A MEMS Magnetic-Based Vibration Energy Harvester

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Abstract. This paper presents the design, analysis and integrated fabrication of a MEMS magnetic-based vibration energy harvester targeted for machine health monitoring. The design consists of Si-springs, permanent magnets as mass, and coils wound on the top and bottom side of the harvester package for mechanical-to-electrical energy conversion based on the Lorentz-force principle. The harvester is optimized to have its translational resonant-mode match external vibrations while separating higher-order modes. Mechanical and magnetic optimization of the harvester is carried out together with optimization of its power and control electronics in order to provide maximum output power from a vibration input that can vary its frequency by ±5%. The harvester achieves an open-circuit voltage amplitude of 145 mV and delivers 165 μW to a matched load at the resonance frequency of 45.7 Hz.

1. Introduction

The increasing importance of autonomous sensing and portable energy harvesting for the IoT domain is leading to miniaturization of energy-transducers that can power those applications [1][2]. Among several types of transducers that are available, MEMS (electro)magnetic-based (EM) vibration energy harvesters are attractive due to their compact form factor and high output-power density. This paper presents such an EM-energy harvester comprising a DRIE-etched silicon suspension, and pick-and-place N42 NdFeB magnets, copper coils, and back-iron. The target application is to provide over 100 μW to autonomous machine-health sensors from near-50-Hz vibrations with amplitudes less than 0.5 g.

2. Design and Optimization

Two high-level optimizations guide the design of the harvester. The first optimization concerns the harvester mechanics shown in Figure 1. The harvester comprises a spring-mass-damper system (K-M-B) that fits within a rectangular volume having dimensions $L_1$, $L_2$ and $L_3$. Here, the design variables are:

- $L_1$: Stroke length
- $L_2$: Suspension length
- $S$: Air gap
- $t$: Wire thickness

These variables are optimized to achieve the desired performance. The optimization process is shown in Figures 2 and 3.

Figure 1. Harvester mechanics and magnetics for optimization of overall dimensions.

Figure 2. Parameter optimization based on mechanics.

Figure 3. Parameter optimization based on magnetics.
$B$ is a proxy for useful energy conversion. The mass moves in the $L_1$ direction, and at rest is centered within the harvester frame. The maximum bidirectional vibration stroke of the mass is $S$. If the harvester frame vibrates in the $L_1$ direction in the sinusoidal steady state with acceleration frequency $\omega$ and amplitude $A$, then the mass-motion amplitude $X$ is given by (1) and the time-average mechanical power $P_M$ harvested through $B$ is given by (2). Solving (1) for $B$ yields (3). Substitution of (3) into (2) shows that $P_M$ is maximized at resonance, characterized by (4). In this case, $P_M$, obtained by combining (2), (3) and (4), becomes (5). Equation (5) expresses $P_M$ in terms of the exogenous inputs $\omega$ and $A$, and the competing on-chip resources $X$ and $M$. This power can only be achieved with: the $B$-loading design of (3), the spring design of (4), and $X \leq S$. From Figure 1 it is apparent that $M$ is given by (6) in which case (7) holds. Finally, (7) is maximized with $X = S = L_1/4$ to yield (8). Several important conclusions can be drawn from (8). First, the competing resources of $M$ and $X$ should be given roughly the same space in the $L_1$ direction, thereby necessitating a large-travel spring. Second, $L_1^2$ in (8) indicates that the mass should move along the longest length. Thus a harvester designed to operate with out-of-plane motion is not optimal. Third, the mass should be designed with the largest possible density $\rho$. Fourth, the harvester should be loaded via $B$ so as to exhibit maximum stroke. Fifth, power per volume ($L_1L_2L_3$) favors long thin designs. Due to these conclusions, magnetic energy conversion is chosen due to its compatibility with long-stroke motion. Permanent magnets are chosen as the mass since they offer the highest net density, and hence the maximum induced coil voltage $V$. For a given $\omega$ and $X$ behaves as in (9). Additionally, the coil resistance $R_{\text{coil}}$ behaves as in (10). Therefore, the maximum time-average electrical output power $P_E = V^2/8R_{\text{coil}}$, achieved with a matched load, behaves as in (11), assuming sinusoidal steady state operation. For a given $T$, $P_E$ is maximized with the smallest permissible $\delta$ and $\Delta = T/2 + \delta$. Thus, a thick coil and a thin gap is desired. A thin gap is also desired to prevent the magnets from moving too far in the transverse direction and locking up if they are shocked towards the backiron. Figure 3 lists the values of the aforementioned design variables resulting out of this magnetics-optimization. Finally, note that the optimal choice of $B$ will not dictate maximum $P_E$ and hence matched electrical loading under all vibration scenarios. Nonetheless designing for maximum $P_E$ permits the greatest operating range.

