Analysis of Radiation Characteristics of Compressed V-shape Dipole Antenna

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ABSTRACT

In order to solve the problem of blind radiation spot of the traditional whip antenna mounted on the surface unmanned boats, a compressed V-shape dipole antenna is designed, which is omnidirectional and has a larger directivity especially when the hull is tilted. Calculated the radiation field strength of the compressed V-shape dipole antenna when it is tilted in various directions; The electrical characteristics of the compressed V-shape dipole antenna were obtained using FEKO electromagnetic simulation software, and the far-field experimental measurement and comparison experiment with the traditional whip antenna and the standard V-shape dipole antenna were carried out. Theoretical calculations, simulations, and experiments all show that the compressed V-shape dipole antenna has better directivity when interfered by the flowing sea surface, and the results are consistent, avoiding the problem of blind working spots, and the radiation process is stable and reliable.

Introduction

Surface unmanned boats are usually used to perform surface tasks, using the whip antenna mounted on the top to send and receive information to short-range maritime and aerial targets[1] . Due to the small size and lightweight of the hull[2] , the height of the antenna mounted on it is greatly restricted. The traditional whip antenna is low in cost, easy to manufacture, and has good omnidirectionality. It can ensure good communication effects when standing upright on the sea surface. Seawater is a good conductor and has good shielding performance against high-frequency electromagnetic waves. In real life, the traditional whip antenna will be affected by the flow of seawater and will be tilted. The electromagnetic waves radiated from the side of the antenna closer to the sea surface will be absorbed by the seawater, which will cause the receiving target to be unable to obtain information[3] . Fig. 1. is a schematic diagram of the whip antenna mounted on the surface unmanned boat tilted under the influence of sea waves. To complete the primary task of the near-field communication system in the tilted state of the surface unmanned boat, it is necessary to design a device that can maintain its good omnidirectionality in the far-field even when the antenna is tilted on the hull, and ensure that it can still transmit(receive) a more accurate signal to(from) the far-field when tilted at multiple angles.[4]
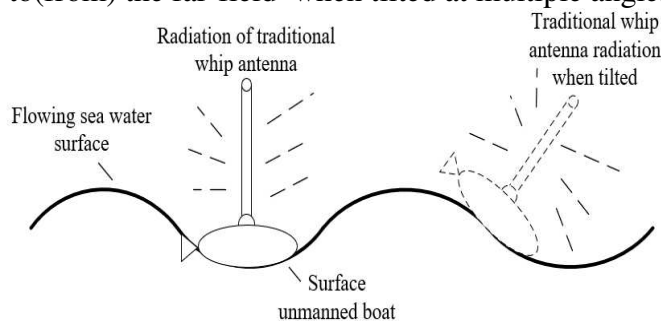

Figure 1: The working state of a surface unmanned craft equipped with a traditional whip antenna on a flowing sea

Combining the practical requirements of short-range maritime communication, a compressed V-shape dipole antenna in the VHF band is designed[5] , which provides a realistic basis for single-point communication of surface unmanned boats in complex sea conditions, and also provides a reference for sea-to-air communication under high sea conditions. The VHF frequency band communication not only guarantees the maritime wireless communication rate, but also enables the receiving target to obtain a better signal-to-noise ratio. The frequency range is 30-300MHz. Combined with the whip antenna of the surface unmanned boat, the whip antenna should not exceed 2 meters. In this paper, 75MHz is selected (Whip antenna resonance length is 1 meter) to verify the design structure and radiation performance of the compressed V-shape dipole antenna.

