A Compact Electromagnetic Vibration Energy Harvester with High Output Voltage

Xingchang Wang, Xuefeng He, Kankan Li, and Senlin Jiang

Key Laboratory of Optoelectronic Technology and Systems of the Education Ministry of China, Chongqing University, Chongqing 400044, China
Email: hexuefeng@cqu.edu.cn

Abstract. Non-resonant vibration energy harvesters (VEHs) attract much attention for the excellent performance in scavenging ambient low-frequency and broadband vibrations. In this paper, effects of the mild steel sheets, thicknesses of the magnets and coils, wire diameter of coils, and inner dimension of the coils on the outputs of a non-resonant electromagnetic vibration energy harvester (EMVEH) were simulated and the optimized geometries was obtained. Numerical simulations show that the mild steel sheets can enlarge the magnetic flux density about 25.0%, agreeing well with the experimental result that the output voltage increased about 29.3%. Under a base excitation of 0.3 g (where 1g = 9.8 m s^{-2}) at 8.3 Hz, the RMS voltage across a 10.4 kΩ resistor of an EMVEH prototype, with the inner volume of 76.26 cm^3, is about 15.53 V. The power density is about 304 µW cm^{-3}, about 18.7% higher than the previous device.

1. Introduction

Vibration energy harvesters (VEHs) which can convert ambient vibrations into electricity are promising substitutes of traditional chemical batteries as the power sources of wireless sensor nodes [1,2]. The output power of common resonant-based VEHs decrease quickly when the excitation frequency deviates from their natural frequencies. Therefore, they are not efficient in scavenging the low-frequency and broadband vibrations in natural environments. Recently, non-resonant VEHs attract much attention for the excellent performance in collecting the low-frequency and broadband vibration [3-7]. Frequency up-conversion technology has been utilized to collect low-frequency vibrations. Frequency up-conversion may be realized by introducing magnetic forces or mechanical collisions into VEHs. Electromagnetic induction, piezoelectric effect and electrostatic induction have been used to convert the mechanical energy into electricity by VEHs [8-18]. Compared with the other two types of VEHs, EMVEHs have the advantages of high power density and high reliability [12]. To scavenge vibrations in natural environments, many non-resonant EMVEHs have been developed in literature [13,14]. But their output voltages are generally low, with the typical value lower than 2V, which complicates the power management circuit. We have developed a non-resonant EMVEH with high output voltage [6], in this paper, its performance will be improved by structural optimizations.

2. Device Structure

Our group has developed a collision-based non-resonant EMVEH for low-frequency and broadband vibrations [6]. In this paper, mild steel sheets are added to the sidewalls of the outside magnets to increase the magnetic flux through the coils, as shown in figure 1, as a result the electrical outputs can be improved. The harvester mainly consists of an inner and an outer frame, which are composed of the magnet array, the mild steel sheets, the springs and the magnet bracket, and the coil array, the coil
bracket and the housing, respectively. The inner frame is supported on the rollers on the floor of the outer frame. Under base excitations, it can move freely with respect to the outer frame in the direction along the slots containing the rollers. After obtaining the magnetic flux density around the coils, the modeling process of the proposed EMVEH is the same with the previous device [6].

![Figure 1. Schematic of the electromagnetic vibration energy harvester.](image)

3. Device Optimization

3.1. Parameters in optimization

For the devices without the mild steel sheets, the influence of the initial gap between the inner frame and the outer frame and the stiffness of the springs on the electrical outputs have been numerically analysed in our previous work [6]. The effects are the same for the devices with the mild steel sheets, therefore, we only analyse the effects of the mild steel sheets, the thickness of the magnet, the thickness of the coil, the diameter of the coil, and the size of the inner dimension of the coils in the following. Some parameters in the simulations are listed in table 1.

3.2. Parameter optimization

3.2.1. Effect of mild steel sheets. The effects of the mild steel sheets on the magnetic flux density near the coils should be simulated before calculating the electrical output of the device. For a 2×3 magnet array with two 1-mm-thick mild steel sheets, as shown in figure 2, the magnetic field distribution was simulated by ANSYS. To obtain the magnetic flux through the coils, the magnetic flux density along the centre line of arbitrary two rows of magnets was worked out, as shown in figure 3. The simulated average magnetic flux density along the centre line between two rows of magnets is about 0.305 T, about 25.0% higher than that of the device without the sheets, with a value of about 0.244 T. The effect of the thickness of the mild steel sheets was simulated. The simulations implies the weak dependence of the magnetic flux density on the thickness of the sheets.

