Research on Mechanical Antenna Performance Based on Rotating Permanent Magnet Triangle Array

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Abstract. Traditional low-frequency antennas have larger volume and higher energy consumption. These characteristics make the traditional antennas easy to be destroyed by the enemy and expensive to maintain. In this paper, a mechanical antenna based on triangular array of rotating permanent magnets is introduced, and a prototype is made according to the proposed theoretical assumptions. Different from the traditional electric antenna, the mechanical antenna adopts the way of motor driving the permanent magnet to rotate, which realizes the miniaturization of the low-frequency transmitting antenna. In this paper, the analytical model of the rotating magnetic dipole is presented. By comparing the simulation results and the experimental data with the theoretical calculation results, it is proved that the mechanical antenna based on the rotating permanent magnet array can emit low-frequency sinusoidal electromagnetic waves, which has a broad application prospect in the Ultra-Low-Frequency/Very-Low-Frequency (ULF/ VLF) communication field.

1. Introduction

Due to the skin effect, the high-frequency electromagnetic wave will generate eddy electric field inside the conductor, which is offset with the original current, resulting in the electromagnetic wave cannot propagate deeply in it [1].

Because of its long wavelength, low-frequency electromagnetic wave can penetrate rock, soil, sea water and other media to carry out underwater submarine communication and underground signal transmission. And low-frequency electromagnetic waves can also use the earth's surface ionosphere for long-distance intercontinental transmission. Therefore, low-frequency electromagnetic wave has a wide application prospect in the military and mining fields in the future [2].

Although low-frequency electromagnetic waves have many advantages, the traditional low-frequency transmitting antenna is limited by Chu's Limit [3]. The size of the antenna has a corresponding relationship with the frequency, which leads to the large volume and structure, complex line feed, large transmitting power and loss power, and low overall radiation efficiency of the traditional low-frequency antenna [4]. In 2017, the U.S. Defense Advanced Research Projects Agency (DARPA) proposed and planned the "A Mechanically Based Antenna" (AMEBA) program, which focused on a new system of low-frequency radiated antennas designed to reduce antenna size. Under the premise of reducing power consumption, it can radiate Ultra-Low-Frequency/Very-Low-Frequency (ULF/ VLF) wave. In recent years, in-depth studies on this project have been carried out at home and abroad and much progress has been made [5].

In this paper, a low-frequency signal transmitting antenna based on triangular array of rotating permanent magnet is introduced, and a prototype is developed based on the theoretical model. A
triangular array of permanent magnets fixed on the disc is driven by a motor to rotate, emitter low-frequency/very-low-frequency sinusoidal wave. In this paper, by comparing the simulation results and the experimental data with the theoretical model, it is found that the simulation results and experimental data accord with the theoretical model of rotating magnetic dipole, which proves that the scheme is suitable for the transmission of low-frequency electromagnetic waves, and it can continuously generate low-frequency sinusoidal wave signals under the condition of low power consumption of the equipment.

2. Theoretical model and structure design of mechanical antenna

The basic radiation mechanism of low-frequency mechanical antennas is that permanent magnet or electret material is used as radiation unit to generate electromagnetic wave in space according to specific motion mode.

2.1. Radiation mechanism of rotating magnetic dipoles

Among them, the rotating permanent magnet and the electret can be equivalent to the rotating magnetic dipole and electric dipole respectively [6], and the electromagnetic radiation generated by the magnetic dipole is stronger at the same rotation frequency [7]. The physical model of the rotating permanent magnetic is shown in Figure 1. Macroscopically, the magnetizing current on the surface of the permanent magnet body is:

$$\alpha = M \times \hat{n}$$  \hspace{1cm} (1)

Where, $M$ is the equivalent surface current density of the permanent magnet in the model, and $\hat{n}$ is the unit vector of the magnetizing direction of the permanent magnet itself. For a mechanical antenna with a rotating permanent magnet as its radiation source, its surface has an equivalent current density $J$ [8]. At time $t$, the retarded potential $A(r, t)$ of the current density $J$ at a spatial point from the rotation centre is:

$$A(r, t) = \frac{\mu}{4\pi} \int \int \int_{V} \left(\frac{J(r', t - \frac{R}{c})}{R}\right) e^{-\frac{i}{c}(r - r')} \, dv'$$ \hspace{1cm} (2)