Antenna design

Antenna structure

The traditional whip antenna is a vertical antenna. It is a widely used horizontal plane omnidirectional antenna. It is usually fed between the bottom of the antenna and the ground[6] . It is one of the antennas equipped on maritime unmanned boats and ships. Fig. 2. shows a compressed V-shape dipole antenna structure. It converts the half-wave symmetrical element into a V-shape antenna, and adds a parasitic radiator in the horizontal direction of its top. The V-shape antenna is mainly responsible for radiation when the antenna is tilted due to the influence of sea waves[7] . The upper parasitic radiator is mainly to generate a certain angle with the V-shaped part to solve the radiation blind area of the antenna in any state[8] . Compared with the traditional whip antenna, the compressed V-shape dipole antenna maintains its resonance point unchanged. At present, there is no public document proposing such an antenna structure, and its structure and electrical characteristics need to be further calculated and deduced in order to solve the specific parameter index.
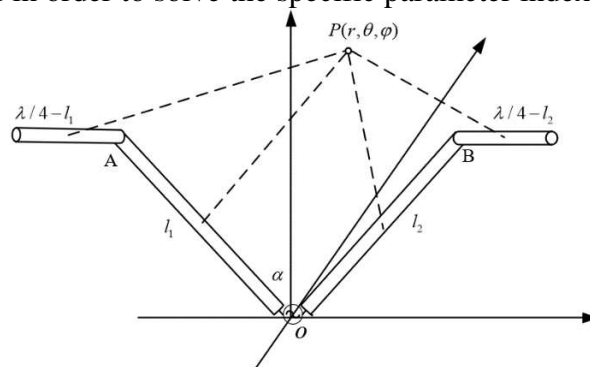
Figure 2: Design drawing of the compressed V-shape dipole antenna

The total length of the antenna in the figure is $\lambda/2$, the physical length of the single side of the V-part antenna is $l_1 = l_2$, and the included angle is α . Taking the single antenna on the left as an example, the single side length of the parasitic radiator can be calculated as $\lambda/4 - l_1$. Number the compressed V-shape dipole antenna nodes, as shown in Figure 2, mark the feed point as O point, the intersection of the V-part antenna and the parasitic radiator as A and B respectively, and the antenna dipole antenna parameters , The superposition field radiated by the four antennas in the far-field is divided into four sections. The four-segment antennas respectively have a certain influence on the field strength at a certain point $P(r,\theta,\varphi)$ in the far-field. Therefore, to solve the parameters of the compressed V-shaped dipole antenna, it is necessary to obtain the superposition field strength of the four-segment antenna radiation in the far field.[9]

Calculation of electric field strength

Without considering the influence of sea waves, calculate the superimposed field strength of each part of the antenna in the far-field. Because the antenna is a symmetrical structure, the current at point O is $I(O)$, and at any point on the antenna, $I_{max} = I(O)$, the current at nodes A and B can be approximately expressed as[10]

$$I(A) = I(B) = I(O)\sin k(\lambda/2 - l_1) \tag{1}$$

Where $k = 2\pi/\lambda$ is the phase shift constant. The unilateral antenna parameters can be solved first, and the total antenna parameters can be solved by analogy. Using the micro-element method to divide the antenna into an infinite number of current elements, establish a polar coordinate system, and refer to related documents. For the electric short dipole, the far-field strength is expressed as[11] [12]

$$E_\theta = j\frac{\pi I l}{\lambda r}\sin\theta e^{-jkr}$$
$$E_r = E_\varphi = 0 \tag{2}$$

where I is the current of the electric short dipole, l is the length, and E_θ, E_r, E_φ is the field strength component.

First consider the radiation of the V-part antenna to a certain point in the far-field. The schematic diagram is shown in Fig. 3..
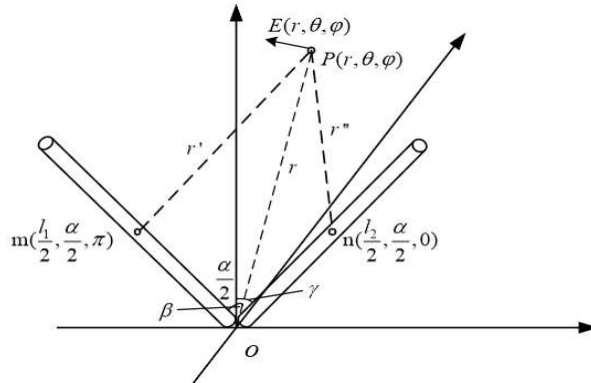

Figure 3: Schematic diagram of radiation of the V-part antenna to a point in the far-field

