9 shows the attenuation characteristics of the magnetic field intensity with the horizontal distance at different depths of the transmitting point and the receiving point. The receiving point is located at different depths in the seawater. The measured field point is located in the horizontal distance of 20–5000 m in the x direction. The dotted line indicates the attenuation characteristics in infinite air, seawater, and seabed media. With the positions change of the magnetic source and the receiving point, the magnetic field propagation paths are different. The direct wave and reflected wave propagating in seawater are the main propagation paths at a small horizontal distance when the magnetic source and the receiving point are located at 50 m underwater, respectively. Since the vertical propagation distances of sea-level side waves and seabed side waves in seawater are equal, the two side wave propagation paths are the main propagation paths at a large horizontal distance. Due to the lossy characteristics of the seabed medium, the side wave will decay rapidly when it propagates to the far field. Therefore, as the horizontal distance continues to increase, the magnetic field takes the sea-level side wave as the main propagation path. The vertical propagation distance of different side waves in seawater and the main propagation path will change when the depth of the magnetic source is constant and the receiving point is close to the air-seawater interface or the seawater-seabed interface. The side wave has the smallest propagation distance and the smallest attenuation in the seawater when the magnetic source is located on the sea surface or the seabed and the receiving point is also located at the same depth. The side wave can be fully utilized, and the magnetic field strength is the largest. In summary, in order to achieve a greater magnetic field strength or farther communication distance, the placement of the magnetic source and the receiving point needs to be able to use the side wave more effectively to minimize the attenuation of the magnetic field on the propagation path.

5.3. The Influence of Working Frequency on Propagation Characteristics. Figure 10 shows the attenuation characteristics of the magnetic field in the x direction at 99 m underwater at different frequencies. The magnetic source rotates horizontally, the magnetic moment is 1000 Am^2, the seawater depth is 100 m, and the magnetic source is located on the water at 1 m and underwater at 99 m, respectively. The magnetic field strength decreases nonlinearly at the same horizontal position with the increase in frequency when the magnetic source is located at the sea level. The frequency increases and the magnetic field strength changes a little when the magnetic source is located at the seabed. The linear propagation from the transmitting point to the receiving point is the main path when the magnetic source is located at 1 m above the water and the horizontal distance is small. The vertical propagation distance of the sea level side wave and the seabed side wave in the seawater is equal, and the attenuation speed is equal at a large horizontal distance. After the direct wave is attenuated, the sea level side wave and the seabed side wave are the main propagation paths. As the distance between the magnetic source and the nearest receiving point is more than 100 m, the direct wave propagating in the seawater has entered the far-field area, so the magnetic field strength decreases with the increase in frequency. The side wave also propagates in the seawater for a certain distance, which also causes the magnetic field strength to decrease with the increase in frequency when the side wave is the propagation path in the long distance. Due to the large propagation distance of sea level side waves in seawater, the attenuation is large. The seabed side waves are the main propagation path after the attenuation of direct waves and reflected waves when the magnetic source is located at 99 m underwater. Because the magnetic source is located at the bottom of the sea, the linear distance from the receiving point is small, and the propagation distance of the seabed side wave in the sea water is very small. The magnetic field intensity is greater than that when the magnetic source is located at 1 m above the water, and within this distance range, the seabed side wave is still in the near-field area. The attenuation speed when propagating in the seabed medium is consistent with that in the air, and the field intensity does not change with the frequency.

Figure 11 shows the variation of the magnetic field intensity at the horizontal distance of 200 m and the horizontal distance with frequency at 100 fT. The magnetic field intensity decreases nonlinearly with the increase in frequency, and the magnitude of the decrease is getting smaller and smaller when the magnetic source is located at the sea level. The magnetic field strength changes a little as the frequency

