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Extremely-Low Frequency Mechanical Antenna Based on Vibrating Permanent Magnet

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Abstract

Extremely-low-frequency (ELF) communication has stimulated widespread research interest during past years. Up to now, most permanent magnet mechanical antennas usually rotate the magnet to generate electromagnetic waves. Here we demonstrate a new mechanical antenna based on vibrating permanent magnet. This mechanical antenna radiates electromagnetic waves through the reciprocating movement of permanent magnets. Finite element simulations and experiments are applied to verify the radiation characteristics of the vibrating mode mechanical antenna. Compare with the rotating permanent magnet mechanical antenna, this antenna can generate an induced voltage with a peak value of 0.179 mV at 1 m. Both the simulated and experimental results indicate that this mechanical antenna can successfully generate stable time-varying electromagnetic waves in the ELF band. This vibrating mode mechanical antenna paves a way for the design of permanent magnet mechanical antenna.

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1. Introduction

Frequencies lying between 3 Hz to 300 Hz have been designated as extremely-low frequency (ELF). With corresponding wavelengths from 1000 km to 100000 km, ELF electromagnetic waves can travel long distances with very little losses.[1] Unlike radio frequency electromagnetic waves, low-frequency electromagnetic waves are an attractive choice for underwater and underground environments where high frequency radio signals have a great loss.[2-7]

Traditional antennas generate electromagnetic waves through current oscillations in conductors. The ELF antennas have a huge power consumption due to their huge and complicated system.[8-9] To solve this problem, the concept of mechanical antennas was proposed by researchers.[10] Unlike traditional antennas, the mechanical antenna radiates electromagnetic waves by physically moving. The radiation efficiency of a conventional electrically small antenna is limited by its ohmic loss, which is the dominating loss mechanism. Mechanical antenna directly converts mechanical energy into electromagnetic energy, thus effectively improving radiation efficiency.[11] It is believed that mechanical antennas can break through the Chu-Harrington limit of traditional antennas' radiation.[12]

Mechanical antennas are mainly divided into two categories: permanent magnet-based mechanical antenna and piezoelectric material-based mechanical antenna. Among them, Kemp *et al.* used the inverse piezoelectric effect of a rod-shaped lithium niobate crystal to design and manufacture a mechanical antenna in the very-low-frequency (VLF) band.[13] Due to the high radiation efficiency, permanent magnet was often chosen as the scheme of transmitting module of mechanical antenna. In 2017, Selvin *et al.* employed rotating magnets to radiate low-frequency electromagnetic waves.[14,15] Madanayake *et al.* designed a small high-efficiency VLF transmitter for underground and subsea wireless communication based on the mechanical rotation of a permanently polarized dipole.[16] Bickford *et al.* proposed a rotating model of a mechanical antenna transmitter and experimentally proved the higher radiation efficiency of the mechanical antenna than traditional antenna.[10,11] A new type of mechanical shutter antenna based on a fixed permanent magnet was proposed by Golkowski *et al.*[17] Srinivas presented an electromechanical system called

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magnetic pendulum array for low-frequency transmission.[18,19] Researches on signal modulation of mechanical antennas are also in progress.[20]

Here we propose a new mechanism of mechanical antenna, which uses a vibrating permanent magnet to generate the time-varying electromagnetic wave. Compared with the permanent magnet mechanical antenna based on rotating form, the proposed mechanical antenna has better electromagnetic radiation performance.

2. Mechanical antenna model analysis

The ELF mechanical antenna system includes radiating unit and receiving unit. The ideal material for the radiating unit is the permanent magnet, which is one of the strongest magnets and can be used as radiating material for the transmitting section. As for permanent magnet mechanical antennas, the radiation intensity is usually determined by the size and the residual magnetic flux density of the permanent magnet. Servo motors and other power sources drive permanent magnets to generate mechanical motions for radiating electromagnetic waves. The vibrating mode based magnet mechanical antenna is feasible, and the frequency of this mechanical antenna is also adjustable, which provides a new idea for the research of mechanical antennas.

