Optimization of a microfluidic based electromagnetic energy harvester for shoe insoles

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Abstract. This paper reports improved performance of the 4ᵗʰ generation microfluidic based energy harvester by finding global optimization among various geometric parameters, resulting in the increase of power density by 6.89 times. Specifically, the power output was optimized by varying diameters and spans of a coil at different frequencies. To verify the optimization, a custom testing platform was constructed, which mimicked the periodic linear movement caused by a human foot. The final device produced total power of 455.77mW from a volume of 20x3.74x0.75cm³, resulting in a power density of 8.13mW/cm³ that was identified as one of the highest power densities among human-body-induced vibration based energy harvesters.

1. Introduction
Despite remarkable progress in micro-scale energy harvesting devices, the conversion efficiency, in comparison to the enormous amounts of ambient energy available, still remains low, resulting in relatively low power output densities, i.e. 100µW/cm³. Such low conversion efficiencies could be attributed to limitations in energy storing capability imposed by tiny dimensions in conventional micro-scale energy harvesting devices.

As one potential solution to enhance energy storing capability, a concept of microfluidic energy conversion was suggested in our previous prototypes [1, 2]. The concept intended to de-amplify the input displacement into a small device, thus enabling larger accommodation of ambient energy under given dimensions. Previously-reported hydraulic energy harvesters demonstrated the proof-of-concept results [1] and multiple-channel systems [2]; however, they produced only moderate power densities of 1.18mW/cm³ [1] and 1mW/cm³ [2] insufficient for numerous practical applications. This paper reports the enhancement of power densities of the 4ᵗʰ
generation microfluidic-based energy harvester by optimizing design parameters, such as coil spans and diameters, to produce sufficient amounts of power density \(8.13 \text{mW/cm}^3\) from foot movements.

2. Microfluidic Electromagnetic Energy Harvesting System

The microfluidic electromagnetic energy harvesting device mainly consists of two reciprocal diaphragms placed respectively at the heel and toes where maximum pressure is alternately exerted from human walk (Figure 2). This alternating pressure onto two diaphragms moves magnets between the chambers under diaphragms, producing electromagnetic energy in association with coils around the channels.

\[ P = \frac{M^2 A_g^2 \omega^2 B_L^2 R_L}{\left[ (K(R_L + R_C) - M\omega^2(R_L + R_C) - D L_C \omega^2)^2 + [D \omega (R_L + R_C) + (B_L^2 \omega + K L_C \omega - M L_C \omega^3)]^2 \right]} \]

where power \(P\) is generated across matching load \(R_L\) for a system of magnet with mass \(M\), electromagnetic coefficient \(B_L\), spring constant \(K\) moving with acceleration \(A_g\) with diffusion coefficient \(D\) and actuation frequency \(\omega\) through a surrounding coil with coil resistance \(R_c\) and inductance \(L_C\). Diffusion coefficient could be assumed close to zero for the fluidic system where magnets are moving without any friction.

To optimize the power generation, four primary parameters of coil turn numbers (\(N_c\)), acceleration (\(A_g\)), spacing of span (\(h_c\)), and coil diameters (\(D_c\)) were varied. First, the voltage output was theoretically computed by utilizing a unit magnet and a unit coil and then verified by COMSOL simulation (Figure 3). The simulation results showed that a permanent magnet of 1.48T moving into 40 turns of 140\(\mu\)m diameter coil produced the output peak-to-peak voltage of 32mV or a power density of 1.2675\(\mu\)W/cm\(^3\) with the matching load of 0.9\(\Omega\). Next, the voltage output was maximized by varying the number of turns (\(N_c\)) and coil diameters (\(D_c\)). For a fixed span distance (\(h_c\)), the number of turns and coil diameters were traded-off. Then, the span distance as well as acceleration was varied while monitoring the power output changes.
4. Experimental Methodology
To realize the periodic acceleration caused by human foot motions, an acrylic energy harvester testing platform was constructed with a stepper motor as the main driving force (Figure 4). The platform consisted of a rotating crank arm and a rod that were precisely-aligned on top of a flat platform that housed multiple channels. The rotating crank connected the stepper motor to the rod by converting a rotational movement into a linear motion with variable acceleration. Figure 5 details the illustrations and the corresponding equations to relate angular speed of a motor with linear acceleration. Resultantly, simple control over the angular motor rotation was capable of mimicking a wide range of variable accelerations. For example, the rotation speeds of 54 rpm (1 Hz), 104 rpm (2 Hz), and 154 rpm (3 Hz) produced a maximum acceleration of 1.316 ms\(^{-2}\), 5.262 ms\(^{-2}\), and 11.83 ms\(^{-2}\), covering the conventional range of human foot acceleration during walking. Further variations were achieved by utilizing different arm lengths of the crank from 10 mm to 30 mm and different crank radii from 10 mm to 20 mm.