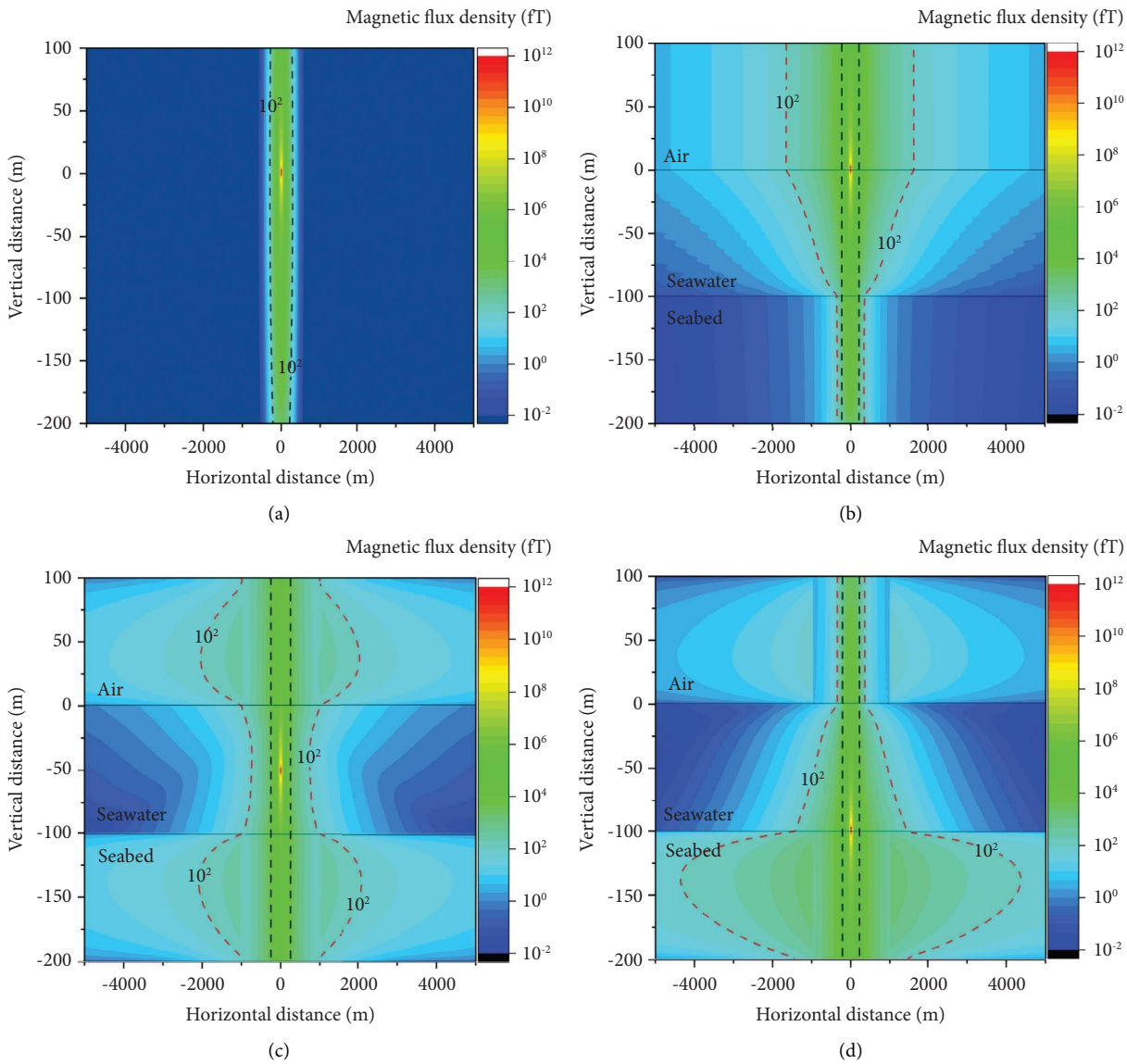


Figure 8: The distribution of magnetic field in the three-layer medium. (a) Uniform seawater. (b) $d = 1$ m. (c) $d = -50$ m. (d) $d = -99$ m.

increases when the magnetic source is located on the seabed. From Figure (b), we can see that if the receiving field strength is 100 fT, the horizontal distance of the magnetic source can reach more than 1000 m when it is located on the seabed and up to 560 m when it is located at sea level. In order to propagate a longer distance at a large vertical distance between the magnetic source and the receiving point, the working frequency can be considered to be reduced, but a too low frequency will lead to a narrower bandwidth. The frequency has little effect on the magnetic field strength and the propagation distance when the magnetic source and the receiving point are located on the seabed, and a higher working frequency can be selected, so it needs to be considered comprehensively in the application.

