Enhanced SLF radiation efficiency in a piezoelectrically driven magnetic pendulum transmitter

Zhaoqiang Chu ; Chenyuan Yu ; Wei Dan ; Shizhan Jiang ; Yuzhu Ren ; Kewen Dong ; Shuxiang Dong

Appl. Phys. Lett. 124, 072901 (2024)
https://doi.org/10.1063/5.0193249
Enhanced SLF radiation efficiency in a piezoelectrically driven magnetic pendulum transmitter

Cite as: Appl. Phys. Lett. 124, 072901 (2024); doi: 10.1063/5.0193249
Submitted: 21 December 2023 · Accepted: 1 February 2024 · Published Online: 16 February 2024

Zhaoqiang Chu,1,2,a) Chenyuan Yu,1 Wei Dan,1 Shizhan Jiang,1 Yuzhu Ren,1 Kewen Dong,1 and Shuxiang Dong3,a)

AFFILIATIONS
1Qingdao Innovation and Development Base, Harbin Engineering University, Harbin 150001, China
2College of Underwater Acoustics Engineering, Harbin Engineering University, Harbin 150001, China
3College of Materials Science and Engineering, Peking University, 100871 Beijing, China

a)Authors to whom correspondence should be addressed: zhaoqiangchu@hrbeu.edu.cn and sxdong@pku.edu.cn

ABSTRACT

Long-wave radio station based on an electrically small antenna and mechanical transmitter based on a rotating permanent antenna are commonly used for super low frequency (SLF, 30–300 Hz) communication. The current challenge is the difficulty in developing both an efficient and a miniaturized SLF transmitter. Enlightened by the advantages of piezoelectric motor over conventional electromagnetic motor in terms of efficiency and the output torque in low frequency band, we propose a piezoelectrically driven magnetic pendulum transmitter by combining a magneto-mechano-electric (MME) cantilever and a swinging magnet in this work. The magnetic force coupling between the MME cantilever and the swinging magnet is optimized by changing the thickness and the attached position of the used Metglas laminates. The experimental results show that the piezoelectrically driven magnetic pendulum transmitter has a working frequency of 57 Hz, and a flux density of 149 fTpk at 100 m distance could be expected with a low power consumption of 40.64 mW. When driving the same magnet with an electromagnetic motor, however, the required power consumption reaches 4.2 W for 57 Hz magnetic field radiation. By dividing the induced magnetic moment over the consumed power, the effective radiation efficiency of our proposed piezoelectrically driven SLF magnetic pendulum transmitter significantly increased from 0.55 to 17.4. This proof-of-concept work is believed to open a dimension for the design and the application of efficient SLF mechanical transmitter in the future.

Published under an exclusive license by AIP Publishing. https://doi.org/10.1063/5.0193249

High frequency wireless communication has enabled convenient interaction between people and different items. However, high frequency communication technology fails in subterranean and underwater environments due to the severe path loss. In contrast, low frequency magnetic/electric field communication allows the information interaction in lossy medium and cross-domain circumstances. Long-wave radio station based on an electrically small antenna and mechanical transmitter based on a rotating permanent antenna are commonly used for extremely low frequency (ELF) and super low frequency (SLF) communication. The current challenge is the difficulty to develop both efficient and miniaturized ELF/SLF transmitter. In 2017, Wang et al. reported the electromagnetic wave propagation across the sea surface over a distance of more than 3 km at SLF band with reasonable transmitting power. The used dipole antenna has a length of 100 m and requires high driving power. Magnetic dipole can be also used in SLF band, and it is known that magnetic field is less attenuated across the air–sea interface since air and seawater have similar magnetic permeability. Chai et al. in 2018 developed a system that uses coils for magnetic induction communication. The transmitter had a cross-sectional area of 4 m² and error-free data communication from a height of 2 m above the surface to a depth of 35 m below the surface. However, huge power consumption of 1000 W was required for this loop antenna.

In comparison with an electrically small antenna, mechanical transmitter is able to circumvent the impedance matching based on the acoustic resonance mode and decrease the ohmic loss via the electric field driving mode. Thus, higher energy transfer efficiency for a mechanical transmitter can be expected. In 2021, Liu et al. demonstrated an SLF mechanical transmitter by using a cylindrical magnet with a diameter of 4 cm and a length of 15 cm. The rotating
permanent magnet antenna was driven by a servo motor, and it consumed only about 2.74% of the power in comparison with an equivalent coil antenna at 30 Hz. A magnetic flux density of 4 pT can be expected at 100 m distance with an average input power of 60.36 W, and it is quite possible to achieve over 100 m undersea magnetic communication. The problem for a rotating permanent magnet antenna is the poor directionality and the difficulty to load the baseband information. In 2022, Fereidoony et al. proposed a novel stacked magnet-swinging array (MPA) as an antenna for efficient SLF transmission. The MPA has a resonance frequency of 715 Hz, and a high transmission field of 700 fT at 100 m is projected with a small input power of 2 W. It should be noted here that the magnet-swinging array has better directionality compared with a rotating permanent magnet antenna and easier information modulation can be enabled.