For antennas with different directions, the coordinate systems they are based on are also different, so coordinate system conversion is required. Take the center point m on the left side of the V-part antenna and the center point n on the right side. The corresponding polar coordinates are $m(\frac{l_1}{2}, \frac{\alpha}{2}, \pi)$, $n(\frac{l_2}{2}, \frac{\alpha}{2}, 0)$, and the angle between a certain point in the far-field and the origin is β and γ respectively, to get the far-field point The distance from the midpoint of the two antennas is[13]

$$r' = \sqrt{(r\cos\varphi\sin\theta + \frac{l_1}{2}\sin(\frac{\alpha}{2}))^2 + (r\sin\varphi\sin\theta)^2 + (r\cos\theta - \frac{l_1}{2}\cos(\frac{\alpha}{2}))^2} \tag{3}$$

$$r'' = \sqrt{(r\cos\varphi\sin\theta - \frac{l_2}{2}\sin(\frac{\alpha}{2}))^2 + (r\sin\varphi\sin\theta)^2 + (r\cos\theta - \frac{l_2}{2}\cos(\frac{\alpha}{2}))^2} \tag{4}$$

According to the law of cosines, the angle can be obtained:

$$\beta = arc\cos(\frac{r^2 + (\frac{l_1}{2})^2 - r'^2}{rl_1}) \tag{5}$$

3

$$\gamma = arc\cos(\frac{r^2 + (\frac{l_2}{2})^2 - r''^2}{rl_2})$$ (6)

Take the current element dz on the antenna element, and integrate it on the lengths l_1 and l_2. The contributions to far filed strength are:

$$E_{l_1}(r,\theta,\varphi) = j\frac{60\pi I(0)l}{\lambda}\frac{e^{-jkr}}{r}\sin\beta\int_{-l_1}^{0}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\beta}\,dz$$ (7)

$$E_{l_2}(r,\theta,\varphi) = j\frac{60\pi I(0)l}{\lambda}\frac{e^{-jkr}}{r}\sin\gamma\int_{0}^{l_2}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\gamma}\,dz$$ (8)

It can be found that if the field strength is superimposed at this time, the two parts of the antenna can cancel each other in some directions. They must be treated separately here, because the different sea states have different effects on the two antennas when sea waves are taken into account. The calculation of the field strength of the parasitic radiator is relatively easy. It can be regarded as a part of an antenna and can be directly calculated by the formula of the electric short dipole. The equivalent diagram is shown in Fig. 4..
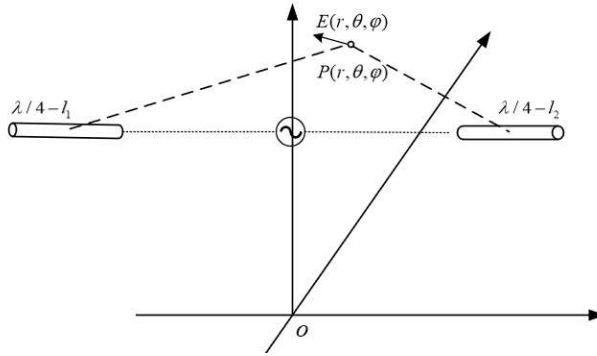

Figure 4: Schematic diagram of radiation equivalent of the parasitic radiator to a point in the far-field

The equivalent symmetrical element is parallel to the horizontal axis of the coordinate system, and the antenna size is small, so for a point $P(r,\theta,\varphi)$ in the far-field, θ can be directly used to represent the angle with the vertical axis. The field strength of the parasitic radiator to a point in the far-field is

$$E_{l_{3,4}}(r,\theta,\varphi) = j\frac{60\pi I(0)l}{\lambda}\frac{e^{-jkr}}{r}\cdot\sin\theta(\int_{-\frac{\lambda}{4}}^{-l_1}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\theta} + \int_{l_2}^{\frac{\lambda}{4}}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\theta})dz$$ (9)

