Y-Stator Vibrating Magnet Antenna

Daniel J. Orfeo [1], Dylan C. Burns [1], Tian Xia [2], and Dryver R. Huston [1]

[1]Department of Mechanical Engineering, University of Vermont, Burlington, VT 05405 USA
[2]Department of Electrical and Biomedical Engineering, University of Vermont, Burlington, VT 05405 USA

A vibrating magnet antenna shows promise as an efficient, compact source for ultralow frequency (ULF) electromagnetic waves. ULF signals are able to penetrate through earthen materials, making this regime desirable for subterranean communication and detection of subterranean features. Oscillating a permanent magnet back and forth across a novel soft-magnet Y-stator projects a switching magnetic field capable of kilohertz frequencies. Arrays with multiple oscillators are favored due to energy scaling and parasitic losses. The permeability of magnetic circuits can be adjusted to change the potential energy of the magneto-mechanical oscillator, altering the natural frequency of vibration for frequency modulation. This article presents a theoretical justification of the Y-stator design, a simulation study performed using COMSOL Multiphysics Modeling Software, and preliminary laboratory results.

Index Terms—**Antenna, magnet, mechanical, Y-stator.**

I. Introduction

ULTRALOW frequency (ULF) electromagnetic waves from 300 Hz to 3 kHz penetrate effectively through earthen materials that deny megahertz-frequency radio signals [1]–[3]. An electrically small sub-kilohertz wire antenna with human-sized dimensions has low radiation resistance and high loss resistances, resulting in low radiation efficiency [4], [5]. This makes traditional antenna designs impractical [2] for many applications in which ULF signaling is desirable. In contrast, a magnetic dipole can be mechanically oscillated to directly produce a propagating electromagnetic wave. Crucially, Srinivas *et al.* [6] demonstrate that mechanical magnetic antennas can attain a much higher radiation efficiency than conventional antenna designs.

This article describes a novel design for a mechanical magnetic antenna capable of transmitting ULF signals. Soft-magnet stators project magnetic fields generated by permanent magnets which vibrate such that the overall magnetic dipole moment switches direction each cycle. Potential communication applications include low-bitrate radio transmission to and from subterranean machines, underwater vehicles, and people in mines. The device also has potential applications as a source for active magnetic sensing. When an oscillating magnetic field encounters a subsurface anomaly, there is a change in the induced magnetic field which is detectable with a magnetometer. It is possible to use an oscillating magnetic field to detect non-ferromagnetic materials by measuring induced eddy currents [7], [8]. This kind of active magnetic sensing has both terrestrial and extraterrestrial applications [9] including the ability to detect and inform about unexploded ordnance (UXO) [10], [11], underground infrastructure [12], soil composition, and ice [13].

Manuscript received September 7, 2020; accepted February 22, 2021. Date of publication March 24, 2021; date of current version June 23, 2021. Corresponding author: D. R. Huston (e-mail: dryver.huston@uvm.edu).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TMAG.2021.3066699.

Digital Object Identifier 10.1109/TMAG.2021.3066699

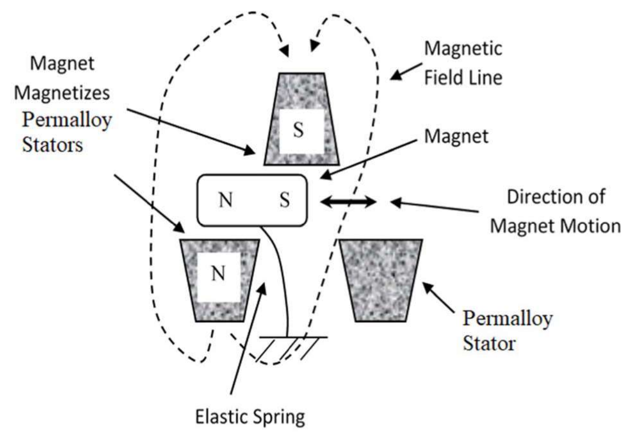

Fig. 1. Y-stator configuration with a single bar magnet oscillator.