The above-mentioned magnet-rotating and magnet-swinging transmitters are driven by an electromagnetic motor or a coil, sharing a similar current excitation mode. It is well known that piezoelectric motors have higher power density, stronger output torque at low frequencies, and a small size in comparison with conventional electromagnetic motors. For a mechanical transmitter, higher energy transfer efficiency can be expected when we consider an electric field excitation mode.

On this basis, we propose to drive the magnet-swinging transmitter through a piezoelectric actuator for realizing improved radiation efficiency in this work. Here, a widely used piezoelectric bimorph is considered as the driving element. By fixing its one end and combing a layer of soft magnetic material (Metglas), a magneto-mechano-electric (MME) cantilever is obtained, which can couple the bending deflection of the piezoelectric bimorph and the swinging angle of the radiation magnet. The coupling magnetic force is optimized by changing the thickness and the attached position of the used Metglas laminates. The experimental results show that the piezoelectrically driven magnetic pendulum transmitter has a working frequency of 57 Hz, and a flux density of 149 fTpk at 100 m distance could be expected with a low power consumption of 40.64 mW. The effective radiation efficiency of our proposed piezoelectrically driven magnetic pendulum transmitter significantly improved from 0.55 to 17.4 in comparison with the driving by an electromagnetic motor.

Figure 1(a) shows the schematic structure of the piezoelectrically driven SLF mechanical transmitter. A piezoelectric bimorph consisting of ceramic PZT-5H and the embedded 304 stainless steel is used here as a cantilever to generate bending displacement through fixing its left end. Metglas laminates are bonded on the bottom and the top side of the free end via epoxy resin and then a magneto-mechano-electric (MME) cantilever is obtained. The dimension of the attached Metglas laminates is varied to control the magnetic coupling intensity between the piezoelectric cantilever and the radiation magnet. Here, the radiation magnet is installed on a plastic frame through a pair of bearings. The bias magnets are used to provide restoring forces, and the bias field can be manipulated to move the resonance frequency of the rotation system close to the working frequency of the first bending mode of the piezoelectric cantilever.

Under the equilibrium state without any excitation voltage, the induced magnetic force between the MME cantilever and the radiation magnet is orthogonal to the provided restoring forces as shown in Fig. 1(a). Figure 1(b) then demonstrates the motion of the MME cantilever and the radiation magnet when applying a sine voltage with a period of T. At the moment t = 0, the whole system is in equilibrium. At t = T/4, the induced deflection of the cantilever results in the variation of the magnetic coupling and forces the clockwise rotation of the radiation magnet. Then the system goes back to the equilibrium state at T/2. At the moment t = 3T/4, the cantilever bends toward the right, and the counterclockwise rotating of the radiation magnet is induced. Finally, the radiation magnet will lie in the equilibrium state again, and it will swing back and forth with the excitation frequency. Consequently, SLF magnetic field can be generated. This is the
magneto-mechano-electric coupling process for our proposed SLF mechanical transmitter.

Figure 1(c) gives the prototype of the piezoelectrically driven SLF mechanical transmitter based on a magnetic pendulum. The dimension of the used piezoelectric bimorph and the radiation magnet is around 60 mm length × 20 mm width and 19 mm height × 13 mm outer diameter × 8 mm inner diameter, respectively. The bias magnets have the diameter of 10 mm and the Metglas foil has the dimension of 20 mm length × 22 mm width × 0.02 mm thickness. High-performance NbFeB permanent magnets with the trademark of N52 are used in this work. The residual magnetization (Br) of the used N52 magnets is 1430 mT, and the coercive field (Hc) is around 10 kOe. The swinging magnets and the bias magnets are magnetized along the radial and the thickness direction, respectively. Here, the coupling intensity between the MME cantilever and the radiation magnet greatly influences the working performance of the proposed SLF mechanical transmitter. In general, both high magnetic coupling intensity and large bending deflection of the cantilever are desired to enlarge the SLF magnetic field level. However, the above-mentioned two parameters are mutually exclusive; thus, the optimization should be conducted first.

