NON-RESONANT VIBRATION ENERGY HARVESTER WITH WOUND MICRO-COIL ARRAYS

Matin Barekatain, Junyi Wang, Akash Roy, Kianoush Sadeghian Esfahani, Jaehoon Lee and Eun S. Kim
Department of Electrical and Computer Engineering, University of Southern California, USA

ABSTRACT

This paper describes a wrist-wearable non-resonant vibrational energy harvester (1.4 cc in volume and 3.2 gram in weight, with two arrays of wound copper coils adjacent to a movable array of magnets suspended by ferrofluid bearing) for generating power from a human's walking motion. Thousand-turn coils are wound with a customized coil winding machine, and two sets of such coils are mounted on the top and bottom of a movable magnet array to obtain 20% improvement (compared to the earlier version based on an electroplated coil array) on the figure of merit (FOM) defined to be the power (delivered to a matched load) divided by the device's volume for a given acceleration of 1 g at 2 Hz.

KEYWORDS

Vibrational Energy Harvesters, Wearable Devices, Wearable Power Generator, Human Motion, Self-power, Sustainable Energy, Power MEMS, Non-Resonant Electromagnetic Harvester

INTRODUCTION

Batteries for cell wearable and hand-held devices need recharging or replacement during or for which the operation is interrupted. Wearable vibration energy harvesters (VEHs) have been explored to convert the mechanical energy of human motion into electrical energy for powering wearable devices. Some are based on triboelectricity [1], while some others use piezoelectricity [2]. These approaches, though, inherently result in a high source impedance, requiring the load to be of high impedance and being able to deliver only a limited current.

On the other hand, an electromagnetic VEH based on magnets and coil presents a very low source impedance (easily down to several ohms) and can deliver a large current. The voltage generated by electromagnetic VEH can be large by increasing the number of turns for the coil (at the cost of increased source impedance and bulkiness of the device). Thus, electromagnetic VEHs can effectively recharge batteries and have been explored mostly with resonant structures which produce enhanced relative displacement (between magnet and coil) at the specific resonance frequencies. However, most of the vibration energy in a human's walking motion is at 1 - 4 Hz [3-4], which presents a major challenge for VEH based on a resonant structure [5-6] since the structure (which needs to be compliant for the sake of such a low resonance frequency) presents a substantial static displacement by gravity.

This paper presents a non-resonant electromagnetic VEH with an array of coils (wound by a programmable winding machine customized for producing subminiature coils with hundreds - thousands of turns) adjacent to an array of magnets that are moveable and suspended by ferrofluid bearings. The ferrofluid bearing allows the magnet array to move with very little friction and leads to a large relative displacement between the magnet array and the coil array in response to an applied vibration.

DESIGN AND FABRICATION

Since the in-plane magnetic field's spatial gradient is the largest at the boundary of abutting magnets (Fig. 1), the diameter of each wound coil is designed to match the magnet width [7]. The acrylic chamber for housing magnet array inside and holding coil arrays outside is made out of an acrylic plate by first making line grooves on the plate with LG-500 Jamieson Laser machine and then folding the plate (aided by the grooves) into a 3D chamber.

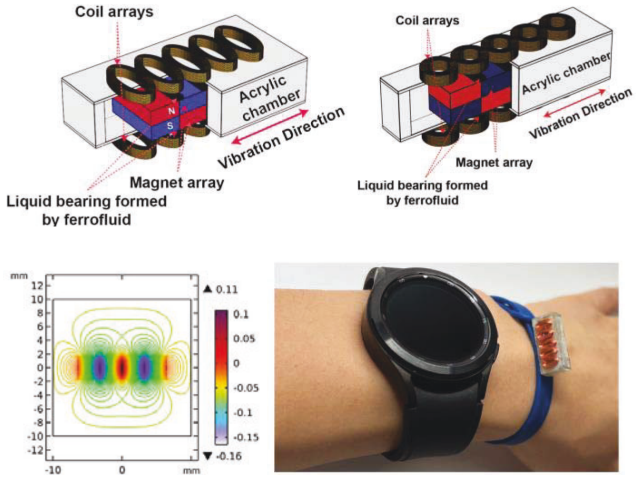

Figure 1: Illustrations of the non-resonant vibrational energy harvester (VEH) composed of five coils on the top and bottom sides of an acrylic chamber containing four rectangular (top left) and square (top right) magnets. (Bottom left) Simulated magnetic field around the four magnets inside the acrylic chamber of VEH. (Bottom right) Photo of the VEH next to Samsung Galaxy watch 4.

