The application of small size spiral tube coil antenna in the development of electromagnetic radiator

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Abstract. When the electromagnetic wave propagates in water, the attenuation will increase with the increase of frequency, so the application of electromagnetic wave in water is limited to the low frequency band. At present, in order to realize the low-frequency electromagnetic wave radiation, the commonly used method is tuning the spiral tube coil antenna (Electromagnetic radiator). In practical application, the electromagnetic radiator used to realize high-power electromagnetic radiation usually has the characteristics of large size and many coil turns. Therefore, for the development of high-power electromagnetic radiator, there are many difficulties, such as high cost and difficult manufacture. Therefore, it is necessary to analyse the relationship between the radiation performances of different sizes of electromagnetic radiator, and use this relationship to guide the development of high-power electromagnetic radiator. Based on this, this paper analysed the radiation characteristics of spiral tube coil antenna, and the application of small-size electromagnetic radiator in the development of electromagnetic radiator.

1. Introduction

As we all know, when the electromagnetic wave propagates underwater, the attenuation is large and will increase with the increase of frequency. Therefore, the application of electromagnetic wave in underwater is limited to the low-frequency range. The low-frequency electromagnetic wave can be used in underwater metal detection, electromagnetic fuze, ship magnetic characteristics simulation and so on. For the radiation of low-frequency electromagnetic wave, the main radiation method is tuning the spiral tube coil antenna (electromagnetic radiator), the tuning method is shown in Figure 1.

![Schematic diagram of electromagnetic radiator tuning](image_url)

Figure 1. Schematic diagram of electromagnetic radiator tuning

The electromagnetic radiator which can realize high-power radiation has the characteristics of large size and heavy weight, so there are many problems in the development of high-power electromagnetic radiator, such as difficult to manufacture, high cost, and inconvenient to test. In practical application, if we directly develop the high-power electromagnetic radiator, and the developed electromagnetic radiator can not meet the actual needs, it will waste time, cause unnecessary waste, and increase the manufacturing cost. In order to save cost, this paper analysed the relationship between the radiation...
intensity of electromagnetic radiator and the test distance, coil turns, length and section size of the electromagnetic radiator. Finally, we draw the conclusion that we can use the radiation performance of small-scale electromagnetic radiator to simulate the radiation performance of high-power electromagnetic radiator.

2. Theoretical analysis of electromagnetic radiator

The electromagnetic radiator is actually a multi-turn coil, the cross section shape of the coil depends on the actual demand, such as circle, rectangle, etc. As shown in Figure 1, for the electromagnetic radiator, when the size of the electromagnetic radiator is far smaller than the observation distance of the field point, it can be approximated as a magnetic dipole the radiation intensity of the electromagnetic radiator is expressed by the magnetic dipole moment M, which is called the magnetic moment. Therefore, the magnetic moment M is an important index to measure the performance of the spiral tube electromagnetic radiator[3].

![Figure 1. Equivalent Schematic Diagram of Spiral Tube Electromagnetic Radiator](image)

For the spiral tube electromagnetic radiator, if the turns of the coil is n, the area of the coil is S, the excitation current is I, the radiation magnetic moment M can be expressed as:

$$M = nIS$$  \((1)\)

In practical application, in order to improve the radiation efficiency of spiral tube electromagnetic radiator, it is necessary to add iron core into the coil, which is made of magnetic material, such as silicon steel. After the core is added, the radiated magnetic moment can be expressed as:

$$M = nKIS$$  \((2)\)

Where k is a coefficient related to relative permeability. Therefore, the magnetic moment of the electromagnetic radiator with iron core is related to the relative permeability of the iron core.

For the electromagnetic radiators which the magnetic moment is M, the spatial distribution of the magnetic field can be expressed as equation \((3)\)[4]:

$$\begin{align*}
B_x &= \frac{3\mu_0 M}{8\pi (R^2+r^2)^{3/2}} \frac{r^2 \sin 2\phi \cos \theta}{R^2+r^2} \\
B_y &= \frac{3\mu_0 M}{8\pi (R^2+r^2)^{3/2}} \frac{r^2 \sin 2\phi \sin \theta}{R^2+r^2} \\
B_z &= \frac{\mu_0 M}{2\pi (R^2+r^2)} \left[1 - \frac{3(r^2 \sin^2 \phi)}{2(R^2+r^2)}\right]
\end{align*}$$  \((3)\)

For the magnetic field radiated by the electromagnetic radiator, in the axial direction (Z axis, $\phi=0^\circ$) and the normal direction (X-Y plane, $\phi=90^\circ$), the magnetic field only has Z component.

When $\phi=0^\circ$, $r \gg R$, we can get:

$$\begin{align*}
B_x &= B_y = 0 \\
B_z &= \frac{\mu_0 M}{2\pi r}
\end{align*}$$  \((4)\)
When $\phi=90^\circ$, $r >> R$, we can get:

$$
\begin{align*}
B_x &= B_y = 0 \\
B_z &= \frac{\mu_0 M}{4\pi r}
\end{align*}
$$

(5)

From equations (5) and (6), it can be seen that in the axial and normal directions of the electromagnetic radiator, the magnetic field only has $z$ component, and at the same distance, the intensity of the axial magnetic field is twice the normal

$$
B_z = \frac{\mu_0 M}{2\pi r} = \frac{\mu_0 nKIS}{4\pi r} \quad \phi=0^\circ
$$

$$
B_z = \frac{\mu_0 M}{4\pi r^3} = \frac{\mu_0 nKIS}{4\pi r^3} \quad \phi=90^\circ
$$

(6)

From equation (6), we can draw the conclusion that the magnetic intensity radiated by the electromagnetic radiator at a certain point in space is directly proportional to the coil area, coil turns and $K$, and inversely proportional to the third power of the distance $r$ from the point to the center of the electromagnetic radiator.