II. Creating an Oscillating Field With a Vibrating Magnet

Rotating a magnet demonstrates the principle of an oscillating magnetic field for low frequencies, but rotation above 1000 Hz is energy-intensive [1] and makes frequency modulation (FM) difficult due to the inertia of the system. Mechanical vibration is easier to achieve at kilohertz frequencies, but vibrating a magnet produces spatial displacement of a magnetic field, not field reversal. However, coupling a vibrating magnet with soft-magnet stators can produce magnetic field reversal. Permalloy is a soft magnetic nickel–iron alloy that has high magnetic permeability and low hysteretic energy loss associated with field reversal. These properties enable permalloy to shape and project magnetic fields while incurring low energy losses. Fig. 1 illustrates permalloy (dark gray) arranged in a novel Y-stator configuration. A sprung permanent bar magnet oscillator moves back and forth, inducing poles in the permalloy stators. Vibration can be induced by the electromagnetic force generated from a solenoid (not shown) acting on the sprung magnet. Fig. 2 demonstrates the direction of the oscillating field changing due to the movement of the magnet.

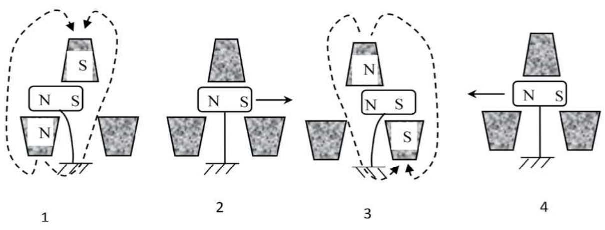

Fig. 2. Diagram of field oscillation due to Y-stator.

III. Y-Stator Arrays

The strength of the projected magnetic field increases when vibrating a stronger magnet or when vibrating a larger volume of magnetic material. Kinetic energy requirements decrease for arrays of small synchronized vibrating magnets compared with a single large magnetic oscillator. Because each magnet is small, less displacement is required to reverse each magnetic field, which saves energy. The kinetic energy T of an array of N rectangular bar magnets of density ρ with a length L twice the width and oscillating with an amplitude equal to L at frequency f is

$$T = \frac{1}{8} N \rho L^5 (2\pi f)^2. \quad (1)$$

The total volume V of the magnets is

$$V = \frac{NL^3}{4}. \quad (2)$$

This leads to an expression of kinetic energy in terms of number of magnets in the array

$$\frac{T}{V} = T' = \frac{1}{2} \rho L^2 (2\pi f)^2 \sim L^2. \quad (3)$$

The kinetic energy requirement increases as a square of the length of an oscillator, so minimizing this length saves significant energy even as the number of oscillators increases.

The coupling of oscillators in an array is controlled by the interaction strength between oscillators [14], the similarity of natural frequencies in a population [15], and the phase difference between individual oscillators [16]. If the range of natural frequencies decreases sufficiently, or if the relative coupling increases beyond a critical measure, a portion of the population of oscillators spontaneously couples [14]. An entirely coupled population of magnetic oscillators produces a coherent oscillating magnetic field.

IV. FM by Resonance Change

In addition to projecting an oscillating field, the permalloy soft-magnet stators increase the natural frequency of the vibrating permanent magnet oscillator. It takes work to move a magnetic field through the permalloy stators since doing so forces the magnetic field to extend through air. This work increases the magnetic potential energy (and therefore the total potential energy) of the mechano-magnetic system

$$U = \frac{1}{2} k_{\text{eff}} x^2. \quad (4)$$

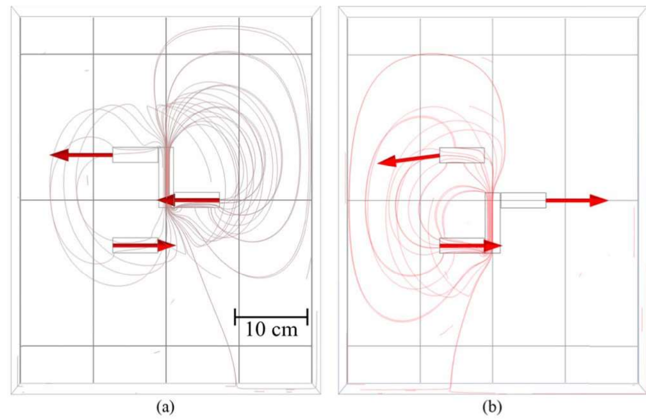

Fig. 3. COMSOL model of Y-stator device in position (a) and position (b). Lines are field lines; arrows are field direction and magnitude at points of interest.

An increase in potential energy raises the effective spring constant, k_{eff}. Increasing k_{eff} necessitates an increase in natural frequency, ω_n, according to

$$\omega_n = \sqrt{\frac{k_{\text{eff}}}{m}} \quad (5)$$

where m is the mass of the oscillating element.