$E_{l_{3,4}}(r,\theta,\varphi)$ represents the total radiation field strength of two parasitic radiators to a certain point outside. Therefore, it can be concluded that the total radiation field strength of the compressed V-shape dipole antenna in the far-field is

$$E(r,\theta,\varphi) = E_{l_1}(r,\theta,\varphi) + E_{l_2}(r,\theta,\varphi) + E_{l_{3,4}}(r,\theta,\varphi)$$

$$= j\frac{60\pi I(0)l}{\lambda}\frac{e^{-jkr}}{r}\sin\beta\int_{-l_1}^{0}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\beta}\,dz + j\frac{60\pi I(0)l}{\lambda}\frac{e^{-jkr}}{r}\sin\gamma\int_{0}^{l_2}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\gamma}\,dz +$$ (10)

$$j\frac{60\pi I(0)l}{\lambda}\frac{e^{-jkr}}{r}\sin\theta(\int_{-\frac{\lambda}{4}}^{-l_1}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\theta} + \int_{l_2}^{\frac{\lambda}{4}}\sin k(\frac{\lambda}{4} - |z|)e^{jkz\cos\theta})dz$$

It should be noted that in the vertical state and there is no occlusion of sea waves, when $\theta = 90^o$, $\varphi = 0^o/180^o$, at this time $\beta \approx \gamma$, $E(r,\theta,\varphi) \approx 0$, which means that in this case, the compressed V-shape dipole antenna has a poor propagation effect on the receiving target near the water surface. However, considering the actual situation: 1. Due to the influence of the flowing seawater in the working state, the compressed V-shape dipole antenna is difficult to be in a vertical communication state. Most of the work is carried out in an inclined situation,

and the waves need to be deducted under the influence of sea waves. Only after absorbing the energy term can the radiation field be superimposed. Once tilt occurs, as the tilt angle becomes larger, the difference between β and γ will continue to increase due to the structure of the antenna. At this time, the difference between $\sin\beta\int_{-l_1}^{0}\sin k(\frac{\lambda}{4}-|z|)e^{jkz\cos\beta}\,dz$

and $\sin\gamma\int_{0}^{l_2}\sin k(\frac{\lambda}{4}-|z|)e^{jkz\cos\gamma}\,dz$ will reduced, and When β and γ are complementary, the two items are superimposed on each other to reach the maximum value. At the same time, $E_{l_{3,4}}(r,\theta,\varphi)$ will be equivalent to the radiation field strength of a tilted symmetric array antenna. The greater the tilt angle, the greater the value; 2. The above-mentioned state $E(r,\theta,\varphi)\approx 0$ is an instantaneous state, which is also the only blind zone condition of the compressed V-shape dipole antenna, but it can still ensure the stable operation of the antenna. For near-surface receiving targets, even if $\theta=90^{o}$, it is difficult to meet $\varphi=0^{o}/180^{o}$. The transverse vector can be equivalent to a symmetrical array antenna placed horizontally, which can still maintain a good directivity at $\varphi\in(0^{o},180^{o})\cup(180^{o},360^{o})$; 3. The tilt angle is variable. For traditional whip antennas, the communication blind zone cannot be determined. When the traditional whip antenna is tilted, there will always be a radiation blind area, which makes the communication process unsteady and reliable. Considering that the receiving target can receive the largest possible radiation field strength, it is necessary to ensure the omnidirectionality of the compressed V-shape dipole antenna. Ensure that the antenna still has a better directivity in all directions when it is tilted, the antenna will appear as shown in Fig. 5. (a) (b) when the antenna is affected by seawater and tilted at ϕ angles (Fig. 5. shows two situations, and others are the superposition of these two cases), multiple states also meet the antenna radiation conditions of the situation described in the last part, the difference is that the length of the equivalent antenna is different, the superimposed field strength will also be different, and in the process of solving, in order to avoid complicated coordinate transformation, it can be equivalent to the antenna state of Fig. 6. (that is, the antenna remains vertical and the sea surface is relatively inclined). After calculating the far-field radiation field strength, rotate ϕ degrees clockwise along the plane where the antenna is located to obtain the field pattern of the compressed V-shape dipole antenna.
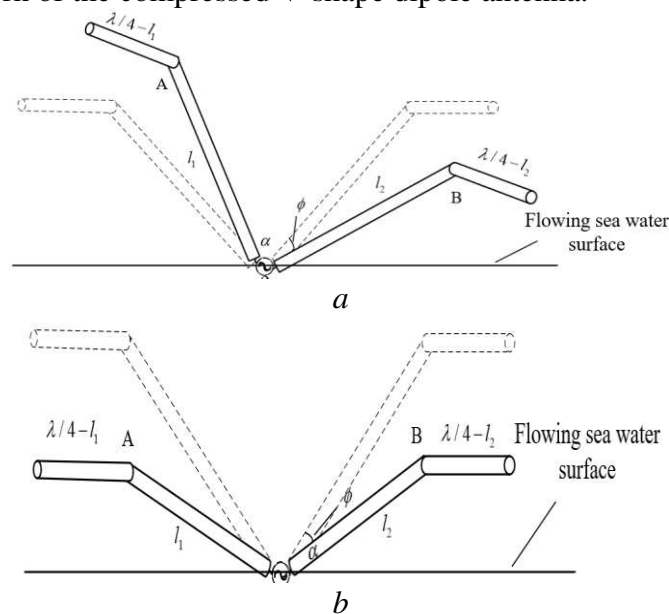