The side walls of the acrylic chamber (Fig. 2) are initially sealed with ultraviolet-light-sensitive resin, which solidifies when exposed to UV light for 2 minutes under 36-watt UV light. The sealing is completed by gluing all contact points with super glue (Krazy cyanoacrylate glue) immediately after placing a magnet array with ferrofluid (self-assembled along the boundaries between the magnets) inside the chamber in order to avoid any evaporation of ferrofluid.

All internal surfaces of the acrylic chamber are coated with a super-hydrophobic layer to make ferrofluidic bearing as spherical as possible. Evaporated silane (from a silane solution at room temperature) is used to treat the surfaces for hydrophobicity while adding negligible thickness (Fig. 2a).

978-4-88686-435-2 ©2023 IEEJ

Two designs are explored; one based on oval μ-coils (OMC) and the other based on circular μ-coils (CMC). Acrylic cylindrical spools of 1.8 mm in height with 4.1 mm and 1.3 mm in diameter are used for OMC, while acrylic cylindrical spools of 1.8 mm in height and 1.3 mm in diameter are used for the CMC to wind 43 AWG (60 μm in diameter) self-bonding copper wire with a coil winding machine, a version of ACME's AEX-01, customized for the first time specifically for the VEH's μ-coils. Ethanol is used to chemically bond the insulating layers of the copper wires during the winding process. After the winding is completed, the spool is carefully taken out from the center of the μ-coil, and the μ-coil is compressed gently with a clamp while being heated to 320 ˚C with a hot gun to reduce the μ-coil height to ~1 mm from 1.8 mm (Fig. 3) and firm the coil structure.

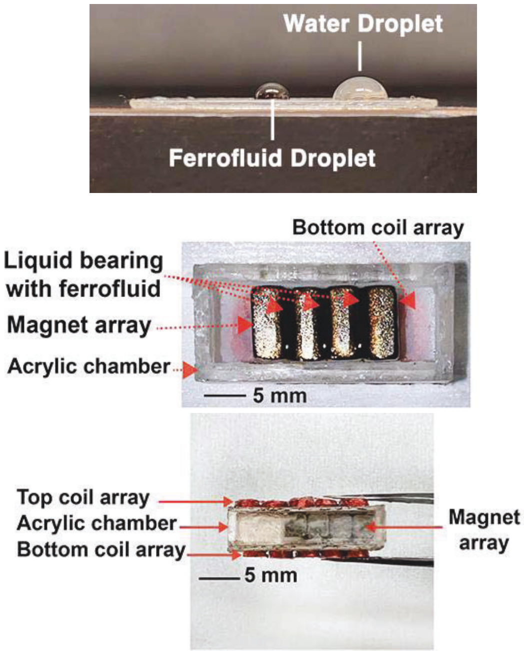

Figure 2: (top) Photo showing the hydrophobicity of a coil plate with a ferrofluid and water droplet on the surface with contact angles of more than 90˚. (middle) Top-view photo of the VEH without the top plate. (bottom) Cross-sectional-view photo of the VEH with five-coil arrays at the top and bottom of the acrylic chamber, along with four rectangular magnets inside the chamber.

A set of five μ-coils are placed over the top plate (as well as under the bottom plate) of the acrylic chamber such that the rotating directions of the coils match (all clockwise or counter-clockwise when viewed from the top face of the coil) for a total of 1,500 turns for OMC and 1,000 turns for CMC per each side (top or bottom). It is critical to make sure the coils are connected so that the coil's voltages add up. Thus, the identical terminals (whether it is inner to inner or outer to outer) must be connected for adjacent coils. Two sets of the five coils in series are attached to the top and bottom of the acrylic chamber to generate double the number of turns and increase the power.

The optimized number of coil turns is calculated by first setting an array of single-turn circular (or oval) coils as the first ring (with 3.2 mm in diameter and 60 μm in thickness) above an array of square (or rectangular) magnets with 0.3 mm gap (equal to the height of the acrylic plate and the ferrofluid bearing). When the number of turns for the coil is increased, the coil height increases. Consequently, the marginal increase of the induced voltage becomes less as the number of turns is increased since the distance between the coil and the magnet increases, leading to an increasingly smaller in-plane magnetic field (and its field gradient) that the added coil experiences, as shown in the top of Fig. 4. Though the induced voltage increases monotonically as the number of the turns increases, the increasing rate of the induced voltage is lower than the increasing rate of the coil resistance (which increases linearly as the length of wire increases). Thus, the power delivered to a matched load (i.e., the load with its resistance being the same as the coil resistance) peaks at a particular number of coil turns, as can be seen at the bottom of Fig. 4. According to our calculation, the optimal number of turns for maximum delivered power to a matched load is higher than that (200 – 300 per coil) which our current winding technique allows.