During our experiment, we manipulated the magnetic force between the MME cantilever and the radiation magnet in equilibrium by changing the layer number and the position of the Metglas laminate. Figure 2 simulates the coupling magnetic force of our fabricated four transmitter samples via finite element analysis. Sample 1 performs the minimum magnetic force. Sample 4 has two layers of Metglas foil on each side and correspondingly generates an increased magnetic force about 16 mN. Please note that a stationary study is performed here to capture the performance difference of the four sample for simplicity. The swinging amplitude of the radiation magnet can be compared directly under a given excitation voltage for the MME cantilever to assess the field radiation performance of the four samples. However, it is still a challenge for us to accurately model such a complex coupling process. In fact, the converse coupling behavior can also be utilized to compare the field radiation performance indirectly. In the case of the converse magneto-mechano-electric coupling, we set the rotating angle of the radiation magnet to be ±10°, and then the induced deflection of the MME cantilever based on the coupling magnetic force is calculated through Multiphysics COMSOL software. The modeling result is shown in Fig. 2. It can be seen sample 2 performs the maximum deflection, which means its magneto-mechano-electric coupling capability could be the largest as well.

Apart from the optimization of the coupling intensity between the MME cantilever and the radiation magnet, it is also necessary to match the resonance frequency of the magnetic pendulum to the first order resonance frequency of the MME cantilever. During our experiment, we first fixed the first order resonance frequency of the MME cantilever and then carefully tuned the resonance frequency of the magnetic pendulum by changing the bias magnetic field. Under the excitation voltage of 80 Vpp, the free-end deflection of the individual MME bimorph for sample 2 was recorded, and the normalized frequency-sweeping curve is given in Fig. 3(a), which tells the first order resonance frequency of the MME bimorph as around 55 Hz. With respect to the magnetic pendulum system alone, its resonance frequency can be determined by measuring the generated field intensity B0 at 20 cm away when applying an excitation field HAC perpendicular to the direction of the bias field HDC as demonstrated in Fig. 3(b). Here, a home-made coil receiver with the dimension of ø34 mm × 60 mm length was used to capture the induced magnetic field components. After the tuning, the peak response occurs at the resonance frequency of 56 Hz as shown in Fig. 3(a), which is very close to the first order resonance frequency of the MME bimorph. Then radiation field Br of the piezoelectrically driven SLF mechanical transmitter was detected by the same receiving coil, and the resonance frequency of the whole antenna system was then determined to be around...
56 Hz by looking for the peak point from the frequency-response curve as plotted in Fig. 3(a).

Figure 4 demonstrates the received magnetic flux density $B_r$ with different excitation voltage. Here, the x-axis data of Fig. 4 represents the simulated magnetic force taken from Fig. 2 for our compared four samples. During the experiment, the receiving coil was placed at 20 cm away from the center of the radiation magnet and the applied voltage to the MME cantilever varied from 40 Vpp to 80 Vpp. Each transmitter sample operated at its resonance frequency. It can be seen that the radiation performance of sample 2 is better than the other samples, which agrees well with the results in Fig. 2.

Then we fabricated another piezoelectrically driven SLF mechanical transmitter and further characterized the radiation performance. The characterization results are given in Fig. 5. Here, we fixed the excitation voltage and the working frequency to be 80 Vpp and 57 Hz, respectively. The resonance frequency performs a very tiny offset compared with the sample in Fig. 3 and, thus, proves the reliability of our proposed antenna design. The induced magnetic field signal was also measured by the above-mentioned receiving coil. During the experiment, the induced voltage from the coil was first passed through a voltage preamplifier (SR560, Stanford Research, USA), and then a spectrum analyzer (SR865, Stanford Research, USA) was used to accurately capture the signal amplitude at the resonance frequency. The received magnetic flux density at different distances was plotted in Fig. 5(a). The obtained flux density at 1 m distance in free space reaches 153 nT, and a predicted flux density of 149 fT at 100 m distance is allowed according to the $1/r^3$ rate of decrease for near-field electromagnetic wave. Then the generated magnetic moment $m$ that contributes to the radiation field $B_{r,air}$ can be calculated as $0.715 \frac{A}{m^2}$ according the formula as follows:

$$B_{r,air} = \frac{\mu_0 m}{2 \pi r^3}.$$  

(1)

Figure 5(b) shows the radiation pattern of our optimized mechanical transmitter. During the measurement, the proposed transmitter was placed on a turntable, and the receiving coil was located at 1 m away at the same height. Conventional SLF mechanical transmitter based on the rotating permanent magnet performs a circular radiation pattern with no directivity. In contrast, the radiation pattern of our proposed piezoelectrically driven SLF mechanical transmitter has a shape of “8,” indicating some level of directivity.