It is necessary to figure out its radiation performance for a magnetic dipole antenna. Here we utilize commercial software Comsol multiphysics to predict the radiation characteristics of permanent magnets in different motion modes. As illustrated in Fig. 1b, the model consists of three parts: permanent magnet, air domain, and infinite element domain. The geometric center of the magnet is located in the center of the air domain, and the permanent magnet material is N50 type Neodymium magnet (NdFeB) permanent with a size of 6 × 2 cm. The magnet is transversely magnetized, and the residual magnetic flux density modulus is 1.2 T. Here we set up the vibration area for the model so that the magnet realizes simple harmonic motion along the y-axis. The vibration equation is:

$$y = A\sin(2\pi ft) \quad (1)$$

As shown in Fig. 1a, the permanent magnet simulation models have two mechanical motions modes: vibration and rotation. The vibration direction of the permanent magnet is set to vibrate up and down along the y-axis, where A is the amplitude and set to 5 cm, f is the vibration frequency and equal to the frequency of generated electromagnetic waves. As the permanent magnet starts to vibrate, it will radiate electromagnetic waves. A probe point is set on the y-axis, 1 m away from the vibration center, to measure the near-field performance of the mechanical antenna.

Due to the transverse magnetization of the magnet, the magnetic field component (B_x) at the probe point is much larger than B_y. Fig. 2 shows the B_x of the mechanical antenna based on vibration permanent magnet at the probe point. When the vibration frequency is set at 5 Hz, 10 Hz, 20 Hz, and 30 Hz respectively, the frequency of the B_x is the same as the vibration frequency. The maximum peak value of B_x can reach 0.314 mT at the probe point. The magnetic field component is positive because the magnetic poles of the permanent magnets are not reversed. The B_x exhibits a sinusoidal change, and its peak value doesn't change with the vibration frequency. Simulation results show that a vibrating permanent magnet can generate sinusoidal signals. The frequency of generating electromagnetic waves generated by rotating permanent magnet mechanical antenna has the following relationship with rotating speed:

$$n = 60f \quad (2)$$

where n is the rotating speed (r/min), and f is the frequency. As shown in Fig 1a, the permanent magnet rotates around its geometric center. Keep the same simulation settings as the mechanical antenna model based on vibration permanent magnet.

As shown in Fig. 3, when the rotating speed is set to 300 r/min, 600 r/min, 1200 r/min, and 1800 r/min respectively, the corresponding frequencies of the generated electromagnetic wave are 5 Hz, 10 Hz, 20 Hz, and 30 Hz. Its magnetic field component (B_x) also exhibits a sine waveform. The reversion of magnetic poles makes the magnetic flux density alternate positive and negative values. The maximum peak value of the B_x at the probe point is 0.241 mT, which is 30.29% lower than the vibrating mode based permanent magnet mechanical antenna. It can be concluded that the mechanical antenna based on vibrating permanent magnet can generate a time-varying magnetic field component in the ELF band. Besides that, vibrating magnets can be used as radiation elements for mechanical antennas.

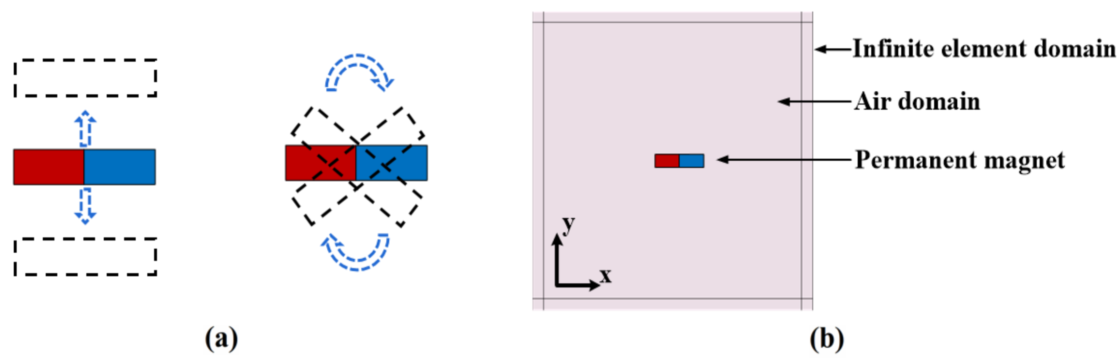

Fig. 1 Schematic diagrams of the finite element simulation model. (a) Vibration and rotational movement modes of permanent magnet. (b) Simulation setup of permanent magnet mechanical antenna.