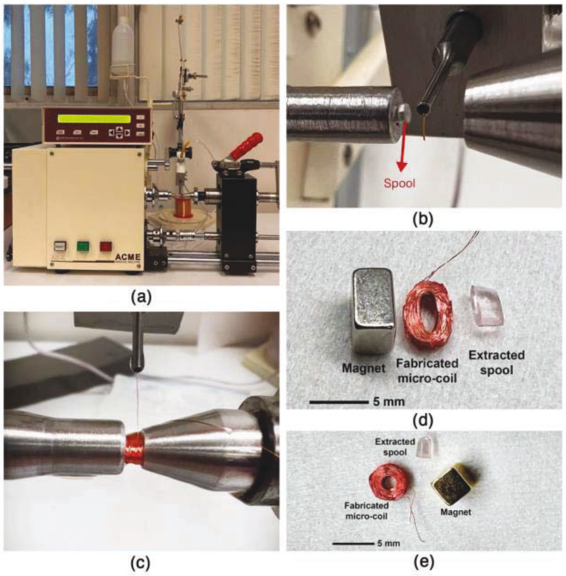

Figure 3: Photos of (a) ACME AEX01 coil winding machine customized for subminiature coils, (b) customized tooling to hold a cylindrical spool (1.8 mm in height and 1.3 mm in diameter), (c) coil winding over the spool, and fabricated (d) OMC and (e) CMC along with the acrylic spools (used for the coil winding) and the magnets (to be used with the fabricated coils).

The performance of the VEHs is characterized by an in-plane linear actuator (Aerotech ACT115DL), of which the operating frequency and acceleration can be controlled with the Soloist Motion Composer. The linear actuator is operated over 2 – 4 Hz while varying the acceleration from 0.5 to 2g. The OMC-based VEH weighs 3.2 grams and occupies a volume of 1.4 cc, and carries ten wound coils with a total of 3,000 turns resulting in a total resistance of 250 Ω (Table 1), while the CMC-based VEH weighs 1.55g occupying a volume of 0.75cc with a total of 2,000 turns and a total resistance of 120 Ω (Table 2). The VEH is connected to a matched load, and an oscilloscope with a sampling rate of 10 kHz is connected in parallel to the device in order to eliminate high-frequency noise coming from the linear actuator (Fig. 5).

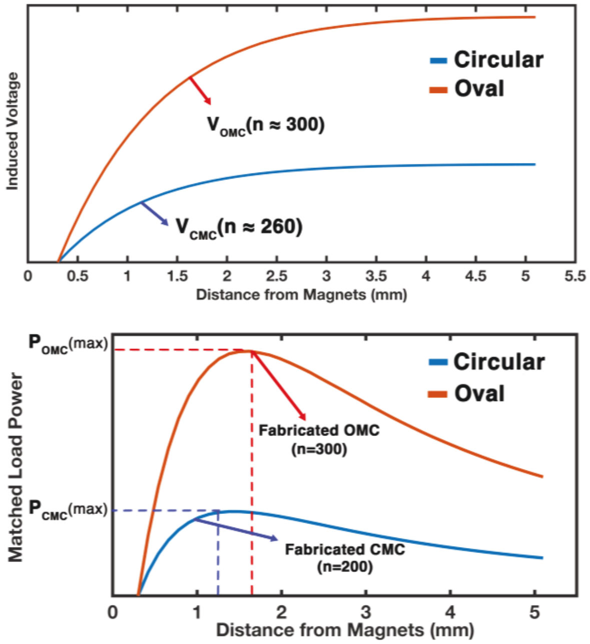

Figure 4: Calculated voltage (top) and power to a matched load (bottom) by VEHs vs the number of turns in the coil; a larger number of turns means a larger average distance between the coil (as the coil becomes thicker/taller with higher turns) and the magnets. The CMC's peak power is ~25% of the OMC peak power for an applied acceleration of 1 g at 4 Hz, as the CMC and OMC have 200 and 300 turns for the coils, respectively.

Table 1: Key parameters of the non-resonant VEH based on rectangular magnets (OMC design).