3.2.2. Effect of wire diameter. For the devices with different wire diameters, the powers across the optimal resistances under the harmonic base excitation of 0.2 g were simulated. In the simulations, it is assumed that the volumes of device is the same. Although the voltage increases when the wire diameter decrease, the output power hardly changes, as a result of the increased resistance of the coils. To increase the voltage, a device with smaller wire diameter is preferred. But for the limitation of the winding of the coils and the assembling of the device, the wire diameter is set as 0.05 mm in this work.
Table 1. Parameters in numerical simulations.

| Parameter                                | Value/Material        |
|------------------------------------------|-----------------------|
| Type of magnet                           | NdFeB (N-50)          |
| Coercive force                           | 907 kA/m [16]         |
| Magnet dimension                         | 20mm×10mm×4mm         |
| Coil dimension                           | 18mm×9mm×3mm          |
| Dimension of coil through-hole           | 12mm×3mm×3mm          |
| Wire diameter                            | 50 µm                 |
| Thickness of mild steel plates           | 1 mm                  |
| Permeability of mild steel               | 4000                  |
| Mass of inner frame                      | 120 gram              |
| Separation between magnet rows           | 7 mm                  |
| Viscous damping coefficient              | 0.68 Ns/m [17]        |
| Damping coefficient of springs           | 0.68 Ns/m             |
| Spring modulus                           | 400 N/m               |
| Initial gap                              | 5 mm                  |
| Coil shape                               | Square                |

3.2.3. Effect of the coil thickness. To estimate the effect of coil thickness, the power densities of the devices with different coil thickness were simulated. The coils thickness is set as 1, 2, 3, 4 and 5 mm, respectively. The simulated power density first increases and then decreases with the thickness of the coil. When the coil thickness is 3 mm and the frequency is 5.7 Hz, the power density of the device reaches the maximum value.

3.2.4. Effect of magnet thickness. For the devices with the magnet thickness of 1, 2, 3, 4 and 5 mm, respectively, under the harmonic base excitation of 0.2 g, the power densities are calculated. The simulated power density increases first and then decreases with the magnet thickness. When the magnet thickness is smaller than 4 mm, the power density increases with the magnet thickness. When the
thickness of the magnet is larger than 4 mm, the power density hardly changes. When the thickness of
the magnet is larger than 6 mm, the power density decreases with the magnet thickness.

3.2.5. Effect of the inner dimension of the coils. The numbers of the coil turns and the resistances of the
coils increase when the coils with smaller inner dimension are used. Under the harmonic base excitation
of 0.2 g, the output power for different coil inner dimensions are calculated. For the devices with the
same volume, when the inner dimension of the coils decreases, the output power increases, but the
increasing gradient decreases. When the inner dimension of the coils is smaller than 12mm×3mm, the
decreasing of output power is negligible.

3.2.6. Optimized device
Base on above simulations, the optimized parameters of the EMVEH are given in table 2.

| Parameter                          | Value     |
|------------------------------------|-----------|
| Separation between two magnet rows | 5 mm      |
| Magnet dimension                   | 20mm×10mm×4mm |
| Coil dimension                     | 18mm×9mm×3mm |
| Dimension of coil through-hole     | 12mm×3mm×3mm |
| Wire diameter                      | 50 µm     |

4. Experimental Results and Discussions

4.1. Load characteristic test of the harvester
An EMVEH prototype with the parameters listed in table 1 was fabricated and then tested on a shaker.
Under a harmonic base excitation of 0.2 g, the root-mean-square (RMS) voltages across resistors with
different resistances were measured. The output power can be worked out according to the experimental
RMS voltage. When the load impedance is between 10 and 11 kΩ, the output power reaches the
maximum, very close to the total resistance of the coil array 10.4 kΩ. A resistor of 10.4 kΩ was
connected with the prototype to evaluate the output performance in the following tests.

4.2. Effects of mild steel sheets
The effects of the mild steel sheets on the electrical output of the harvester were measured under base
excitation of 0.1 and 0.3 g. As expected, the measured RMS voltage of the device with the mild steel
sheets is higher than that without the mild steel sheets. Taking the base excitation of 0.3 g as an example,
after adding mild steel sheets to the walls of the outside magnet rows, the maximum RMS voltage
increased about 29.3%, from 12.01 V to 15.53 V, very close to the simulated increase of 25.0% of the
magnetic flux density. Therefore, adding the mild steel sheets is an effective method to increase the
electrical outputs.