a

b

Figure 5: The state diagram of the compressed V-shape dipole antenna tilted at angle ϕ
(a) Horizontal direction, (b) Orthogonal direction

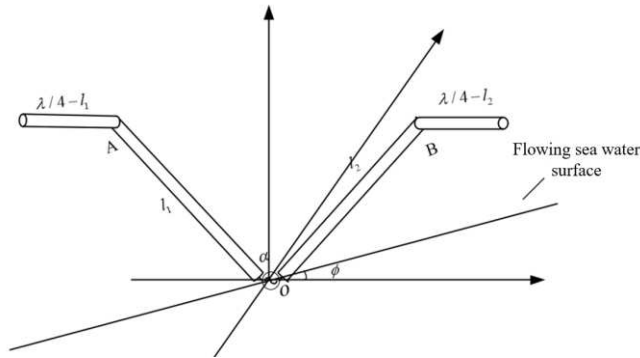Figure 6: The equivalent ocean wave relative tilt state diagram of the compressed V-shape dipole antenna

Simulation Verification

The FEKO electromagnetic simulation software was used for simulation verification, a compressed V-shape dipole antenna model on the sea surface was established, and the electrical characteristics of the antenna were solved by the method of moments. At this time, setting the parameters of the antenna is also an important process for parameter optimization in the later stage. Assuming that the "V"-shaped antenna includes an angle $\alpha = 45^o$,(Because the inclination angle of the hull generally does not exceed 45°, even when the inclination exceeds 45°, the antenna on one side will be submerged