5.4. The Influence of Magnetic Moment on Propagation Characteristics. Figure 12 shows the variation of the magnetic field intensity at a horizontal distance of 200 m and the horizontal distance at 100 fT with the magnetic moment. The magnetic sources are located at 1 m above the water and at 99 m below the water, respectively, with a frequency of 60 Hz and a sea depth of 100 m. As shown in Figure (a), as the magnetic moment increases, the magnetic field also increases, and the increase of the magnetic moment is consistent with the increase of the field strength, showing a linear relationship. The magnetic field strength of the magnetic source located at the seabed is much higher than that when the magnetic source is at the sea level. The reason is that the linear distance is larger when the magnetic source

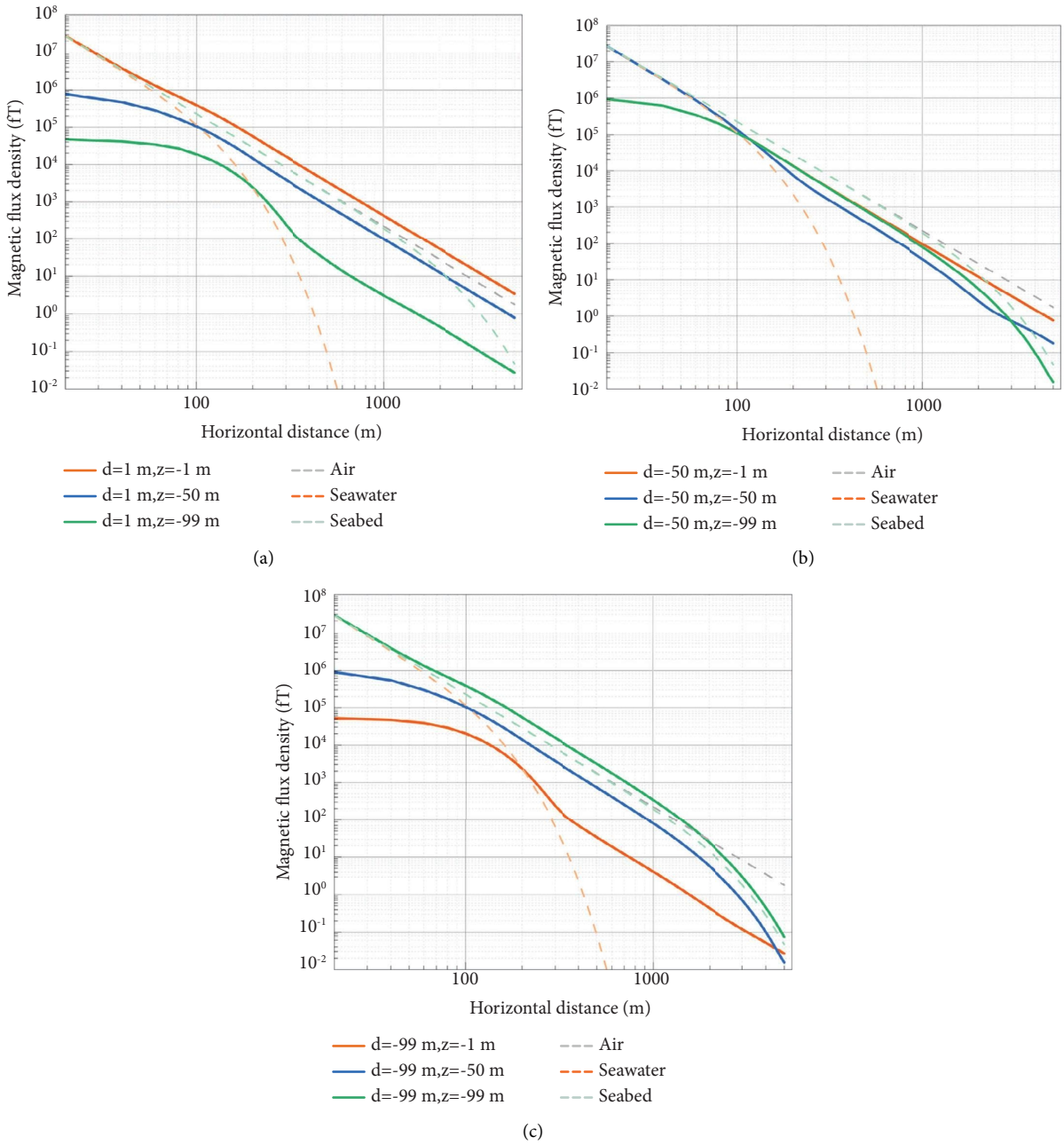


Figure 9: Attenuation characteristics of magnetic field strength with horizontal distance. (a) $d = 1$ m. (b) $d = -50$ m. (c) $d = -99$ m.