Total Volume	1.4 cc
Total Weight	3.2 g
Magnet Size (mm^3)	6.4 × 3.2 × 3.2
Movable Range of Magnet Array	6 mm
Spool Size (mm^3)	4.1 × 1.3 × 1.8
Coil Size (mm^3)	6.4 × 3.2 × 1
Number of Coils	10
Total Coil Turns	3,000
Total Resistance (Ω)	250 Ω

Table 2: Key parameters of the non-resonant VEH based on square magnets (CMC design).

Total Volume	0.75 cc
Total Weight	1.55 g
Magnet Size (mm^3)	3.2 × 3.2 × 3.2
Movable Range of Magnet Array	6 mm
Spool Size (mm^3)	1.3 × 1.3 × 1.8
Coil Size (mm^3)	3.2 × 3.2 × 0.8
Number of Coils	10
Total Coil Turns	2,000
Total Resistance	120 Ω

RESULTS

Typical open-circuit voltages (Fig. 6) produced by the OMC VEH for a 2g, single-cycle 2 Hz sinusoidal acceleration (applied intermittently) show that the bottom coil plate produces a slightly higher voltage than the top coil plate, likely due to the magnet coil being closer to the bottom coil due to gravity. When the top and bottom coil plates are connected in series, the induced voltage is indeed the sum of the voltages produced by the top and bottom coil plates, as expected. As can be seen in Fig. 6, two voltage spikes (with opposite signs) occur during each period, each by a one-way trip of the magnet array.

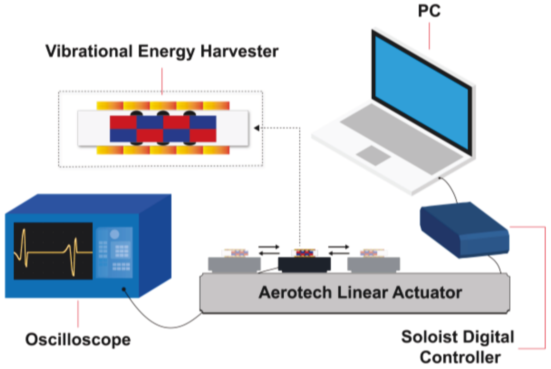

Figure 5: Experimental setup for VEH characterization.

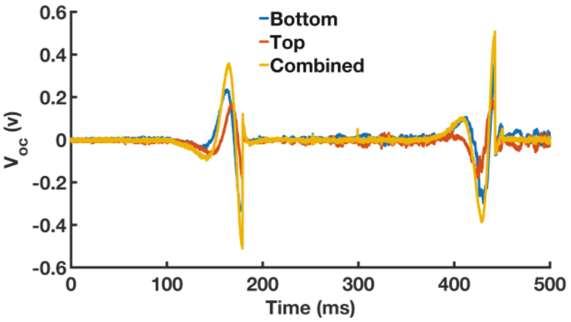

Figure 6: Measured voltages from the bottom, top, and combined coil arrays when VEH is driven with 2g acceleration at 2 Hz.

With the OMC VEH connected to a matched load of 250 Ω, the voltage induced in the wound coils is measured with an oscilloscope. The power delivered to the matched load vs. applied acceleration as a function of vibration frequency over 2 - 4 Hz is shown in Fig. 7.

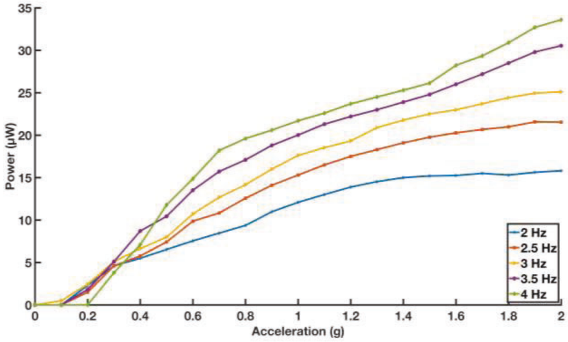

Figure 7: Measured power vs. acceleration as a function of frequency for the VEH with a 250 Ω source resistance.

Taking the power delivered to a matched load per the VEH volume as the figure of merit (FOM), the VEH based on wound µ-coils presented here outperforms the previous device [8] based on electroplated planar coils by 15-20% due to the lower resistance of copper wires used in the wound coil than that of the electroplated copper electrode which has substantial contact resistances when the coil plates are stacked [8].

