Comprehensive performance analysis of coil electromagnetic radiator

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Abstract—The coil electromagnetic radiator is widely used in underwater weapon system and underwater active electromagnetic detection, and it’s an essential part of electromagnetic fuze, active electromagnetic detection and other systems. The main parameters to measure the electromagnetic radiator are coil turns, inductance and radiation intensity. In this paper, the relationship between coil turns, inductance and radiation intensity of electromagnetic radiator is analyzed. Through theoretical analysis and experimental test, we can draw the following useful conclusion: Although increasing the number of coil turns can improve the radiation magnetic moment of unit exciting current, too many turns of coil is not good for engineering implementation. Therefore, in practical application, the relationship between coil turns, size, inductance and magnetic moment of the radiator should be considered comprehensively.

1. INTRODUCTION

Almost all the fuze systems and active electromagnetic detection systems of underwater weapons use magnetic signals to achieve specific functions. The energy radiated by coil type electromagnetic radiator is mainly magnetic. Therefore, coil electromagnetic radiator is widely used in underwater weapon system and active electromagnetic detection system. In practical applications, especially underwater electromagnetic detection usually requires electromagnetic radiators to radiate strong magnetic field signal. The radiation magnetic moment of the electromagnetic radiator can be improved by increasing the exciting current amplitude and increasing the coil turns of the electromagnetic radiator. However, in practical application, because of the limitation of space layout of the system, the limitation of overall weight of the system and the matching circuit of the electromagnetic radiator, the radiation capacity of the electromagnetic radiator can’t be improved only by increasing the exciting current or increasing the number of coil turns, so when we designing the electromagnetic radiator, the relationship between size, inductance and magnetic moment of the electromagnetic radiator should be considered comprehensively[1].

2. THE ANALYSIS OF COIL ELECTROMAGNETIC RADIATOR

In practical application, coil electromagnetic radiator is generally multi turn coil with iron core, and its cross-section shape is mostly circular and rectangular. The structure of coil type electromagnetic radiator is shown in figure 1.
As shown in Figure 1, the coil electromagnetic radiator with length \( l \) and equivalent radius \( R \) of cross section can be regarded as composed of \( n \) magnetic dipoles in series, so its radiation field is similar to that of magnetic dipole. When the electromagnetic radiator is placed vertically, the space radiation field of coil electromagnetic radiator can be expressed as (1)\(^2,3\):

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

In (1), \( \mu \) is the permeability of the space medium, \( r \) is the distance from the field point to the center point of the radiator, and \( M \) is the radiation magnetic moment. The radiation magnetic moment is an important index to measure the radiation performance of the electromagnetic radiator. The magnitude of the radiation magnetic moment is related to the exciting current \( I \), the number of coil turns \( n \), the cross-sectional area \( S \) of the radiator, and the effective permeability \( \mu_e \) of the iron core, and the radiated magnetic moment \( M \) can be expressed as (2):

\[
M = \mu_n IS
\]

Where \( \mu_n \) can be expressed as (3):

\[
\mu_n = \frac{\mu_e}{1 + (\mu_e - 1) N_d}
\]

Where \( N_d \) is demagnetization factor, and can be expressed as (4)\(^4,5\):

\[
N_d = \frac{D^2}{I^2} \left( \ln \frac{2l}{D} - 1 \right)
\]
In addition, the inductance of coil type electromagnetic radiator can be expressed as (5):

\[ L = \frac{k\rho_i \mu_0 N^2 s}{l} \]  

(5)

Where \( k \) is the Nagaoka coefficient[6].

The coil type electromagnetic radiator is an inductive load. Therefore, in order to improve the radiation efficiency of the electromagnetic radiator, it is necessary to use capacitor to tune the electromagnetic radiator, and the tuning method is shown in Figure 2.

![Figure 2. Schematic diagram of electromagnetic radiator tuning](image)

The equivalent circuit is shown in figure 3.

![Figure 3. Equivalent circuit for the tuning of electromagnetic radiator](image)

It can be seen from figure 3 that the tuning of the electromagnetic radiator is to form a series resonant circuit by using capacitor connected in series with the electromagnetic radiator. The impedance \( Z \) of the circuit can be expressed as (6):

\[ Z = R + j \omega L - \frac{J}{j \omega C} \]  

(6)

Where \( R \) is the resistance of the coil, \( L \) is the inductance of the electromagnetic radiator, and \( C \) is the capacitance value of matching capacitor.

When the frequency of the signal is \( f = \frac{1}{2\pi \sqrt{LC}} \), the circuit is in resonant state. At this time, the impedance of the circuit is the minimum and the radiation efficiency of the electromagnetic radiator is the highest, and (6) can be expressed as (7):

\[ Z = R \]  

(7)

When the circuit composed of electromagnetic radiator and capacitor is in resonance state and the exciting current is \( I \), the terminal voltage peak value of matching capacitor or radiator is (8):

\[ U_c = U_L = 2\sqrt{2} \pi fL I = \frac{1}{\sqrt{2}\pi fC I} \]  

(8)

In practical application, the terminal voltage of the capacitor must be less than the withstand voltage of the capacitor, Otherwise, it will cause the breakdown of the capacitor and affect the normal operation of the whole system.