A resonant oscillator vibrates at its natural frequency, ω_n, a low-energy state. Changing the natural frequency of a system is a low-energy method for FM since the frequency of vibration will spontaneously converge to the natural frequency. A Y-stator magnetic source could encode information by FM accomplished with resonance change. Adjusting a bias current in the permalloy soft magnetic stators changes the effective magneto-elastic stiffness of each oscillator, thereby changing its natural frequency.

V. Y-Stator Simulation Study

COMSOL Multiphysics Modeling Software was used to simulate the Y-stator magnetic source. The model space was filled with air (relative permeability $\mu_r = 1$) and an iron magnet ($\mu_r = 4000$) was magnetized lengthwise at 750 000 A/m. Soft-magnet stators ($\mu_r = 800\,000$) were assigned the preloaded material "nickel steel supermalloy." The closest approach between the magnet and permalloy stators was set to 1 mm, as a conservative estimate of tolerances in a future first prototype of the device.

Fig. 3 shows a Y-stator with three permalloy stators and a single bar magnet oscillator. Thin lines trace the magnetic field paths. Arrows begin at points of interest and aim according to field direction and magnitude. Fig. 3(a) shows the bar magnet in its first position. The two permalloy stators adjacent to the bar magnet project the field as expected, as indicated by the two topmost magnetic vector arrows. Fig. 3(b) shows the bar magnet in its second position. The projected field has reversed direction, as indicated by the two bottommost magnetic vector arrows. [There is also a slight angle change to the topmost vector in Fig. 3(b). Edge effects of the air box could be the cause.] Interestingly, the "extra" stator farthest away from the

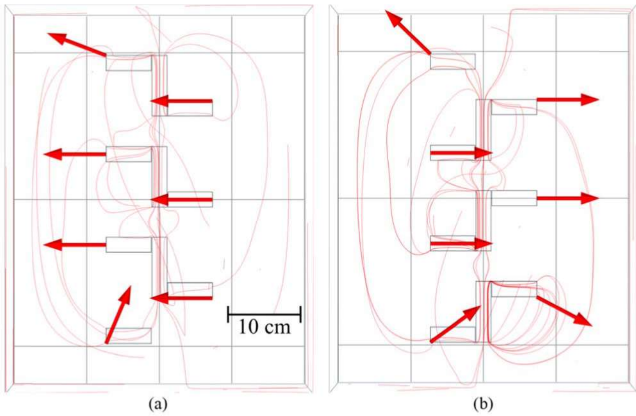

Fig. 4. COMSOL model of Y-stator array in position (a) and position (b). Lines are field lines; arrows are field direction and magnitude at points of interest.

magnet projects a field in the opposite direction of the net field [bottom arrow in Fig. 3(a) and top arrow in Fig. 3(b)]. It has a parasitic effect on the strength of the net projected oscillating field.

Fig. 4 shows the simulation results for a Y-stator array with three oscillators. While the field exhibits some off-axis angling, the net projected field shows good reversal. Note there is still only one "extra" stator projecting a parasitic field: the bottom arrow in Fig. 4(a) and the top arrow in Fig. 4(b). In the three-oscillator Y-stator array, one-in-seven stators projects a parasitic field compared with one-in-three stators in the case of the single-oscillator Y-stator. This leads to the conclusion that Y-stator arrays with more oscillators may provide improved device performance.

VI. Experimental Evidence Supports Y-Stator Design

A simplified Y-stator was built to verify the effect of permalloy stators on the natural frequency of a permanent magnet oscillator. Fig. 5(a) shows an accelerometer and a permanent magnet attached to a plate suspended by guitar strings. Two permalloy stators (visible at the bottom of the image) are located so that they do not interact with the magnet. Accelerometer spectral measurements determine that this system has a natural frequency of 8.25 Hz, shown in Fig. 5(b). Fig. 5(c) shows the permalloy stators in a half-Y configuration so that they project the magnetic field. Fig. 5(d) shows that the addition of permalloy stators increases the natural frequency of the vibrating system to 10.0 Hz. The narrowness of this peak indicates low damping, as expected for permalloy stators which have high magnetic permeability. The decrease in amplitude of the 10.0 Hz feature, compared with the 8.25 Hz feature in Fig. 5(b), is due to unequal input forces used to initiate free vibration. Even though this simple experiment is conducted at frequencies far below ULF range, experimental demonstration of this frequency shift provides important validating evidence for the design of the Y-stator vibrating magnet antenna.