4.3. Performance comparison
The internal dimension of the prototype is 82mm×31mm×30mm, with the volume of about 76.26 cm³.
The performances of prototype are compared with literature, as shown in table 4. Compared with the
previous device [6], the power density of the optimized device with the mild steel sheets increased from
256 to 304 µW cm⁻³, with an increase of about 18.7%. 
Table 3. Comparison with References.

| Reference       | Acceleration (m s\(^{-2}\)) | Frequency (Hz) | Voltage (V) | Power density (µW cm\(^{-3}\)) |
|-----------------|-------------------------------|----------------|-------------|---------------------------------|
| Haroun [3]      | 12.38                         | 3.33           | 0.012       | 180                             |
| Luo [6]         | 3                             | 8.5            | 16.5        | 256                             |
| Ashraf [4]      | 9.8                           | 18             | 1.44        | 342                             |
| Galchev [5]     | 0.54                          | 2              | 0.059       | 0.0535                           |
| Foisal [18]     | 0.5                           | 10             | -           | 52.02                            |
| This work       | 3                             | 8.3            | 15.53       | 304                             |

5. Conclusions

The electrical outputs of a non-resonant EMVEH are enlarged by adding mild steel sheets on the walls of outside magnet rows. Based on the numerical simulations, the effects of the mild steel sheets, the thicknesses of the magnets and coils, the wire diameter of coils and the inner dimension of the coils on the electrical outputs were analysed and optimized. Simulations show that the mild steel sheets enlarge the magnetic flux density by about 25.0%, agreeing well with experiments. Under base excitation of 0.3 g at 8.3 Hz, the RMS output voltage of the prototype is about 15.53 V, with the power density of about 304 µW cm\(^{-3}\).

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Nos. 61774026 and 61376116) and the National Key Research and Development Program of China (Nos. 2016YFC0101100 and 2016YFE0125200).

References

[1] Paradiso JA, Starner T 2005 *IEEE Pervas. Comput.* 4 pp 18-27.
[2] Roundy S, Wright PK 2004 *Smart Mater. Struct.* 13 pp 1131-1142.
[3] Haroun A, Yamada I and Warisawa S 2015 *Sens. Actuators A Phys.* 224 pp 87-98.
[4] Ashraf K, Khir M H M, Dennis O J and Baharinudin A Z 2013 *Smart Mater. Struct.* 22 049601.
[5] Galchev V T, McCullagh J, Peterson L R and Najafi K 2011 *J. Micromech. Microeng* 21 104005.
[6] Luo Q, He X, Jiang S and Wang X, 2017 *Energies* 10 1848.
[7] Zhang H, He X and Jiang S 2017 *Appl. Phys. Lett.* 110 223902.
[8] Wang P, Tanaka K, Sugiyama S, Dai X, Zhao X 2009 *Microsyst. Technol.* 15 pp 941-951.
[9] Beeby SP, Torah RN, Tudor MJ, Glynnejones P, O'Donnell T 2007 *J. Micromech. Microeng.* 17 pp 1257-1265.
[10] Erturk A, Inman DJ 2008 *J. Vibration & Acoustics* 130 pp 1257-1261.
[11] Galchev T, McCullagh J, Peterson RL, Najafi K 2011 *Int. Conf. on Solid-State Sensors, Actuators and Microsystems (Transducers, 2011)*, June 5–9, Beijing, pp 1661-1664.
[12] Xing X, Yang GM, Liu M, Lou J, Obi O 2011 *J. Appl. Phys.* 109 pp 17-22.
[13] Sari I, Balkan T, Kulah H 2008 *Sens. Actuators A Phys.* 145 pp 405-413.
[14] Yuksek NS, Feng ZC, Almasri M 2014 *Appl. Phys. Lett.* 105 p 3437.
[15] Haroun A, Yamada I, Warisawa S 2015 *J. Sound Vib.* 349 pp 389-402.
[16] Duan J 2012 *BMC Genomics* 13 p 392.
[17] Bendame M, Abdelrahman E, Soliman M 2016 *J. Micromech. Microeng* 26 115021.
[18] Foisal ARM, Hong C, Chung GS 2012 *Sens. Actuators A Phys.* 182 pp 106.