It can be seen from (2) and (3) that the radiation magnetic moment \( M \) of the electromagnetic radiator
is directly proportional to the number of coil turns $n$, and the inductance of the coil radiator is directly proportional to the square of the coil turns $n$. Although the radiation magnetic moment of the electromagnetic radiator can be improved by increasing the number of turns of the coil, the inductance of the radiator will also increase with the increase of the number of coils, and the increase speed of the inductance is faster than that of the radiation magnetic moment. When the inductance of the electromagnetic radiator is too large, the voltage withstand requirement of the matching capacitor is also improved. In addition, for capacitors with the same capacitance value, the higher the withstand voltage, the larger the volume of the capacitor, when the system space is relatively compact, the overall layout of the system is more difficult. Therefore, in practical application, the radiation capacity of the electromagnetic radiator can’t be improved by only increasing the number of coils. The relationship between the size, inductance and magnetic moment of the radiator should be considered comprehensively. We should comprehensively consider the relationship between size, inductance and magnetic moment of the radiator.

3. THE ANALYSIS OF TEST DATA

In order to verify the relationship between turns, inductance and radiated magnetic moment of coil electromagnetic radiator analyzed above, three electromagnetic radiators were fabricated, and the parameters of electromagnetic radiator are shown in Table I.

| The number of radiators | Iron core material | Turns | Cross-section size | Length |
|-------------------------|--------------------|-------|--------------------|--------|
| Radiator 1              | Fe based amorphous | 400   | 1.5cm×2cm          | 45cm   |
| radiator 2              | Fe based amorphous | 800   | 1.5cm×2cm          | 45cm   |
| radiator 3              | Fe based amorphous | 1200  | 1.5cm×2cm          | 45cm   |

The electromagnetic radiator is tested by using the signal whose frequency is 1000Hz and the amplitude of exciting current is 1 A, and the test results are shown in Table II.

| The number of radiators | inductance | Tuning capacitor | magnetic moment | Capacitor terminal voltage |
|-------------------------|------------|------------------|----------------|---------------------------|
| Radiator 1              | 21.66mH    | 1.17uF           | 22.07A.m²      | 192V_p                   |
| radiator 2              | 86.81mH    | 0.29uF           | 45.35 A.m²     | 771V_p                   |
| radiator 3              | 195.16mH   | 0.13uF           | 67.96 A.m²     | 1733V_p                  |

Assuming that the radiation magnetic moment of the electromagnetic radiator is 100A.m², and then the excitation current amplitude and capacitor terminal voltage of the radiator with different turns are shown in Table III.

| The number of radiators | excitation current | magnetic moment | Capacitor terminal voltage |
|-------------------------|--------------------|----------------|---------------------------|
| Radiator 1              | 4.6A               | 101.52A.m²     | 885V_p                   |
| Radiator 2              | 2.2A               | 99.77          | 1969V_p                  |
| Radiator 3              | 1.5A               | 101.94A.m²     | 2600V_p                  |
It can be seen from table III that when the radiated magnetic moment of the electromagnetic radiator is the same, the terminal voltage of the matching capacitor is different, and the more the coil turns, the higher the voltage. When the number of coil turns is 400, the matching capacitor terminal voltage peak value \( V_{p=400} = 885v \); when the coil turns is 1200 turns, the matching capacitor terminal voltage peak value \( V_{p=1200} = 2600v \).

Although in the case of the same radiated magnetic moment, the less the coil turns, the smaller the terminal voltage of the matching capacitor, and the lower the voltage withstand requirement of the capacitor, but this does not mean that the less the coil turns, the better, because the less the coil turns, the greater the excitation current required. When the electromagnetic radiator works, there is heat loss, which is proportional to the square of the excitation current amplitude. Therefore, in practical application, the relationship between size, coil turns, radiated magnetic moment, inductance and heat loss of the electromagnetic radiator should be considered comprehensively.

4. CONCLUSION

In this paper, the relationship between the number of turns, the radiation magnetic moment and the inductance of the radiator is analyzed, and three electromagnetic radiators with different turns were tested. Through analysis and test, we get the following conclusions: The radiation magnetic moment is proportional to the number of coil turns, and the inductance of radiator is proportional to the square of coil turns; For any two electromagnetic radiators with the same core but different coil turns, when the radiation magnetic moment is the same, the excitation current is inversely proportional to the ratio of the coil turns, and the terminal voltage of the matching capacitor is directly proportional to the ratio of the coil turns.

The conclusions obtained in this paper can be used to guide the comprehensive analysis of coil electromagnetic radiator and guide the design of electromagnetic radiator.

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