Utilizing the testing platform, the actuation frequency \(\omega\) was varied from 1 Hz to 3 Hz by controlling the rotation speed per minute of the stepper motor for different arm distances (10 mm and 20 mm) and magnet/spacer combinations (1 magnet or 2 magnets/1 spacer), while the output voltage \(V_{p-p}\) and the power density for a single coil span of 9.52 mm were monitored. Additionally, various coil diameters were tested with respectively physically-possible numbers of turns in the fixed span distance of 9.52 mm with an actuation frequency of 3 Hz: 63 \(\mu\)m (151 turns), 127 \(\mu\)m (74 turns), 160 \(\mu\)m (59 turns), 202 \(\mu\)m (47 turns), 255 \(\mu\)m (37 turns), 329 \(\mu\)m (29 turns) and 405 \(\mu\)m (23 turns). COMSOL simulation was also performed for verification.

5. Results
The COMSOL simulation (Fig.6) showed that (1) increasing actuation frequencies from 1 to 3 Hz linearly increased the power density by 9 times from 0.1237 \(\mu\)W/cm\(^3\) to 1.114 \(\mu\)W/cm\(^3\); (2) increasing arm lengths from 10 mm to 20 mm produced proportionally increase of 4.84 times in power density from 1.114 \(\mu\)W/cm\(^3\) to 5.392 \(\mu\)W/cm\(^3\); and (3) doubled number of magnets from 1 to 2, as expected, increased power density by 4.83 times from 4.456 \(\mu\)W/cm\(^3\) to 21.56 \(\mu\)W/cm\(^3\). In combination, a total enhancement of 174.29 times was achieved. Such simulation results were closely matched to experiments as below.
Figure 6: COMSOL simulation of power density for 4 different magnet and spacer combinations with different arm distances and frequencies to verify experimental data from device setup.

Figure 7: Optimization of power density by experiment for different coil diameters and their respective physically possible turn number in a fixed span (9.52mm) while also varying device thickness from 5mm to 11mm.

Experimental measurement showed that power output was optimized at different wire diameters depending on the restrictions on the device thicknesses. Figure 7 summarizes such optimization results.

First, each diameter of coil determined the maximum discrete number of turns to fit in a given span length of 9.52 mm. For example, coil diameters of 63μm, 127μm, 160μm, 202μm, 255μm, 321μm and 405μm could be wound at 151, 74, 59, 47, 37, 29, and 23 times within a single span. Second, each diameter of coil also determined the layer numbers under the device thickness restrictions. For a device thickness of 8 mm, coil diameters of 63μm, 127μm, 160μm, 202μm, 255μm, 321μm and 405μm could form layers of 17, 8, 7, 5, 4, 3, and 3. Resultantly, the optimized power outputs were found at different coil diameters depending on the target device thicknesses. For a device thickness of 8mm (purple line), the optimized power density was measured at a coil diameter of 160μm as 11.6318mW/cm³, while another device with a thickness of 6mm (red line), the maximum power density was measured at a coil diameter of 405μm as 4.5866mW/cm³.

The optimized designs significantly improved the total power generation by 12.31 times experimentally, in comparison to previous generation (Fig.8). The final device produced total power of 455.77mW from a volume of 20x3.74x0.75cm³, resulting in a power density of 8.13mW/cm³ that was identified as one of the highest power densities among human-body-induced vibration based energy harvesters.

6. Conclusion

The 4th generation microfluidic based electromagnetic energy harvester has improved the power density 6.89 times compare to the previous generations by enhancing power extraction with the accommodation of larger input force. The device was fabricated and evaluated in terms of power density with previously reported generations in figure 8. The optimized harvester produced total power of 455.77mW with a power density of 8.13mW/cm³ from a volume of 20x3.74x0.75cm³ resulting in 6.89 times enhancement in power density, compare to the previous generation devices.
7. References

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Acknowledgments

The authors disclose that they have financial conflict of interests to Solefire. The authors would also like to thank Moses Noh for helping with the AutoCAD design and processing of the acrylic materials.