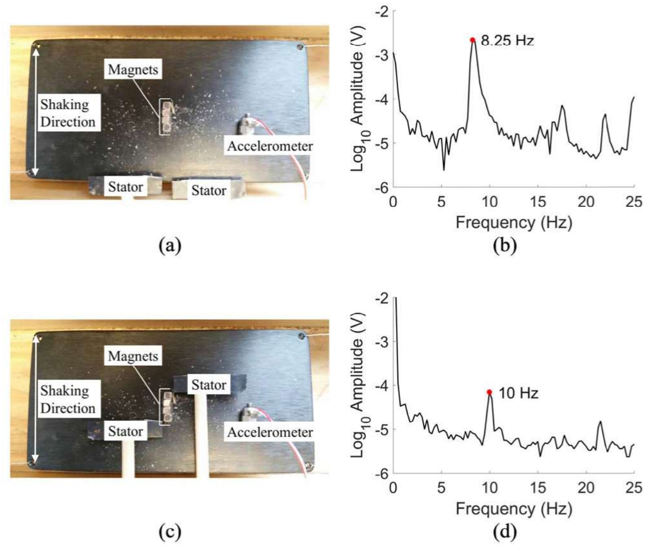

Fig. 5. (a) Permanent magnets and an accelerometer are attached to a metal plate and (b) with a natural frequency of 8.25 Hz. (c) Permalloy stators are introduced in a half-Y configuration and (d) natural frequency increases to 10.0 Hz.

VII. Limitations of This Inquiry

This inquiry has limitations which will need to be considered to develop the Y-stator vibrating magnet antenna into a fully functional prototype. First, a radio frequency (RF) model should be created to compute far-field radiation patterns for selected Y-stator arrays. Determination of effective radiated power (ERP) will be crucial for optimizing the size, shape, and number of magnetic oscillators. A potential software solution is the COMSOL RF Module; however, as the design moves forward, care should be taken to avoid overlooking certain phenomena. For example, the current COMSOL simulation study does not take into account the Barkhausen effect [17], [18], in which the magnetization of a material changes discontinuously as magnetic domain walls move over material defects. In the event these discontinuities are significant enough to degrade the spectral quality of the Y-stator oscillators, it may be necessary to replace permalloy with an engineered soft magnetic material such as NANOPERM [19].

Finally, more work is needed to characterize the behavior of oscillators in Y-stator arrays. As seen in Fig. 5, the presence of soft-magnet stators introduces frequency nonlinearities that may complicate coherent coupling of the oscillators. Indeed, models for coupled oscillators such as those developed by Kuramoto [16] and Winfree [20] consider a population of oscillators with different natural frequencies, but not different nonlinearities.

VIII. Discussion

This work is intended to demonstrate the feasibility of the Y-stator vibrating magnet antenna as a low-power, compact source for ULF radio signaling. A theoretical basis for device operation is described, including generation of oscillating fields, energy scaling, and FM. A COMSOL simulation study is presented to demonstrate the concept of field switching with permalloy Y-stators. A key finding of the simulation study is the effect of the "extra" stator in generating a parasitic field—this further reinforces the efficiency advantage of Y-stator arrays with multiple oscillators.

A promising application for the vibrating magnetic transmitter is as a source for through-the-earth (TTE) communication systems used by coal miners in emergency scenarios. In emergency situations, it is important to have a portable means of communication with the surface that does not depend on large-scale mine infrastructure, which could become damaged in a disaster [21]. A vibrating magnet array could be both compact and low-power, making it appealing for this application. Furthermore, the existing TTE systems are generally low-bitrate and operate between 300 and 8000 Hz [21], [22], frequencies and throughput for which a vibrating magnet array may be well-suited. Continued development of the vibrating magnet transmitter prototype may provide more evidence for the usefulness of the technology for this and other applications.

ACKNOWLEDGMENT

This work was supported in part by the U.S. National Science Foundation under Grant 1647095 and Grant 1640687, in part by U.S. Army under Contract W911NF-13-1-0301, and in part by U.S. Office of Naval Research (ONR) under Grant N00014-16-1-2981.

REFERENCES

[1] M. Golkowski, J. Park, J. Bittle, B. Babaiahgari, R. A. L. Rorrer, and Z. Celinski, "Novel mechanical magnetic shutter antenna for ELF /VLF radiation," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2018, pp. 65–66.