is located at the sea level, and the direct wave attenuates greatly and the side wave also attenuates when it propagates in seawater. The linear distance is small when both the receiving and transmitting ends are located at the seabed, and the direct wave attenuates little and the side wave has a small attenuation. As shown in Figure (b), under the same magnetic moment, the horizontal distance to reach 100 fT when the magnetic source is located at 99 m underwater is 4 times that of the magnetic source located at 1 m above the water. With the increase in the magnetic moment, the increase in the horizontal distance when it reaches 100 fT is getting smaller and smaller, gradually saturated, and has a nonlinear relationship with the magnetic moment. In order to obtain greater field strength at the receiving point, the magnetic field can propagate farther, and the magnetic source and receiver can both be located on the seabed. The increase in the magnetic moment can obtain greater field strength, and the increase in the magnetic moment is

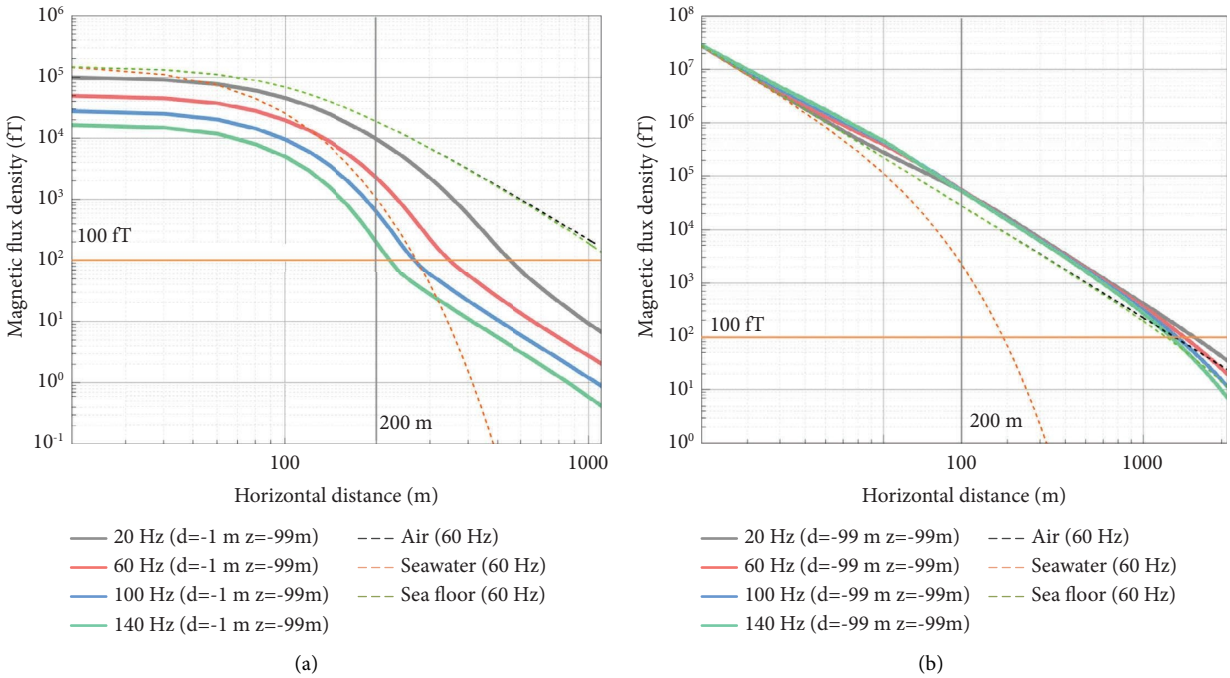


Figure 10: Attenuation characteristics of magnetic field strength with horizontal distance. (a) The magnetic source is located at 1 m above water. (b) The magnetic source is located at 99 m underwater.