If the cross-sectional area of electromagnetic radiator 1 is $S_1$, the number of coil turns is $n_1$, and the excitation current is $I_1$, the cross-sectional area of electromagnetic radiator 2 is $S_2$, the number of coil turns is $n_2$, and the excitation current is $I_2$. In addition, electromagnetic radiator 1 and the radiator 2 is made of the same material. Then the magnetic fields of the electromagnetic radiator 1 and the electromagnetic radiator 2 in the direction of $\phi=90^\circ$ can be expressed as Equation (7).

$$
\begin{align*}
B_{z1} &= \frac{\mu_0 n_1 K I_1 S_1}{4\pi r^3} \quad \text{Radiator 1} \\
B_{z2} &= \frac{\mu_0 n_2 K I_2 S_2}{4\pi r^3} \quad \text{Radiator 2}
\end{align*}
$$

(7)

From equation (7), we can draw the conclusion that: If $I_1=I_2$, $n_1=\alpha n_2$, $r_1=\alpha r_2$, then $B_{z1}=B_{z2}$.

3. The analysis of test data

In order to verify the relationship between the cross-sectional area, turns, test distance and magnetic field strength of the spiral tube electromagnetic radiator analysed above, two electromagnetic radiators are made, and the parameters of the electromagnetic radiator are shown in table 1.

| Table 1. Parameters of electromagnetic radiator |
|-----------------------------------------------|
| The number of radiators | Turns | Cross-section size | Length |
|----------------------------|-------|--------------------|--------|
| Electromagnetic Radiator 1 | 800   | 2cm×3cm            | 45cm   |
| Electromagnetic radiator 2 | 80    | 0.2cm×0.3cm        | 4.5cm  |

In order to test the radiation performance of electromagnetic radiator, signal source, power amplifier, power supply, electromagnetic sensor and tuning capacitor are needed. When testing the radiation performance of electromagnetic radiators, the excitation current of electromagnetic radiator 1 and electromagnetic radiator 2 are both 1A. The test data are shown in table 2 and table 3:

By analyzing the test data, we can get the following conclusion: When the amplitude of the excitation current signal of the two electromagnetic radiators is the same, although the test distance, the number of coil turns, the length and the section size of the electromagnetic radiator 1 and the electromagnetic radiator 2 are different (the test distance, coil turns, length and section size of the electromagnetic radiator 1 are 10 times that of the radiator 2.), the measured magnetic field strength is the same.
Table 2. The test data of electromagnetic radiator 1

| Test distance/m | Magnetic induction intensity/nT |  |
|-----------------|---------------------------------|---|
|                 | Bx/nT          | By/nT          | Bz/nT          | B/nT          |
| 3               | 167.2          | 5.7            | 8.9            | 167.5         |
| 4               | 70.3           | 6.6            | 5.6            | 70.8          |
| 5               | 35.4           | 3.5            | 2.1            | 35.6          |
| 6               | 20.4           | 2.2            | 2.1            | 20.8          |
| 7               | 12.2           | 1.7            | 2.6            | 12.6          |
| 8               | 8.2            | 1.8            | 2.1            | 8.7           |
| 9               | 6.3            | 1.4            | 1.2            | 6.6           |
| 10              | 4.2            | 1.3            | 1.0            | 4.5           |

Table 3. The test data of electromagnetic radiator 2

| Test distance/cm | Magnetic induction intensity/nT |  |
|------------------|---------------------------------|---|
|                  | Bx/nT          | By/nT          | Bz/nT          | B/nT          |
| 30               | 171.2          | 6.7            | 8.0            | 171.5         |
| 40               | 72.8           | 5.9            | 6.1            | 73.3          |
| 50               | 35.9           | 4.2            | 5.7            | 36.6          |
| 60               | 21.1           | 4.2            | 7.6            | 22.8          |
| 70               | 12.6           | 3.4            | 3.9            | 13.6          |
| 80               | 8.4            | 2.6            | 2.3            | 9.1           |
| 90               | 6.1            | 1.6            | 1.6            | 6.5           |
| 100              | 4.2            | 1.7            | 1.2            | 4.7           |

4. Conclusion and Application
In this paper, the radiation theory of spiral tube electromagnetic radiator is analyzed, and two spiral tube electromagnetic radiators are manufactured and tested. Then, the relationship between the number of turns, section size, length, magnetic field test distance of spiral tube electromagnetic radiator and the radiation intensity of spiral tube electromagnetic radiator is obtained. When the excitation current amplitude is the same, if the coil turns, cross-section size, length and magnetic field test distance of the spiral tube electromagnetic radiator 1 are \( \alpha \) times that of the spiral tube electromagnetic radiator 2, the magnetic field intensity will be the same.

The conclusion of this paper can be used to simulate the radiation characteristics of large-scale electromagnetic radiator with the radiation characteristics of small-scale electromagnetic radiator, and guide the development of large-scale and high-power electromagnetic radiator.

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