It is now very important to know the power consumption of our proposed piezoelectrically driven SLF mechanical transmitter for understanding its efficiency advantage over electromagnetically driven magnet-rotating transmitter. Here, we define an effective near-field radiation efficiency $\eta_{effe} \left( \frac{A}{m^2}/W \right)$ as follows:

$$\eta_{effe} = \frac{m}{P},$$  

(2)

where $m$ is the induced magnetic moment, and $P$ is the consumed power. As given in Fig. 5(c), we measured the real power consumption as a function of the excitation voltage for our optimized piezoelectrically driven SLF mechanical transmitter. It can be seen that the power consumption is increasing linearly as we enlarge the driving voltage. For calculating the consumed real power, the excitation voltage and the excitation current are monitored at the same time. The time-domain monitoring waveform is given in the inset of Fig. 5(c). A phase difference $\theta = 57^\circ$ was induced when we excited the transmitter with 80 Vpp voltage. Then the power consumption $P$ is calculated as $P = U I \cos(\theta) = 41 \frac{mW}{\text{wav}}$. To compare the radiation efficiency over
conventional magnet-rotating transmitter, we also excited the used radiation magnet with a commercially available electromagnetic motor at the same working frequency of 57 Hz [see Fig. 1(d)]. The corresponding power consumption, radiation capability, and the effective radiation efficiency are included in Table I. A 42 W input power is required in the case of electromagnetic motor driving; thus, we conclude that the effective radiation efficiency of our proposed piezoelectrically driven magnetic pendulum transmitter significantly increases from 0.55 to 17.4. It should be noted here that driving a bigger rotating magnet will contribute to the increase in the radiation efficiency for our compared electromagnetically driven magnet-rotating transmitter, but a heavy rotating magnet will first make high-speed information loading difficult, and the efficiency increase is limited as well.

Table I summarizes the radiation performance of previously reported magnet-swinging antenna and magnet-rotating transmitter. It can be seen that the proposed piezoelectrically driven SLF mechanical transmitter performed a significantly improved radiation efficiency compared with other SLF antenna design. For further enhancing the radiation efficiency of our proposed piezoelectrically driven magnetic pendulum transmitter, we can first consider a high-Qm piezoelectrically driven magnetic pendulum transmitter significantly increases from 0.55 to 17.4. It should be noted here that driving a bigger rotating magnet will contribute to the increase in the radiation efficiency for our compared electromagnetically driven magnet-rotating transmitter, but a heavy rotating magnet will first make high-speed information loading difficult, and the efficiency increase is limited as well.

Table 1 summarizes the radiation performance of previously reported magnet-swinging antenna and magnet-rotating transmitter. It can be seen that the proposed piezoelectrically driven SLF mechanical transmitter performed a significantly improved radiation efficiency compared with other SLF antenna design. For further enhancing the radiation efficiency of our proposed piezoelectrically driven magnetic pendulum transmitter, we can first consider a high-Qm piezoelectrically driven bimorph, and an optimization about the size of the radiation magnet will also work. We repeated another test and enlarged the height of the swinging magnet from 19 mm to 32 mm, the radiated magnetic flux density at 100 m distance increased from 162 fTpk to 237 fTpk, while the consumed power decreased from 33 mW down to 27 mW. Further study about the theoretical limit of the radiation efficiency of our proposed piezoelectrically driven mechanical transmitter will be continued in the future.

In summary, a piezoelectrically driven magnetic pendulum transmitter was proposed to achieve an improved radiation efficiency in this work. The magnetic force coupling between the MME cantilever and the magnetic pendulum was optimized by changing the thickness and the attached position of the used Metglas laminates. The experimental results show that the piezoelectrically driven magnetic pendulum transmitter has a working frequency of 57 Hz, and a predicted flux density of 149 fT at 100 m distance is allowed with a low power consumption of 40.64 mW. In comparison with electromagnetically driven magnet-rotating/swinging antenna, the effective radiation efficiency of piezoelectrically driven magnetic pendulum transmitter significantly increased from 0.55/2.47 to 17.4. This proof-of-concept work is believed to open a dimension for the design and application of efficient SLF mechanical transmitter in the future. By using an array configuration with 50 elements, the piezoelectrically driven magnetic pendulum transmitter is expected to produce magnetic flux density more than 10 pT level at 100 m distance with a high energy transfer efficiency.

This work was supported by the National Natural Science Foundation of China (Grant Nos. 52101227 and U22A2019), the National Key R&D Program of China (Grant No. 2022YFB3205700), and the Natural Science Foundation of Shandong Province, China (Grant No. ZR2021QF021).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Zhaoqiang Chu: Conceptualization (lead); Funding acquisition (lead); Investigation (lead); Writing – original draft (lead); Writing – review & editing (lead). Chenyuan Yu: Data curation (equal); Formal analysis (equal); Validation (equal); Visualization (supporting). Wei Dan: Data curation (supporting); Software (supporting); Visualization (supporting). Shizhan Jiang: Data curation (supporting); Visualization (supporting). Yuzhu Ren: Data curation (supporting); Visualization (supporting). Shuxiang Dong: Conceptualization (lead); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

REFERENCES