Electrostatic Force-induced Broadband Effect in Electret-based Vertical Vibration Energy Harvesters using Fine-grained Stainless Steel Oscillator

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Abstract. We propose a fine-grained stainless-steel as a promising material for a robust oscillator and investigate the dependence of frequency band width, resonance frequency, and output power on initial air gaps in electret-based vertical vibration energy harvesters. Beams of the oscillator showed a shallow side-etched depth less than 10 μm, as well as smooth edges. The oscillator succeeded in travelling over 1-mm displacement without fracture. Also, we found that broader frequency band, as well as lower resonance frequency, can be achieved with reducing the initial air gap, whereas the output power exhibited a peak value at an optimal initial air gap. The results may be attributed to the soft spring effect induced by the stronger electrostatic force. Maximum output power density and FWHM of frequency band width of our harvester are 4.7 $\mu W/cm^3$ and 14 Hz at initial air gap 0.3 mm and acceleration 4.9 m/s^2.

1. Introduction
Recently, considerable attention has been devoted to a miniature vibration energy harvester (VEH) as a power source for building an autonomous wireless sensor network [1-3]. An electrostatic VEH using a charged dielectric called "electret" is considered to be one of the promising power sources [4-10]. Electret-based VEHs are divided into two groups in terms of vibrational direction, vertical (or out-of-plane) and horizontal (or in-plane) one. An electret-based vertical VEH [6-10] has the advantage of low fabrication cost compared to a horizontal one because it can exclude the process of patterning electret, whereas it has problem with the development of a robust oscillator withstanding large displacement. Stainless steel with 83 times higher fracture toughness than that of silicon would be a promising material, however, an oscillator formed by wet etching bulk stainless steel involves in deeply side-etched beams and thus malfunction of vibration. Recently, a fine-grained stainless steel was developed for micro fabrication and robust springs [11], and it would meet our demands. Also, an initial air gap between the oscillator and the electret plays a critical role in the performance (frequency band width, resonance frequency, and output power) of electret-based vertical VEHs. Our intention in this study is to develop a side-etch free oscillator from a fine-grained stainless steel and to investigate the dependence of output power on initial air gaps.

2. Fabrication
We used a fine-grained stainless steel (Nippon Steel & Sumitomo Metal, Japan, SUS301L-SE1, grain size: 2 μm) and a typical stainless steel (Nilaco, Japan, SUS 304, grain size: 20-30 μm) with the same

thickness of 0.08 mm to fabricate oscillators, and compared the resulting beam shape of them. Oscillators were fabricated through photolithography followed by immersed wet-etching with ferric chloride solution (38 wt%, 45 °C). Figure 1 shows images of a beam observed by laser scanning microscope and scanning electron microscope. The fine-grained SUS oscillator showed a shallower side-etched depth less than 10 µm and smooth edges, whereas the typical SUS one showed an over 60-µm side-etched depth and coarse edges, resulting in malfunction of vibration. Therefore, the fine-grained SUS is a promising material for a robust oscillator in electret-based vertical VEHs.

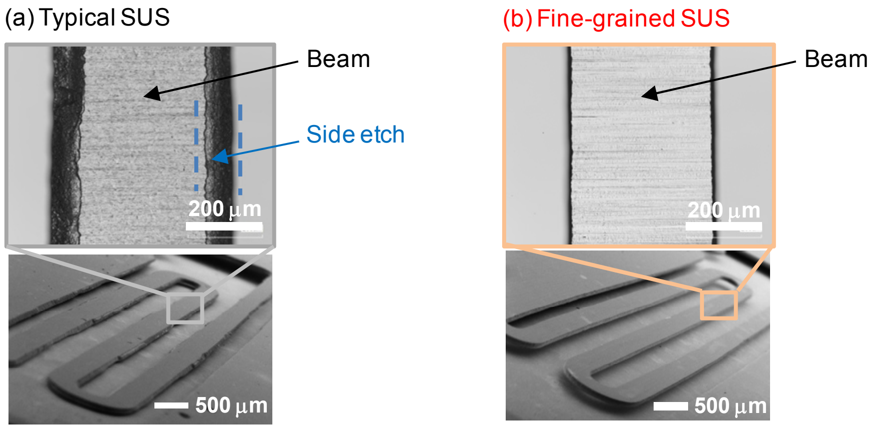

Figure 1. Images of oscillator's beam of (a) typical SUS and (b) fine-grained SUS observed by laser scanning microscope (upper) and scanning electron microscope (lower).