The power out of the OMC VEH is about five times larger than that of the CMC VEH (Fig. 8), and thus, the OMC VEH's FOM is more than twice that of the CMC VEH. This observation matches the simulated results shown in Fig. 4, which shows the peak power of the CMC design with the number of turns limited to 200 turns per coil due to fabrication difficulties is about 20% of that of OMC-based VEH with 300 turns per coil.

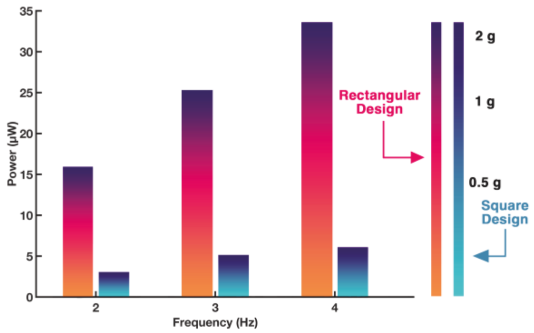

Figure 8: Power vs. frequency for the two different designs (Fig. 1a and 1b).

SUMMARY

This paper presents a non-resonant electromagnetic vibration energy harvester (VEH) (1.4 cc and 3.2 grams) for harvesting power from the human's walking motion (of which the energy is mostly below 4Hz) without loading the person. This VEH is an improvement from the previous non-resonant VEH (1.1cc and 2.6gram) [8]. The improvement has been obtained by (1) using a programmable coil winding machine that enables a very large number of turns with extremely thin wire (60 µm in diameter, AWG 43) and (2) mounting coil arrays on both top and bottom sides of the magnet array, ensuring minimum spacing between the top coil array and the magnet array through optimized acrylic chamber height. The VEH is measured to deliver 16 - 34 µW power to a matched load (250 Ω) from 2g acceleration at 2 - 4 Hz.

ACKNOWLEDGEMENT

This paper is based on the work supported by National Science Foundation under grant ECCS-1911369.

REFERENCES

[1] F. Rahimi Sardo et al., "Recent Progress of Triboelectric Nanogenerators for Biomedical Sensors: From Design to Application," Biosensors, vol. 12, no. 9, p. 697, Aug. 2022, doi: 10.3390/bios12090697.

[2] H. Zhou, Y. Zhang, Y. Qiu, H. Wu, W. Qin, Y. Liao, Q. Yu, and H. Cheng, "Stretchable piezoelectric energy harvesters and self-powered sensors for wearable and implantable devices," Biosensors and Bioelectronics, vol. 168, p. 112569, 2020.

[3] J. E. A. Bertram and A. Ruina, "Multiple walking speed–frequency relations are predicted by constrained optimization," J. Theor—Biol., vol. 209, no. 4, pp. 445–453, 2001.

[4] F. Danion, E. Varraine, M. Bonnard, and J. Pailhous, "Stride variability in human gait: The effect of stride frequency and stride length," Gait Posture, vol. 18, no. 1, pp. 69–77, 2003.

[5] S. Wu, P. C. K. Luk, C. Li, X. Zhao, Z. Jiao, and Y. Shang, "An electromagnetic wearable 3-dof resonance human body motion energy harvester using ferrofluid as a lubricant," Applied Energy, vol. 197, pp. 364–374, 2017.

[6] C. Li, S. Wu, P. C. K. Luk, M. Gu and Z. Jiao, "Enhanced Bandwidth Nonlinear Resonance Electromagnetic Human Motion Energy Harvester Using Magnetic Springs and Ferrofluid," in IEEE/ASME Transactions on Mechatronics, vol. 24, no. 2, pp. 710-717, April 2019, doi: 10.1109/TMECH.2019.2898405.

[7] Q. Zhang and E.S. Kim, "Vibration Energy Harvesting Based on Magnet and Coil Arrays for Watt-Level Handheld Power Source," Proceedings of the IEEE, vol. 102, no. 11, pp. 1747 – 1761, 2014.

[8] Y. Wang, Q. Zhang, L. Zhao, and E.S. Kim, "Non-Resonant Electromagnetic Broad-Band Vibration-Energy Harvester Based on Self-Assembled Ferrofluid Liquid Bearing," in Journal of Microelectromechanical Systems, vol. 26, no. 4, pp. 809-819, Aug. 2017, doi: 10.1109/JMEMS.2017.2669978.

CONTACT

*M. Barekatain, tel: +1-323-4498986; barekata@usc.edu