3. Simulation and Analysis

Once the high-level optimizations yield the overall harvester dimensions for a targeted power, a spring design is chosen to provide the desired stroke $S$ and resonant frequency. Accordion and 4-bar-linkage designs are considered for this purpose. While accordion springs provide the largest $S$ with minimum underutilized area, their higher-order resonant modes (in-plane rotation and off-axis translation) are close to the desired fundamental translational mode. The 4-bar linkage has good modal separation but uses volume for anchors that could potentially be used for the mass. Therefore a combination of the two designs in the form of linked-accordion springs is chosen to provide good modal separation and the desired $S$. The beam-width $w$ ($w = 30 \mu m$ must be larger than the minimum width of $25 \mu m$ imposed by process limitation.) and beam length are optimized using simulations performed in ANSYS which show the lowest resonant modes are: translational motion along $L_1$ at 47 Hz; rotational motion about the $L_3$ direction (magnetic pole direction) at 283 Hz; and translational motion along $L_3$ at 575 Hz.
Next, the coil-winding configuration is designed to maximize the mechanical-to-electrical transduction coefficient $G$ while minimizing the coil resistance $R_{\text{coil}}$. This is done by computing the magnetic vector potential $A$ by solving (12) in the space above and below the magnets where the coils are placed. Here $M_K$ is the $K$-th Fourier component of magnetization given by (13) in region II, where $M_0 = 1.3$ T is the magnetization of the permanent magnets, $l$ is the length of each magnetic pole in the stroke direction and $M_K = 0$ in regions I and III. The closed-form solutions for $A_K$ are given by (14) in regions I and III and are given by (15) in region-II. The field distribution is computed numerically in Matlab using the boundary conditions highlighted in Figure 4 and is shown for the equilibrium position in Figure 5. Finally, the time-dependent voltage across each turn of the coil can be computed numerically using (16), where $v(t)$ is the velocity, and $\omega_0$ is the radial resonant frequency. The choices for the total number of layers $N_{\text{layers}}$ of 100 $\mu$m-diameter copper coils within $T$ and the number of turns in each such layer $N_{\text{turns}}$ are determined based on this magnetic-simulation and listed in Figure 3. The optimization-goal is to maximize the metric $G^2/R_{\text{coil}}$ for efficient power extraction.

4. Fabrication and Packaging

The spring suspension is fabricated in silicon using a single cookie-cutter deep-reactive-ion through etch. To do so, 3 $\mu$m of CVD oxide is deposited on a 525-$\mu$m-thick wafer, and densified. The oxide serves as a hard mask for the through etch. Next, resist is spun on and patterned using direct-write technology and chemical development. Using the resist as a mask, the oxide is patterned using reactive-ion etching, and the resist is then removed. Finally, the through etch is executed. Importantly, the mask for the through etch is haloed [4] using 40-$\mu$m-wide trenches to reduce etch loading, resulting in essentially vertical etch side walls. Additionally, the through-etch mask is biased to accommodate a 5-$\mu$m blow-out per side wall. With this fabrication process, a minimum feature size of about 25 $\mu$m is possible. A spring photograph is shown in Figure 6 along with images of the spring-mass system during operation. 3D-printed plastic parts form the assembly that holds the MEMS spring and the two coils that are wound from 39 AWG wire on a mandrel using a lathe. Each coil has 100 turns resulting in a total $R_{\text{coil}} = 16$ $\Omega$. The full assembly with the plan- and side-views is shown in Figure 7.

![Figure 4](image-url)  
Figure 4. Magnetization and boundary conditions for voltage computation.

![Figure 5](image-url)  
Figure 5. (a) Magnetic field distribution in the harvester and the magnetic flux densities along y-direction ($B_y$) that determine voltage across each turn in the top and bottom coil-layer.

![Figure 6](image-url)  
Figure 6. (a) SEM images of a spring and (b) images of beam-bending at various deflection-points during its motion.

![Figure 7](image-url)  
Figure 7. (a) Top-view of the fabricated suspension and magnets along with (b) individual 3D-parts and full harvester assembly.
Figure 8. Measured and simulated (a) $V_{\text{rms}}$ vs. frequency and (b) time-domain-$V_{OC}$.