3. Experimental

We theoretically and experimentally investigate the dependence of output power (P_{out}) and peak-peak amplitude ($Amp_{p\text{-}p}$) of the oscillator on initial air gaps. Figure 2 shows a schematic of assembling of our harvester, photographs of the oscillator and harvester set on the shaker, and an experimental set-up for evaluation of output power. We used a laser Doppler vibrometer to measure amplitude of the oscillator during vibration. Applied acceleration and electrical load are 4.9 m/s^2 and 50.5 MΩ, respectively. The oscillator has the whole size of 2×2 cm^2, and the center square has the size of 1×1 cm^2. ABS resin was employed to form frames defining air gap distance by machined cutting. An electret was prepared by implanting charges onto a 10-µm-thick CYTOP polymer film (Asahi Glass, CTL-809M) spin-coated on a 1-mm-thick rigid copper plate using the point-to-grid corona discharging method.

We evaluated P_{out} and $Amp_{p\text{-}p}$ by numerically solving the following coupled differential equations, *equation of motion* (1) and *Kirchhoff's voltage law* (2) [7, 8]. Q, x, and y are the induced charges on the oscillator, the relative displacement of the oscillator, and the displacement forced by the shaker, respectively. Dot denotes the time derivation. First, we computed the air capacitance C_{air} and the spring constant k using FEM simulator (COMSOL Multiphysics), and substitute them into the coupled differential equation. The parameters are summarized in Table 1.

$$\begin{cases} m\ddot{x} + b\dot{x} + kx - \dfrac{d}{dx}\left(\dfrac{Q^2}{2C_{tot}}\right) - mg = -m\ddot{y}, \quad where \quad \dfrac{1}{C_{tot}(x)} = \dfrac{1}{C_{electret}} + \dfrac{1}{C_{air}(x)} & (1) \\ R\left(-\dot{Q}\right) = V_s + \dfrac{Q}{C_{tot}(x)} & (2) \end{cases}$$

Table 1. Parameters in numerical simulation.

Parameters		Value	Unit
Acceleration	a	4.9	m/s^2
Load	R	50.5	MΩ
Inertia mass	m	0.078	gram
Spring constant	k	37	N/m
Viscous damping coefficient	b	1.3×10^{-3}	Ns/m
Surface potential	V_s	-430	V
Relative permittivity	ε_r	2.1	-
Electret thickness	t	10	μm

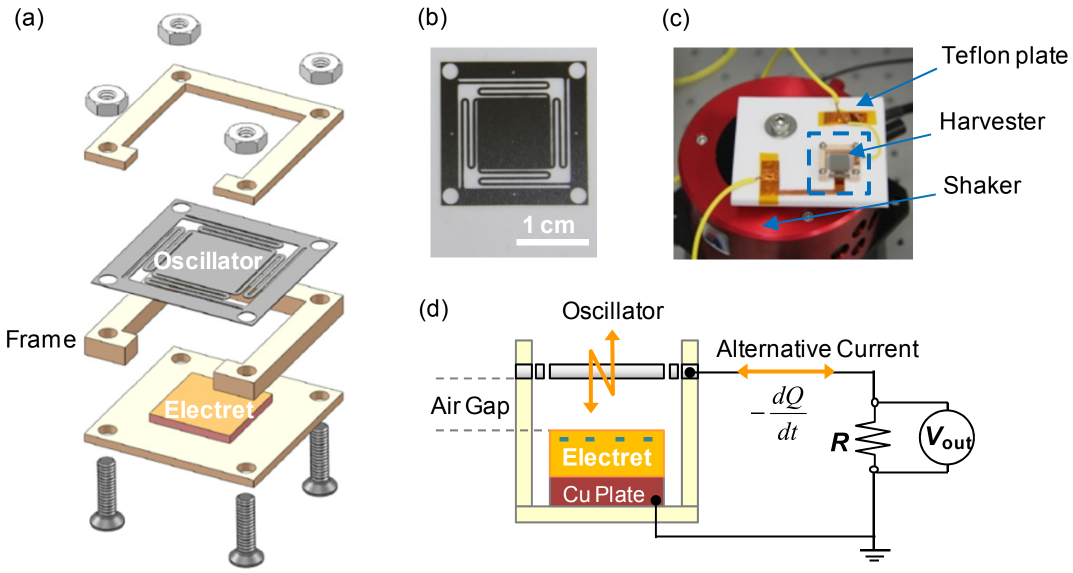

Figure 2. (a) Schematic of assembling, photographs of (b) oscillator and (c) harvester set on shaker, (d) an experimental set-up for evaluation of output power.