[2] W. Shi, Q. Zhou, and B. Liu, "The performance analysis of a spinning magnet as a mechanical antenna," in *Proc. Photon. Electromagn. Res. Symp. Fall (PIERS Fall)*, Dec. 2019, pp. 1265–1269.

[3] D. Orfeo *et al.*, "Mechano-magnetic telemetry for underground water infrastructure monitoring," *Frontiers Built Environ.*, vol. 4, p. 29, Jun. 2018.

[4] L. J. Chu, "Physical limitations of omni-directional antennas," *J. Appl. Phys.*, vol. 19, no. 12, pp. 1163–1175, Dec. 1948.

[5] R. F. Harrington, "Effect of antenna size on gain, bandwidth, and efficiency," *J. Res. Nat. Bur. Standards D, Radio Propag.*, vol. 64D, no. 1, p. 1, Jan. 1960.

[6] S Prasad *et al.*, "Magnetic pendulum arrays for efficient ULF transmission," *Sci. Rep.*, vol. 9, no. 1, p. 13220, Dec. 2019.

[7] J. García-Martín, J. Gómez-Gil, and E. Vázquez-Sánchez, "Non-destructive techniques based on eddy current testing," *Sensors*, vol. 11, no. 3, pp. 2525–2565, Feb. 2011.

[8] W. Ezequelle, D. Orfeo, D. Burns, T. Xia, and D. Huston, "Active magnetic sensing for subterranean urban target discrimination," *Proc. SPIE Smart Struct. Nondestruct. Eval.*, vol. 11380, Apr. 2020, Art. no. 1138006.

[9] R. J. Farrell, "Rotating magnetometry for terrestrial and extraterrestrial subsurface explorations," M.S. thesis, Graduate College Diss., Mech. Eng., Univ. Vermont, Burlington, VT, USA, 2018, vol. 945.

[10] H. Huang and I. J. Won, "Characterization of UXO-like targets using broadband electromagnetic induction sensors," *IEEE Trans. Geosci. Remote Sens.*, vol. 41, no. 3, pp. 652–663, Mar. 2003.

[11] S. J. Norton and I. J. Won, "Identification of buried unexploded ordnance from broadband electromagnetic induction data," *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 10, pp. 2253–2261, Oct. 2001.

[12] C.-Y. Chan, "Magnetic sensing as a position reference system for ground vehicle control," *IEEE Trans. Instrum. Meas.*, vol. 51, no. 1, pp. 43–52, Aug. 2002.

[13] G. Liu and A. Becker, "Airborne electromagnetic sensing of sea-ice thickness," in *Proc. SEG Tech. Program Expanded Abstr.*, 1987, pp. 52–54.

[14] S. H. Strogatz, "Spontaneous synchronization in nature," in *Proc. Int. Freq. Control Symp.*, 1997, pp. 2–4.

[15] D. D. Quinn, R. H. Rand, and S. H. Strogatz, "Singular unlocking transition in the winfree model of coupled oscillators," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 75, no. 3, Mar. 2007, Art. no. 036218.

[16] Y. Kuramoto, "Self-entrainment of a population of coupled non-linear oscillators," in *Proc. Int. Symp. Math. Problems Theor. Phys.*, vol. 39, Kyoto, Japan. Berlin, Germany: Springer, 1975, pp. 420–422.

[17] H. Barkhausen, "Zwei mit Hilfe der neuen Verstärker entdeckte Erscheinungen," *Physik Z*, vol. 20, no. 17, pp. 401–403, Sep. 1919.

[18] G. Durin and S. Zapperi, "The Barkhausen effect," *Sci. Hysteresis*, vol. 2, pp. 1–51, Apr. 2004.

[19] *Material: Nanoperm*. [Online]. Available: https://www.magnetec.de/en/materials-products/

[20] A. T. Winfree, "Biological rhythms and the behavior of populations of coupled oscillators," *J. Theor. Biol.*, vol. 16, no. 1, pp. 15–42, Jul. 1967.

[21] N. Damiano, "Through-the-earth, post-accident communications—An emerging technology," CDC NIOSH Technology News, Pittsburgh, PA, USA, Tech. Rep., 2012.

[22] T. Barkand, N. Damiano, and W. Shumaker, "Through-the-earth, two-way, mine emergency, voice communication systems," in *Proc. Conf. Rec. IEEE Ind. Appl. Conf. 41st IAS Annu. Meeting*, vol. 2, Oct. 2006, pp. 955–958.