AN ELECTROMAGNETIC ENERGY SCAVENGER FROM DIRECT AIRFLOW

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Abstract: This paper presents two types of electromagnetic power generators exploiting direct conversion of airflow into mechanical vibration: 1) a windbelt-based vibratory linear micro-generator targeting strong airflows, and 2) a Helmholtz resonator based generator capable of scavenging energy from weaker airflows, *i.e.* environmental airflows. Both devices consist of two tightly coupled parts: a mechanical resonator, which produces high-frequency mechanical oscillation from quasi-constant airflow; and a permanent magnet/coil system, which generates electrical power from the resonator's motion. The proposed micro-generators obviate the typically required matching of the resonant frequencies of the scavenger and the ambient energy sources it taps. This enables a device that is simpler, smaller, and higher-frequency than previously reported resonant power generator. The windbelt-based micro-generator demonstrated a peak-to-peak output voltage of 81mV at 0.53kHz, from an input pressure of 50kPa. The Helmholtz-resonator based micro-generator achieved a peak-to-peak output voltage of 4mV at 1.4kHz, from an input pressure of 0.2kPa, which is equivalent to 5m/s (10mph) of wind velocity

Key words: windbelt, Helmholtz resonator, electromagnetic generator, airflow

1. INTRODUCTION

Advances in low-power integrated circuit (IC) technology have created great fervor for MEMS-based energy scavengers as power sources for use in distributed wireless sensor networks [1]. Ambient vibration is an attractive energy source because of its abundance in nature and compatibility with MEMSbased resonator technology. However, most reported vibration-driven devices generate maximum energy output only from a narrow frequency band, throttling their utility in environments with fuzzy and/or lowfrequency vibrations [2]. Though researchers have addressed this by adopting mechanical up-converters [3] or wide-band mechanical resonator arrays [4], these devices still require vacuum packaging and controlled-frequency excitation. Meanwhile, airflow is ever-present in nature and is also regarded as an environment-friendly energy source. Rotary permanent magnet generators to harness this source have been developed [5], but such machines typically comprise complex mechanical constructions, including rotor bearings, and also require high pressure airflow for significant power output. The intricate fabrication and ruggedness dictated by these factors also confine viable implementations of rotary air-powered generators to the macro-scale. A concept of using the air-flow as a direct source of mechanical vibration has been demonstrated at a macro scale windbelt generator [6], but the implementation of such concept in small scale has not been reported.

In this research, we have designed and fabricated vibratory micro-generators, which utilize air-flow to directly drive mechanical vibration. The presented devices synergistically combine aspects of scavenging power from both airflow-based and vibratory energy scavenging, while avoiding the limitations of both approaches with much reduction in the structural complexity.

2. DESIGN

For the realization of scavenging energy from direct airflow, electromagnetic power generators closely coupled with two different kinds of wind-powered oscillators are designed as shown in Figure 1: 1) a windbelt-based micro-generator (Fig. 1(a)) and 2) a Helmholtz resonator-based micro-generator (Fig. 1(b) and 1(c)). The windbelt-based vibratory linear microgenerator is composed of a polymer resonator with embedded permanent-magnets, polymer housing, and copper windings. The moving part of the microgenerator is composed of a vibrating membrane positioned in the middle of the flow channel, with an attached set of permanent-magnets (Fig.1(a)). The housing has appropriately located inlet and outlet air ports, to provide optimally distributed airflow for maximal wind-to-vibration conversion efficiency. For the verification of the vibrator geometry, modal analysis was performed using finite element analysis (FEA) as shown in Figure 2. Also, axisymmetric magnetic FEA was carried out for optimization of the electromagnetic power generator (Figure 3). A $12 \times 2mm^2$ polymer membrane and three vertically stacked Ø2mm×0.5mm NdFeB magnets were used for the simulations.



Figure 1: 3-dimensional schematics of the proposed energy scavengers; (a) exploded view of the windbeltased micro-generator, (b) cross-sectional view and (c) exploded view of the Helmholtz resonator based micro-generator.



(a) 1st mode, 138Hz (b) 3rd mode, 664Hz Figure 2 : Modal analysis results of the 50/m-thick Mylar with magnets. (The 1st and 3rd resonant frequencies in the case of the 25/m-thick Kapton as a windbelt are 45 and 217Hz, respectively.)



Figure 3: Magnetic FEA results for the windbelt-based micro-generator (winding region: 1.6 < r < 2.5mm, 0.25 < z < 2.25mm); (a) a magnetic flux distribution and (b) a radial magnetic field intensity distribution at various position of magnets.

A Helmholtz resonator is simply a gas-filled chamber with an open neck, in which a standard second-order (i.e. spring-and-mass) oscillation occurs. The air inside the neck acts as the mass and the air inside the chamber acts as the spring. In response to airflow across the opening, a single-frequency, largeamplitude acoustic wave develops, and can then be exploited for power generation. Figure 4 illustrates the principle of operation for the proposed energy scavenger. To achieve maximal coupling efficiency and design simplicity, the electricity-generating diaphragm resonator is integrated into the Helmholtz resonator, as the bottom wall of the chamber. When compared to the piezoelectric type energy scavengers based on a similar principle [7], the proposed design offers simpler implementation as well as simpler matching of mechanical and Helmholtz frequencies. This aspect is vital to making the devices operable with extremely weak air flows.



Figure 4: Schematics showing the operation principle of the proposed energy scavenger (a) at rest and (b) at resonance by external air flow.



Figure 5: Calculated frequency responses of the mechanical resonator as a function of the diaphragm diameter. The resonant frequency of the Helmholtz resonator is also plotted.