into the sea water and will lose its radiation effect. At this time, the antenna on the other side will be equivalent to a whip antenna and continue to radiate energy outward. The worst case of a compressed dipole antenna is also equivalent to a whip antenna.) the length of the two arms is $l_1 = l_2 = 0.75m, 0.5m, 0.25m$, the frequency $f = 75\text{MHz}$, and the antenna diameter is 6mm. Traditional whip antennas and standard V-shape dipole antenna use the same physical size as compressed V-dipole dipole antenna. In order to avoid the influence of seawater on the antenna current, the antenna is wrapped with a layer of polyethylene for insulation. The established sea antenna model is shown in Fig. 7..
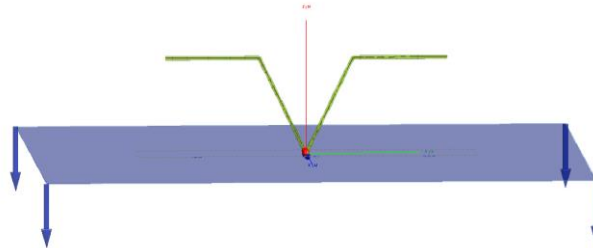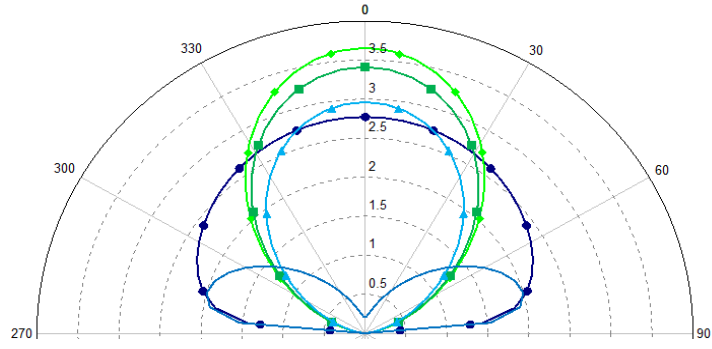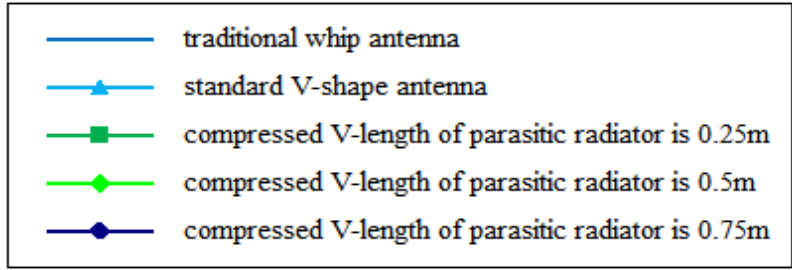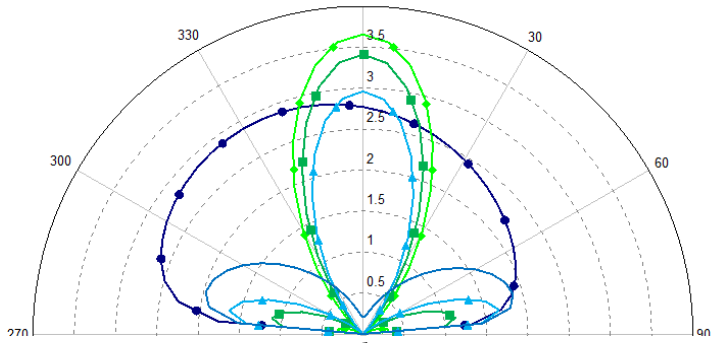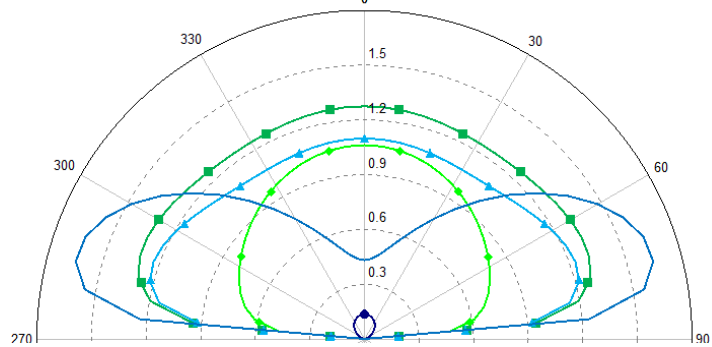