Where into, $R$ is the distance between the field point $r$ and the source point $r'$, $V$ is the integral region of the volume, $c$ is the speed of light, $J(r', t')$ is the volume current density of the source point $r'$ at time $t'$;

By using the definition of $A(r, t)$, and according to the ampere-current model, the analytical expression for magnetic flux density $B(r, t)$ of the point at the distance $r$ from the centre point is:

$$B = \nabla \times A(r, t) = \frac{\mu m}{4\pi r^3} e^{i(kr - \omega t)} \left[ 2(1 - jkr) \sin \theta \hat{r} + (1 + jkr + k^2 r^2) \cos \theta \hat{\theta} + (jkr - k^2 r^2) \hat{\varphi} \right] e^{j\varphi}.$$ \hspace{1cm} (3)

Where: $m$ is the magnetic dipole moment, and $\theta$ is the polar Angle that is the angle between the direction vector of the measuring point and the positive direction of the Z axis. $\varphi$ is the azimuth angle, which is the angle between the direction vector of the measuring point and the positive direction of the y axis. It can be seen from the expression that the near-field magnetic flux density of the rotating permanent magnet is inversely proportional to the distance $r^3$ of the measuring point. This is an important parameter of its near-field radiation characteristics.

Figure 1. Rotating permanent magnet.
2.2. Structural design of mechanical antenna
The structure of mechanical antenna is shown in Figure 2. The transmitter based on three radial permanent magnet fixed to the disc is set on the xo-z plane and rotate around the y-axis. The residual flux density of NdFeB material is 1.23 T with strong magnetism and low cost. Under proper functioning, the magnetic field intensity of the same size permanent magnet is higher than that of the exciting coil [9]. Therefore, the NdFeB magnet is used as the material of the radiation unit. In the experiment, the maximum output power of the motor is 120 W, the rated torque is 0.85 Nꞏm. It can meet the requirements. At the same time, the transmission mode uses transmission belts for buffering and shock absorption.

Each permanent magnet is cylindrical with radius \( R = 5 \) mm and height \( H = 3 \) mm. The diameter of the disk is \( D = 100 \) mm and the thickness of it is \( W = 2 \) mm. And the material of the disk is aluminium alloy with very low magnetic permeability (approximately equal to air). Under the premise of ensuring the structural strength, the influence on the electromagnetic field of the antenna is the least [10].

![Figure 2. Structure of rotating permanent magnet triangular array.](image)

3. Simulation results and analysis
Since the mechanical antenna proposed in this paper requires transient analysis of the electromagnetic field generated by its rotating motion, the software ANSYS Maxwell is used in this paper to carry out simulation analysis on the antenna. The material is NdFeB35.

The speed of motor is set as 500 rev/s. The time-step value of 10 ms is used here to have 200 sample points in every period. The origin is in the center of the disk, and the rotation plane is xo-z plane and rotate around the y-axis. The direction of the coordinate axis is shown in Fig.1. The time domain profile of \( B \)-field components at point P1 along the x-axis (1000 mm away from the center of rotation) is plotted in Figure 3. (a). The actual value of magnetic flux density at the receiving point is obtained by combining the x, y, and z axis components [8], and the calculation formula is:

\[
B = \sqrt{B_x^2 + B_y^2 + B_z^2}
\]

Then MATLAB is used to complete the Fourier transform from time domain to frequency domain, and the frequency domain curve of \( B_x \) components as shown in Figure 3. (b) is obtained.

![Figure 3. (a) Time domain waveform of point P1. (b) Frequency domain waveform of point P1.](image)
Considering the transient characteristics of the mechanical antenna, the near field distribution of $B$-field vector in the $xoz$ plane at the time $t=0.005s$ is selected as shown in Figure 4. (a). As can be seen from the figure, the distribution of $B$-field is strongest at the two magnetic poles of the permanent magnet during the whole working process. Based on the rotating permanent magnet model, the $B$-field distribution of the mechanical antenna was further simulated. The $B$-field in the $xoz$ plane was simulated, and the $B$-field amplitude distribution was obtained as shown in Figure 4. (b).