Figure 9. (a) $P_L$ vs. $V_{\text{load}}$ and (b) PD vs. $a$ showing saturation due to stroke-limitation.

5. Experimental Performance

The measured frequency-sweep of open-circuit rms-voltage ($V_{\text{rms}}$) is shown in Figure 8 along with time-domain waveform of $V_{OC}$, indicating a peak $V_{OC} = 145 \text{ mV}$ at a high quality factor of 133, which is matched well by simulation. At low input acceleration ($a$), the optimum load resistance $R_L$ at resonance is matched to $R_{\text{coil}} + R_B$, the sum of coil and mechanical-damping resistance of harvester, which amounts to 1100 $\Omega$. However since the maximum spring-stroke is limited to 1 mm before fracture, the maximum load-power $P_L$ is delivered when this stroke is achieved at high $a = 0.4$ g, at which point the load-matching condition is $R_L = R_{\text{coil}} = 16$. Figure 9 shows $P_L$ versus load-voltage $V_{\text{load}}$ measured by increasing $a$, and demonstrates $P_L=165 \mu\text{W}$ at $a = 0.4$ g. Given the active volume of 0.43 cm$^3$ (1 cm x 1.3 cm x 0.33 cm), the harvester achieves a power density (PD) of $382 \mu\text{W/cm}^3$ (also shown in Figure 9), the highest among MEMS-based harvesters reported to date and summarized in Table 3 of [2]. The normalized power density (NPD) is $2400 \mu\text{Wcm}^{-3}\text{g}^{-2}$ at $a = 0.4$ g with the peak NPD=4062 $\mu\text{Wcm}^{-3}\text{g}^{-2}$ at $a = 0.15$ g. A better figure-of-merit (FoM) to compare EM-harvesters is to normalize NPD to the resonant frequency, since the reported harvesters have different natural frequencies. This FoM is $98 \mu\text{Wcm}^{-3}\text{Hz}^{-1}$ which is highest among EM-harvesters [2][3]. The harvester design can be further optimized with the inclusion of backiron and a larger spring travel, for which simulations show the power density increasing to 1146 $\mu\text{W/cm}^3$ and NPD=7162 $\mu\text{Wcm}^{-3}\text{g}^{-2}$.

6. Summary & Conclusions

This paper presents a compact MEMS-based EM-harvester designed for near 50-Hz vibrational energy harvesting. Optimizing design guidelines are provided along with the fabrication details. The harvester demonstrates an open-circuit voltage of 145 mV and a load-power of 165 $\mu\text{W}$ with a record power density of 382 $\mu\text{W/cm}^3$.

Table of Equations

| Equation | Description |
|----------|-------------|
| (1) $X^2 = \frac{M^2A^2}{(K-M\omega^2)^2 + B^2\omega^2}$ | |
| (2) $P_M = B\omega^2 X^2/2$ | Power at resonance |
| (3) $B = \sqrt{\frac{M^2A^2}{\omega^4} - \frac{(K-M\omega^2)^2}{\omega^2}}$ | |
| (4) $K = M\omega^2$ | Spring constant |
| (5) $P_M = \omega XMA/2$ | Power at resonance |
| (6) $M = \rho(L_1 - 2S)L_2L_3$ | Mass of harvester |
| (7) $P_M = \rho \omega AL_2^2L_3/16$ | Power at resonance |
| (8) $V \propto T/(T + 2\Delta + 2\delta)$ | Voltage vs. time |
| (9) $V \propto T/(T + 2\Delta + 2\delta)$ | Voltage vs. time |
| (10) $R_{\text{coil}} \propto 1/\Delta$ | Load resistance |
| (11) $P_E \propto \Delta T^2/(T + 2\Delta + 2\delta)^2$ | Power vs. frequency |
| (12) $\nabla^2 A = -\mu_0 \sum_{k=0}^{\infty} (\nabla \times M_K)$ | Electromagnetic field |
| (13) $M_K = \frac{4\mu_0}{\pi k^2} \sin^2(kl/2)$ | Magnetic moment |
| (14) $A_k(x,y) = \frac{\mu_0 M_k}{k} \frac{\sinh(\Delta k) - \sinh(\Delta k)}{\sinh(2\Delta T + \Delta k)} \cos(kx)$ | Magnetic potential |
| (15) $V(t) = \omega_0 L_3(A(x_1(t)) - A(x_2(t))) = v(t)L_3(B_y(x_1(t)) - B_y(x_2(t))) = v(t)G(t)$ | Voltage vs. time |

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