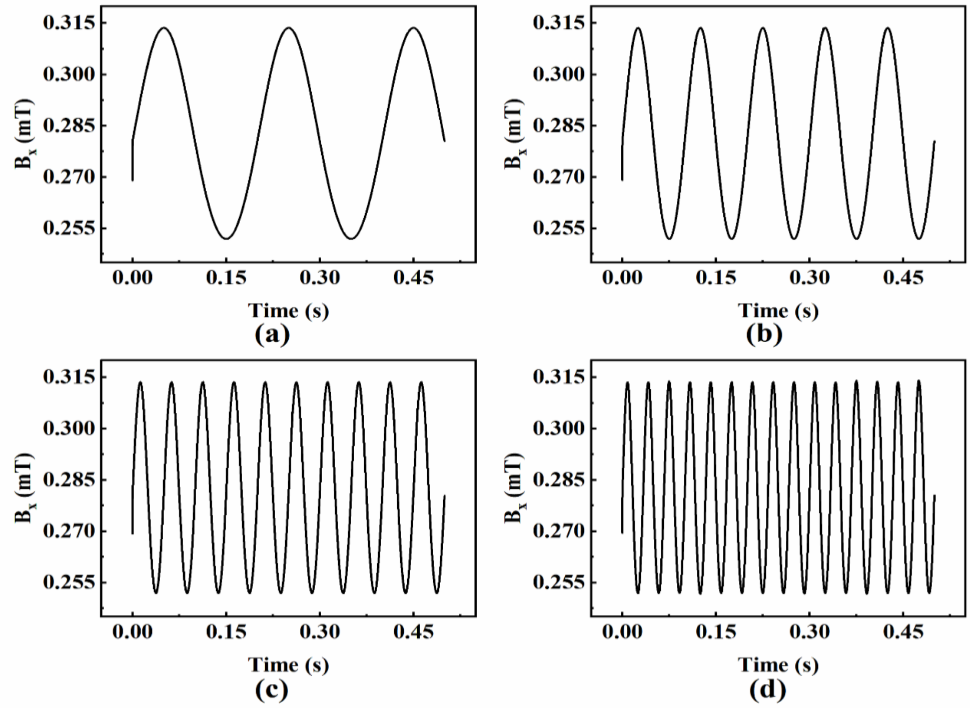

Fig. 2 Simulated magnetic field component (B_x) with the vibration frequencies of (a) 5 Hz; (b) 10 Hz; (c) 20 Hz and (d) 30 Hz at the probe point.

3. Mechanical antenna measurement system

To evaluate the ELF signals generated by the vibration based permanent magnet mechanical antenna, a near-field measurement was performed with the help of a vibration motor and a magnetic loop antenna receiver. And a rotating permanent magnet mechanical antenna is measured in the same system to provide a comparison reference. ELF signal emission terminal includes servo drive motor and permanent magnet. The permanent magnet is a grade N50 NdFeB with dimensions of 5 × 1.5 × 0.5 cm^3 and is magnetized in the radial direction. The permanent magnet and the servo motor are installed together through an adhesive. The servo motor is powered by a mobile power supply.

As shown in Fig. 4, the servo rotating motor and reciprocating vibration motor are used to rotate or vibrate the permanent magnet. It should be noted that the servo drive

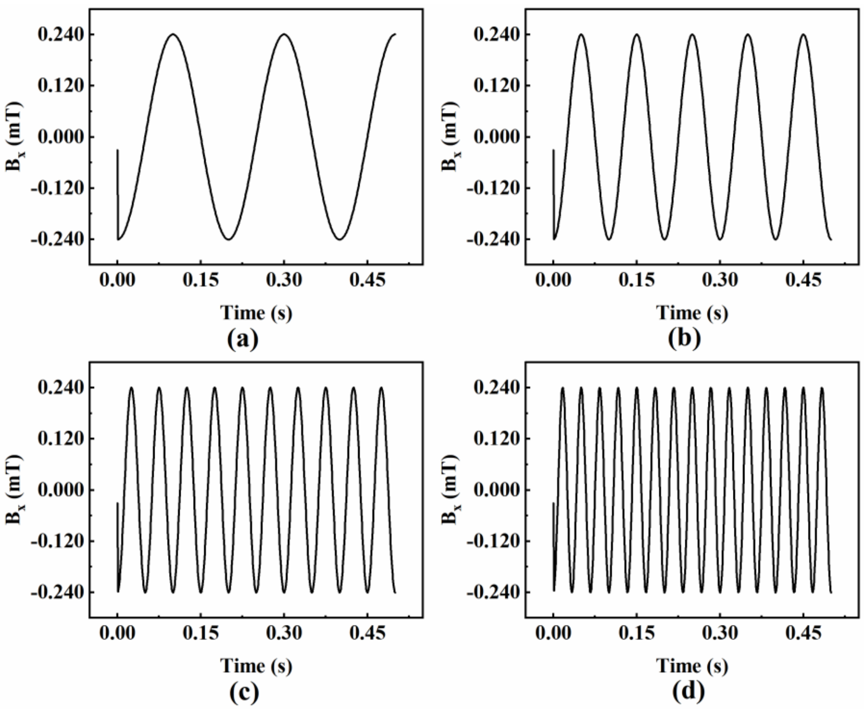

Fig. 3 Simulated magnetic field component (B_x) with the rotating speeds of (a) 300 r/min; (b) 600 r/min; (c) 1200 r/min and (d) 1800 r/min at the probe point.