4. Results and discussion

Figure 3 shows simulated results of $Amp_{p\text{-}p}$ and P_{out} versus frequency with three different initial air gaps (0.4, 0.5, 1.0 mm). In simulation, a pull-in that the oscillator sticks to the electret was observed with initial air gaps less than 0.4 mm. Interestingly, although it decreased maximum P_{out} from the value obtained at the initial air gap of 0.5 mm, the reduced initial air gap of 0.4 mm exhibited broader frequency band and lower resonance frequency. These results may be attributed to the soft spring effect induced by the stronger electrostatic force.

Subsequently, we employed three different initial air gaps (0.3, 0.48, 1.05 mm) to investigate the theoretical prediction shown in Figure 3. Figure 4 shows experimental results corresponding to Figure 3. The oscillator fabricated from the fine-grained SUS succeeded in travelling over 1-mm displacement without fracture. Similarly, broader frequency band and lower resonance frequency have been observed by reducing initial air gaps. At 0.3-mm initial air gap, maximum P_{out} and FWHM are

2.8 μW (4.7 μW/cm^3 normalized with the volume) and 14 Hz, respectively. The discrepancies of output power between the simulation and the experiment may result from parasitic capacitance and/or inclination of the oscillator installed on machine-cut frames with design errors. Therefore, we found that a reduced initial air gap is effective in broader frequency band and lower resonance frequency in electret-based vertical VEHs.

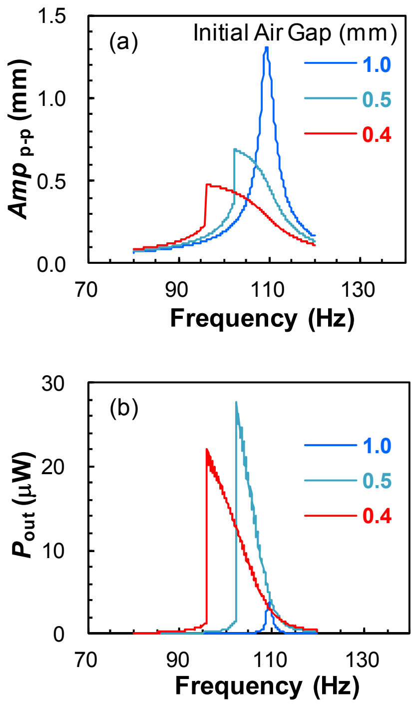

Figure 3. Simulated results of (a) peak-peak amplitude vs frequency and (b) output power vs frequency with three different initial air gaps.

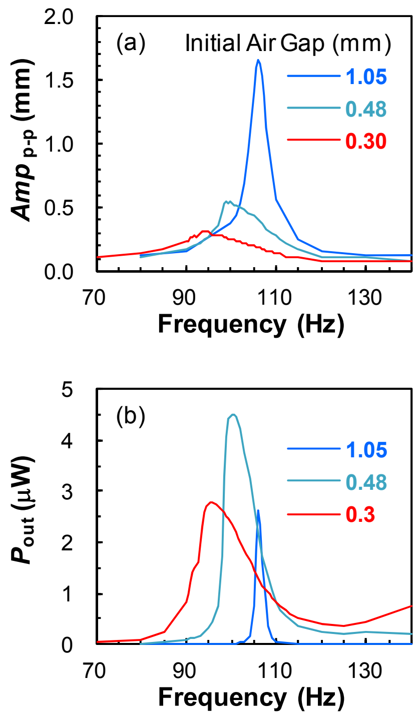

Figure 4. Experimental results of (a) peak-peak amplitude vs frequency and (b) output power vs frequency at three different initial air gaps.

5. Conclusion

In this study, we proposed a fine-grained stainless steel as a promising material for a robust oscillator and investigated the dependence of output power on initial air gaps in electret-based vertical vibration energy harvesters. Beams of the oscillator showed a hardly side-etched depth and smooth edges, and the oscillator succeeded in travelling over 1-mm displacement without fracture. Also, we found that reduced initial air gaps yields broader frequency band and lower resonance frequency, whereas it decreased output power from the value obtained at the optimum.

Acknowledgements

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