The Helmholtz resonator, with a designed acoustic resonance frequency of 1.7kHz, has a Ø3mm×5mm cylindrical neck and a Ø19mm×5mm cylindrical air chamber. The 50µm-thick Mylar diaphragm was chosen to set its resonant frequency to the same 1.7kHz. These calculations took into account the

Ø1.3mm×2.4mm cylindrical NdFeB permanent magnet attached to the diaphragm. Figure 5 shows the calculated resonant frequency as a function of diaphragm radius, indicating 4.6mm as an ideal diaphragm diameter for maximal wind-to-vibration conversion efficiency.

3. FABRICATION

Both micro-generators are composed of a lasermicromachined polymer vibrating assembly and a stereolithography (SLA) fabricated epoxy housing. Permanent magnets and coil windings are assembled into the polymer vibrator after it is machined. This is then assembled into the epoxy housing, yielding the finished, integrated electromagnetic energy generator.



Figure 6: SLA-fabricated micro generators with electromagnetic electrical power generator; (a) Windbelt-based micro-generator and (b) Helmholtz resonator based micro-generator

Figure 6 shows the fabricated electromagnetic micro-generators. In the windbelt-based micro-generator shown in Figure 6(a), $12mm \times 2mm$ vibrating elements were fabricated either from a 25μ m-thick Kapton or from a 50μ m-thick Mylar films by CO₂ laser micromachining. These are then assembled with three vertically stacked Ø2mm×0.5mm cylindrical NdFeB permanent magnets. Epoxy-acrylate-based SLA was used to form the coil bobbins as well as the housing, with inlet and outlet air ports were fabricated. 90 turns of 100μ m diameter magnet wire were wound around the bobbins, giving a nominal resistance of 3.7Ω . The calculated volume of the assembled device, not including the extruded air inlet and outlet was $0.86cm^3$. Its measured weight was 0.70g.

A Helmholtz resonator based micro-generator is composed of a Helmholtz resonator and the electromagnetic power generator (Figure 6(b)). This device consisted of an SLA-fabricated Helmholtz resonator and housing, a laser micromachined diaphragm, magnets and a coil (Fig. 6(b)). A Ø1.3mm×2.4mm cylindrical NdFeB permanent magnet was mounted to a Ø4.6mm×50µm-thick Mylar diaphragm to form the membrane resonator. For both micro-generators, all parts were assembled with epoxy adhesive and tested.

4. EXPERIMENTAL

Pressure-regulated compressed N₂ gas was used to generate controllable airflow. The windbelt microgenerator demonstrated a linear relationship between the input pressure and open-circuit voltage. A peak-topeak output voltage of 81mV was produced at 0.53kHz, at an input pressure of 50kPa (Fig. 7(a)). A linear relationship between the input pressure and opencircuit voltage was obtained for both windbelt materials, 25µm thick Kapton and 50µm thick Mylar, except for an abrupt shift observed for the latter case (Fig.7(b)). The irregular output waveform can be mainly ascribed to structural asymmetry induced by manual assembly. The resonant frequency of the vibrator was higher than the expected 1st order resonant frequency, and increased with the input pressure (Fig. 8). This confirms that the device is actually vibrating at higher order vibration modes which in turn suggest the possibility of further performance improvement by utilizing the higher order vibration. Maximum open-circuit voltages of 81mV at 0.53 kHz and 50mV at 0.41kHz were measured for Mylar and Kapton vibrators, respectively.



Figure 7: Measured characteristics of the windbeltbased micro-generator; (a) open-circuit voltage waveform and (b) peak-to-peak open-circuit voltage as a function of the input pressure.



Figure 8: Resonant frequency as a function of the input pressure

In the Helmholtz resonator based micro-generator, the Helmholtz resonator generated a significant, audible acoustic signal with a frequency of 1.4kHz from a constant airflow of roughly 5m/s, corresponding to a 0.2kPa pressure measurement taken 200mm from the 2.5mm diameter outlet of the gas supply (Fig. 9). Figure 10(a) shows the peak-to-peak output voltage of 4mV from the electromagnetic generator at the resonators' coupled frequency, as driven by a 5m/s airflow. Also, the output characteristic of the generator, which is observed at varying wind strengths, demonstrates well-maintained frequency response while the output voltage increased with the wind strength, as shown in Figure 10(b).



Figure 9: Retrieved acoustic spectrum from the recorded acoustic signal generated by the Helmholtz resonator.



Figure 10: Measured voltage output from the pick-up coil (a) when 5m/s air blows around the open neck and (b) when different strength of air-flow are applied.

5. DISCUSSION AND CONCLUSION

By integrating electromagnetic power generators with windbelt and Helmholtz resonators, the proposed energy scavengers have successfully demonstrated the harvesting of energy from ambient airflow. In the windbelt-based micro-generator, the output characteristics are improved by increasing the wind speed, and further performance improvement can be achieved by utilizing the higher order vibration in the polymer vibrator. The Helmholtz resonator based micro-generator also shows increased output voltage with larger wind-velocity, but an invariant frequency. The performance of the proposed generators can be further improved by optimizing the resonator design for maximal wind-to-vibration conversion efficiency, increasing the resonant frequency through further miniaturization, exploiting arrayed deployments, and improving the magnetic circuit.

Table	1:	Specifications	of	the	proposed	energy
scaven	gers					

Windbelt-based micro-generator					
Size	12mm×12mm×6mm				
Coil resistance	3.70hm (90turns)				
f _{mechanica} (@ 50kPa)	0.53kHz				
Output voltage (@ 50kPa)	81mV _{pp}				
Helmholtz resonator based micro-generator					
Size	19mm (D)×5mm (t)				
facoustic, measured (@ 5m/s wind)	1.4kHz				
Coil resistance	7.60hm (200turns)				
Output voltage (@ 5m/s wind)	4mV _{pp}				

6. ACKNOWLEDGEMENT

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