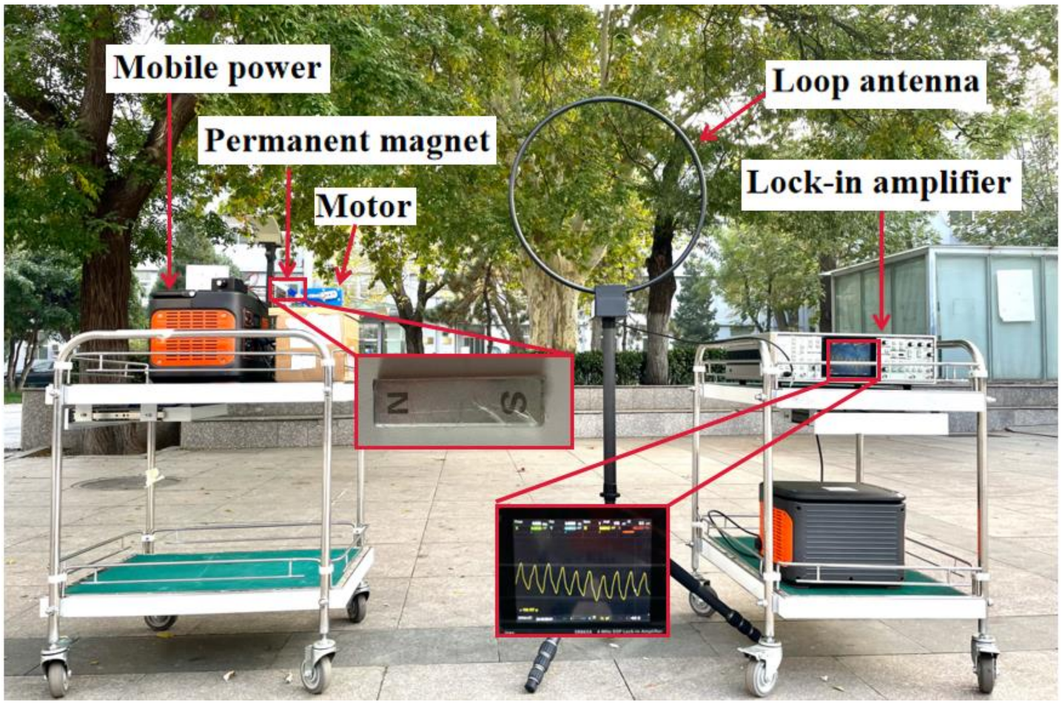

Fig. 4 Experimental mechanical antenna device.

motor adjusts the speed by adjusting drive, and the reciprocating vibration motor adjusts the speed through the knob device. As mentioned above, the radiation frequency of ELF electromagnetic waves can be adjusted by controlling the motor speed and vibration frequency. The receiving device is shown in Fig 4, including a loop antenna and a lock-in amplifier. The loop antenna can detect the magnetic flux variation and generate induced voltage. The lock-in amplifier can extract a weak signal from an extremely noisy environment. Normally, the environment noise can be effectively filtered out by the lock-in amplifier. The attenuation frequency of the filter is set to 24 dB and the loop antenna is placed at a distance of 1 m from the transmitting device. Besides, the motion center of the permanent magnet is on the same horizontal plane as the loop antenna.

As the speed of the servo rotating motor is set to 300 r/min and 900 r/min, the frequencies of the corresponding emission signals are 5 Hz and 15 Hz respectively. As shown in Fig. 5, the frequency of the signals received by the loop antenna has changed significantly, and the signal waveform has a sinusoidal form. As shown in Fig. 5a, the maximum induced voltage of the signal can reach 0.114 mV, and the minimum value is 0.0353 mV. The maximum induced voltage of the received signals can reach 0.112 mV, and the minimum value is 0.0317 mV in Fig. 5b. The peak voltage presents a stable form and almost does not change when the frequency changes. The experimental results coincide with the simulation results as shown in Fig. 3.