Figure 7: The antenna model of the compressed V-shape dipole antenna on the sea surface
In order to ensure that the antenna can not only communicate at sea, but also achieve close-to-air communication, $\phi = 0^o, 20^o, 45^o$, $\varphi = 0^o, 90^o$ is selected to compare the gain and pattern of the compressed V-shape dipole antenna，the standard V-shape dipole antenna and the traditional whip antenna. The simulation results are shown in Fig. 8.(a-f).
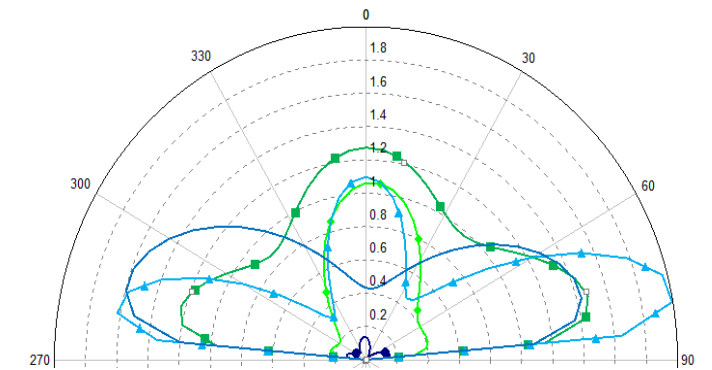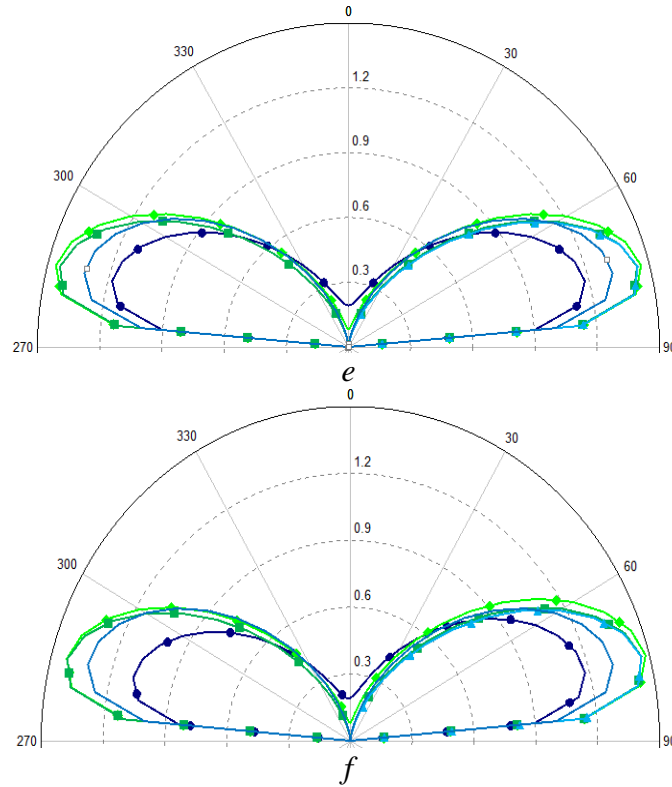
e

f

Figure 8: Comparison of the field pattern of the compressed V-shape dipole antenna with the traditional whip antenna and the standard V-shape dipole antenna

$(a)\phi = 0^o, \varphi=0^o;$ $(b)\phi = 0^o, \varphi=90^o;$
$(c)\phi = 20^o, \varphi=0^o;$ $(d)\phi = 20^o, \varphi=90^o;$
$(e)\phi = 45^o, \varphi=0^o;$ $(f)\phi = 45^o, \varphi=90^o.$

By comparing the field patterns of the compressed V-shape dipole antenna with the traditional whip antenna and the standard V-shape antenna, it can be found that the compressed V-shape dipole antenna has good omnidirectionality and relatively stable directivity, thus solving the blind spot problem of the traditional whip antenna. However, when the antenna is tilted more than 45°, the seawater will submerge one side of the antenna. At this time, the other side of the antenna is almost vertical, similar to the whip antenna, and there will also be a blind spot for reception. However, this is an unavoidable situation and the only possibility for the blind spot of the compressed V-shape dipole antenna. Compared with the standard V-shape antenna, it has a larger directivity; Compared with the traditional whip antenna, it solves the blind spot problem. And once the whip antenna touches the waves, it will lose its radiation performance, and the compressed V-shape antenna can solve this problem very well. Therefore, the antenna can be applied to the real marine environment, and the working state is reliable and stable.

Far-field experiment

In order to further verify the radiation performance of the compressed V-shape dipole antenna, the simulation model was made into real objects for far-field experimental measurement, and the dual-antenna measurement method was used to compare the compressed V-shape dipole antenna with the whip antenna and standard V-shape antenna to measure whether the far-field field strength is consistent. Fig. 9. shows the model of the compressed V-shape dipole antenna homemade. The far-field distance of 1km is selected. Considering the actual ocean environment, the flowing sea surface usually brings the antenna

to the maximum tilt of 45º, so the tilt angle ϕ selects $10^o, 30^o, 45^o$. Since the antenna radiation is a symmetrical structure for the four quadrants, the horizontal plane direction φ chooses two angles 0°、90°, and to reflect the omnidirectionality of the compressed V-shape dipole antenna, the vertical plane measurement angle θ chooses 90°. The lengths of the V-part on one side are set to 0.25, 0.5, and 0.75m, respectively, the included angle of the antenna is 45º, and the total length of one side is 1m and the radius is 3mm, which is consistent with the simulation process. For the compressed V-shape dipole antenna, standard V-shape dipole antenna and the traditional whip antenna, a total of 30 points were measured to obtain the field pattern in each direction. Traditional whip antennas and standard V-shape dipole antenna use the same physical size as the compressed V-dipole dipole antenna. The comparison results are shown in Table 1.