![Figure 4](image)

Figure 4. (a) B-field Vector distribution of magnetic flux density in the xoz plane. (b) Distribution of B-field amplitude in the xoz plane.

The strength analysis of the magnetic field signal of the mechanical antenna is mainly to simulate the $B$-field signal at a given distance. The amplitude of the $B$-field signal at each point is obtained through simulation, and the relationship between the magnetic field signal and the distance is obtained. Table 1 shows the simulation data of the magnetic field signal changing with distance when the speed of motor is 500 rev/s.

| Distance (mm) | magnetic flux density (μT) | Distance (mm) | magnetic flux density (μT) |
|--------------|--------------------------|--------------|--------------------------|
| 100          | 30.76                    | 400          | 3.821                    |
| 150          | 6.181                    | 500          | 2.88                     |
| 200          | 5.69                     | 600          | 1.927                    |
| 300          | 4.682                    | 700          | 1.02                     |

Simulation verify the near field radiation characteristics, comparison of the magnetic flux density of mechanical antenna with distance is shown in Figure 5. Among them, the curve in the figure is the analytic model of MATLAB simulation, and the scatter point is the simulation data of Maxwell. Good agreement is observed between the simulation results of Maxwell and the theoretical model calculated by MATLAB. It proves that radiation characteristics of the mechanical antenna near-field and theoretical models are the same, can be used for low frequency signal transmission.

![Figure 5](image)

Figure 5. Variation of the magnetic flux density with distance.
4. Experimental verification

4.1. The test environment for the experiment

As shown in Figure 6 below, the transmitting antenna is a mechanical antenna proposed in this paper, and the magnetic field signals emitted from the antenna are received by the receiver in a given sampling plane and then transmitted to the oscilloscope via cable. The oscilloscope converts the changing magnetic field signals into electrical signals and outputs them to the screen, and finally completes the display and storage of data. \( r \) is the distance between the transmitter and the receiver.

Figure 6. (a) Photo of Mechanical Antenna and receiver. (b) The time domain waveform displayed by oscilloscope.

By faraday law of electromagnetic induction, the transformation relationship between magnetic flux density and induced electromotive force is:

\[
U_r = 2\pi f B N_1 S_1 \cos \theta_1 \tag{5}
\]

As can be seen from the above equation, when the number of turns of the receiving antenna \((N_1)\) and the cross-sectional area \((S_1)\) are determined, the value of the magnetic flux density value at a certain position can be calculated through the measured value of the induced electromotive force \((U_r)\).

4.2. Experimental results and analysis

In the experiment, the speed of the motor was set at 900 rpm, and the statistical results of the amplitude of the signals emitted by the mechanical antenna received at different distances were shown in Table 2 below.

The statistical signal amplitude in the above table is compared with the theoretical results, and the results shown in Figure 7 are obtained. By comparison, it can be found that the experimental data are basically consistent with the theoretical calculation results, which indicates that the \( B \)-field in the near region of the designed permanent magnet array structure is approximately proportional to \( 1/r^3 \). The source of the error may be the distance between the center of rotation and the center of the magnet.

Table 2. The variation of the signal amplitudes with distance.

| Distance (mm) | 150 | 200 | 300 | 400 | 500 |
|---------------|-----|-----|-----|-----|-----|
| Voltage (mV)  | 11.8| 8.6 | 4.2 | 2.0 | 0.85|

Figure 7. Comparison of signal amplitudes.
5. Conclusion
A low frequency signal transmitting antenna based on rotating permanent magnet triangular array is proposed in this paper. The time domain and frequency domain waveform in the near field are obtained by simulation. The distribution characteristics of $B$-field amplitude and Vector are analyzed by simulation. By comparing the experimental data and simulation results with the theoretical model, it is found that the magnetic flux density value of the mechanical antenna in the near field is approximately inversely proportional to $1/r^3$ ($r$ is the distance from the measuring point to the center of rotation). In summary, this mechanical antenna can emit low-frequency sinusoidal electromagnetic waves of the corresponding frequency by rotating at a fixed speed, which can penetrate the buildings and be used for underwater and underground communication. Its small size and low energy consumption can significantly improve the miniaturization and portability of the low-frequency antenna.

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