In the measurements, unlike the rotary motor, the reciprocating motion of the vibrating motor is often affected by inertia, which will generate a time delay when the vibrating motor drives the permanent magnet in the opposite direction. Affected by the mechanical structure of the motor, the vibration motor will appear severe jitter at a high frequency. Therefore, the frequency of the motor is set below 7 Hz. The received voltage graph shows a sine wave, which means that vibrating permanent magnets can also generate electromagnetic waves. As shown in Fig. 6a, the maximum

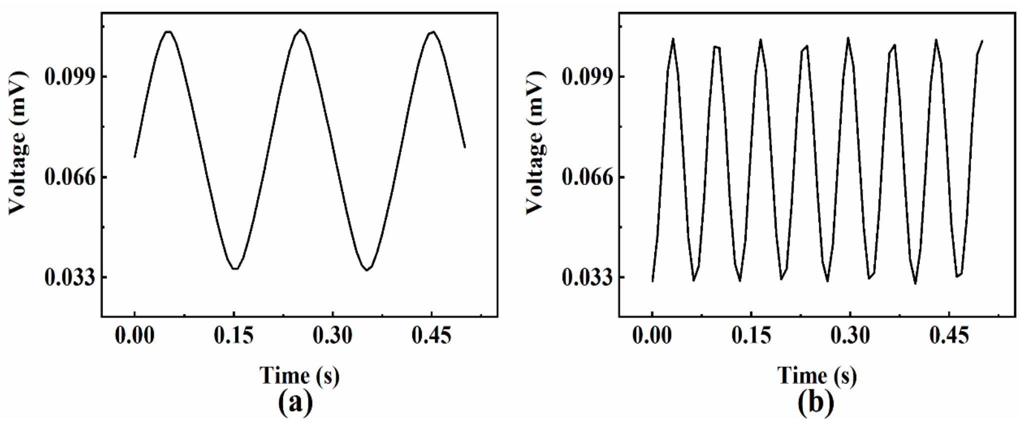

Fig. 5 Received signals as the rotating speeds of the transmitter are set to (a) 300 r/min and (b) 900 r/min.

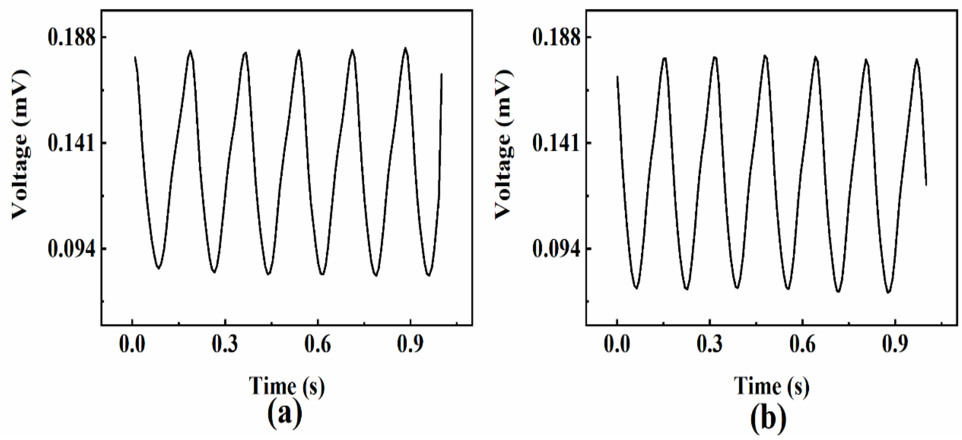

Fig. 6 Received signals as the vibrating speeds of the transmitter are set to (a) 5.8 Hz and (b) 6.4 Hz.

induction voltage received by the loop antenna is 0.179 mV when the vibration frequency is 5.8 Hz. The maximum induction voltage is also 0.179 mV when the vibration frequencies are 6.4 Hz in Fig. 6b. Its induced voltage increases by 57.02% compared with the rotating permanent magnet mechanical antenna. The behavior of the experimental data is in good agreement with the simulated results. Therefore, employing vibration magnets as a radiation element can effectively improve the signal strength of the mechanical antenna.

4. Conclusion

A new mechanical antenna based on vibrating permanent magnet was presented and analyzed. The feasibility of this new type of permanent magnet mechanical antenna is demonstrated through finite element simulation and experiment. The proposed mechanical antenna vibrates the permanent magnet to generate electromagnetic waves in the ELF band. When the vibration frequency of the permanent magnet is adjusted, the frequency of electromagnetic waves generated by mechanical antennas also changes accordingly. The signal strength of the mechanical antenna has been significantly improved compared with the permanent magnet mechanical antenna based on rotating mode. This mechanical antenna provides a new way for the design of low-frequency wireless transmission systems.

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Conflict of interest

There are no conflicts to declare.

Supporting information

Not applicable.

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