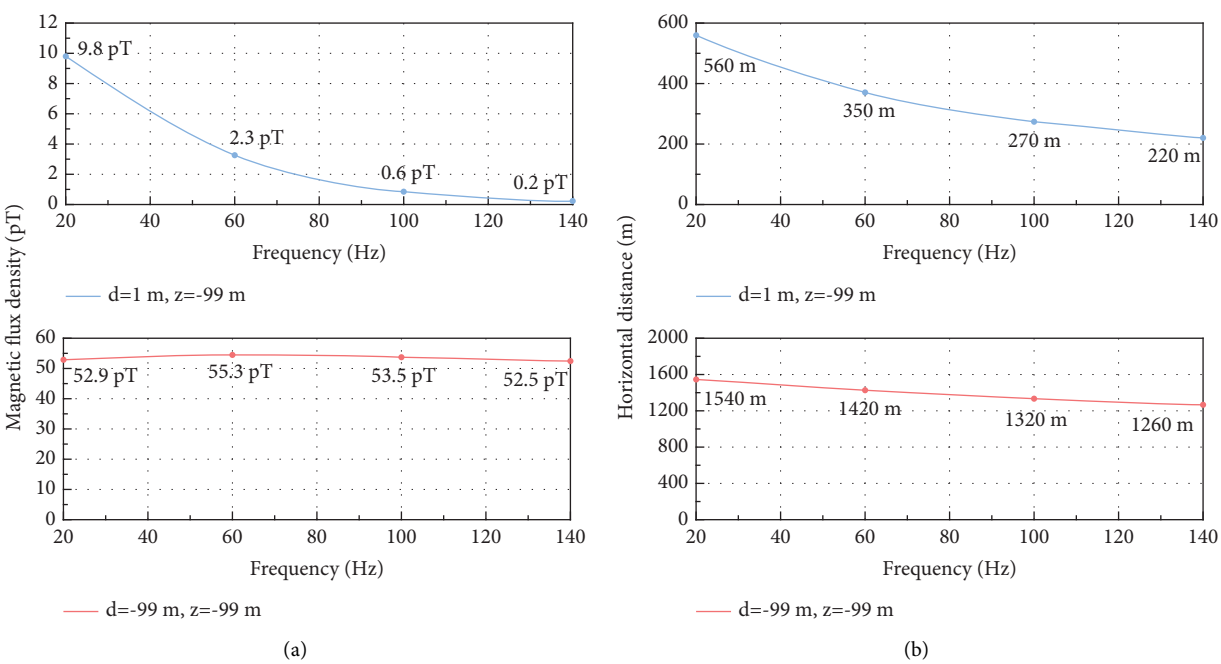


Figure 11: The magnetic field strength at the horizontal distance of 200 m and horizontal distance at 100 fT varies with frequency. (a) The magnetic field strength at the horizontal distance of 200 m. (b) The horizontal distance at 100 fT.