Figure 9: Homemade compressed V-shape dipole antenna

Tilt angle ϕ	Horizontal direction angle φ	Traditional whip antenna	Standard V-shape dipole antenna	Compressed V-shape dipole antenna $l_1=l_2=0.25$m	Compressed V-shape dipole antenna $l_1=l_2=0.5$m	Compressed V-shape dipole antenna $l_1=l_2=0.75$m
10	0	11.48	20.63	22.63	25.32	28.43
10	90	11.16	15.46	16.51	18.04	17.54
30	0	10.87	24.45	25.94	27.96	29.64
30	90	10.43	15.38	17.01	17.95	17.62
45	0	8.46	27.65	15.43	30.41	31.68
45	90	8.11	16.13	16.87	17.54	17.14

Table 1: Receiving field strength in all directions at different tilt angles(mV/m).

It can be seen from Table 1 that compared to the traditional whip antenna and standard V-shape dipole antenna, the compressed V-shape dipole antenna has higher receiving field strength at multiple angles. As the receiving distance increases, this gap will become more obvious. Through this experiment and simulation results, the following conclusions can be drawn:

1. The compressed V-shape dipole antenna makes up for the blind area problem of the traditional whip antenna in sea-to-air communication. It maintains the directivity of the traditional whip antenna near the water surface and also has a good radiation effect in the upper air field, which fully reflects the omnidirectionality of the compressed V-shape dipole antenna;

2. As the tilt angle of the antenna continues to increase, its directivity in the upper air field will gradually decrease, but it still maintains a better communication effect than the traditional whip antenna and standard V-shape dipole antenna, and its directivity near the

water continues to increase，which provides a good proof for the communication stability and reliability;

3. when the parasitic radiator is about 0.25m after analysis, its radiation performance is better than that of traditional whip antenna and standard V-shape antenna;

4. Assuming operating in high sea conditions, the influence of sea waves on antenna radiation will be huge. For the traditional whip antenna, the antenna energy cannot be radiated due to the tilt; and for the compressed V-shape dipole antenna, no matter how the ocean waves tilt it, there is always a side structure that can radiate to the outside, thus ensuring a good communication effect. This makes it possible for unmanned surface boats to go to the deep sea. Of course, this is only an idea, but it will also become a major focus that needs to be studied and resolved in the future.

Conclusions

This paper calculates the electrical characteristics of the proposed compressed V-shape dipole antenna structure, verifies its theoretical applicability, and obtains its radiation performance parameters in all directions; based on the new dipole antenna structure, in the electromagnetic simulation software FEKO, the antenna radiation model on the sea surface was established, the field pattern, and reflection coefficient of the VHF antenna were simulated and verified, and the compressed V-shape dipole antenna, the traditional whip antenna and standard V-shape dipole antenna were calculated and verified under the vertical and inclined conditions. The compressed V-shape dipole antenna solves the blind area problem of the traditional whip antenna well, and has better omnidirectionality comparing with standard V-shape dipole antenna, and this superiority continues to increase as the tilt angle of the antenna is affected by the waves increases; the results show that, the compressed V-shape dipole antenna is an efficient, stable and omnidirectional antenna structure, and provides a new, omnidirectional antenna form for sea-to-sea and sea-to-air short-range communication of surface unmanned boats, and It provides theoretical support for the compressed V-shape dipole antenna for surface communication under high sea conditions.

Data Availability

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

Acknowledgements

Competing interests

The authors declare that there is no competing interests.

Author contributions statement

Data curation, M.X.; Formal analysis, S.F.; Funding acquisition, L.L.; Methodology, L.L.; Project administration, S.F.; Resources, M.X.; Software, M.X.; Validation, M.X.; Writing – original draft, M.X & L.L..; Writing – review & editing, S.F..

Additional information

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