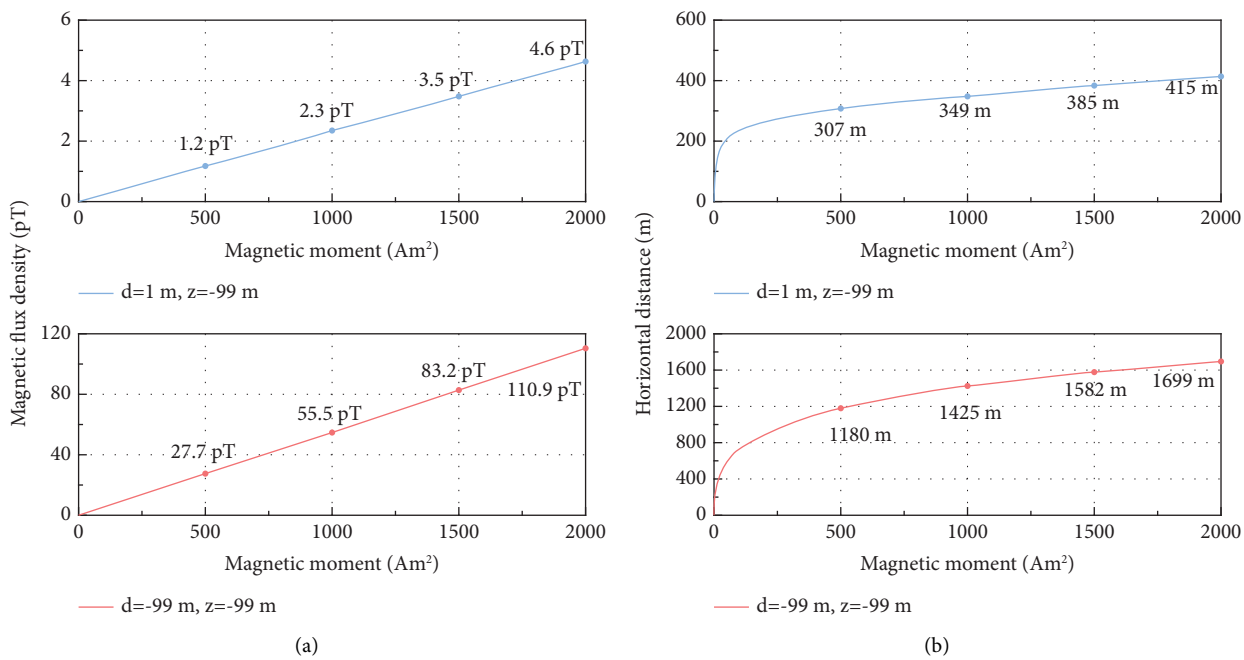


Figure 12: The magnetic field strength at the horizontal distance of 200 m and horizontal distance at 100 fT varies with the magnetic moment. (a) The magnetic field strength at the horizontal distance of 200 m. (b) The horizontal distance at 100 fT.

consistent with the increase of the magnetic field strength. However, the increase in the magnetic moment will also increase the volume and mass of the permanent magnet, and the burden on the motor will also increase, which needs to be considered comprehensively in the application.

6. Conclusion

In this paper, the propagation characteristics of a rotating permanent magnet mechanical antenna in the air-seawater-seabed three-layer medium are analyzed. Based on the equivalent relationship of the constant current loop of the static magnetic field of the permanent magnet, the radiation propagation model of the rotating magnetic source in the three-layer medium is established. The effects of the magnetic source placement method, the depth of the magnetic source and the receiving point, the rotation frequency of the magnetic source, and the magnetic moment on the propagation characteristics of RMBMA in the three-layer medium are analyzed. The summary is given as follows:

(1) It is omnidirectional on the horizontal plane when the magnetic source rotates horizontally. It shows a certain direction when the magnetic source rotates vertically. When the position of the magnetic source is different from the relative position of the medium interface, the direction of the maximum magnetic field intensity is also different. In underwater long-distance communication applications, the horizontal rotation of the magnetic source is better than the vertical rotation.

(2) Due to the side wave effect, when the distance exceeds a certain distance, the magnetic field attenuation of the rotating permanent magnet in seawater is significantly lower than that of the infinite seawater medium, which is conducive to expanding the underwater communication distance. The side wave has the smallest propagation distance in seawater when both the magnetic source and the receiving point are located at the seabed or sea level, which can reduce the loss of magnetic field propagation in seawater and achieve longer communication distance and greater magnetic field strength.

(3) When the vertical distance between the magnetic source and the receiving point is large, the smaller the working frequency, the greater the communication distance and the magnetic field strength, but the low frequency leads to the decrease in the communication rate. When the magnetic source and the receiving point are close to the dielectric interface, the size of the operating frequency has little effect on the magnetic field strength, and a higher operating frequency can be selected to improve the transmission rate, so it needs to be considered comprehensively in the application.

(4) The magnetic moment of the permanent magnet is proportional to the magnetic field intensity, but as the magnetic moment increases, the horizontal distance to the 100 fT receiving field strength increases nonlinearly, and the increase is getting smaller and smaller. Therefore, increasing the magnetic moment of the permanent magnet can increase the magnetic field strength at the receiving position, but the communication distance will not increase much. Limited by permanent magnet

materials and rotating drive technology, it is difficult to achieve long-distance applications at present. However, based on the advantages of miniaturization and low power consumption, it has broad application scenarios in underwater communication and other fields.

The actual marine environment is complex and changeable. There are many factors that are not analyzed in this paper for the underwater application communication of RMBMA, such as the influence of ocean waves, seawater depth, and uneven seawater. In future research, it is necessary to use the method of theoretical deduction or engineering statistics according to the actual situation to obtain a more suitable propagation model for the application scenario.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China (Project no. 61971431).

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