Airflow energy harvesters of metal-based PZT thin films by self-excited vibration

E Suwa, Y Tsujiura, F Kurokawa, H Hida and I Kanno
Department of Mechanical Engineering, Kobe University, 1-1 Rokkodai-cho, Nada-ku, Kobe, Japan

E-mail: kanno@mech.kobe-u.ac.jp

Abstract. We developed self-excited vibration energy harvesters of Pb(Zr,Ti)O₃ (PZT) thin films using airflow. To enhance the self-excited vibration, we used 30-μm-thick stainless steel (SS304) foils as base cantilevers on which PZT thin films were deposited by rf-magnetron sputtering. To compensate for the initial bending of PZT/SS304 unimorph cantilever due to the thermal stress, we deposited counter PZT thin films on the back of the SS304 cantilever. We evaluated power-generation performance and vibration mode of the energy harvester in the airflow. When the angle of attack (AOA) was 20° to 30°, large vibration was generated at wind speeds over 8 m/s. By FFT analysis, we confirmed that stable self-excited vibration was generated. At the AOA of 30°, the output power reached 19 μW at wind speeds of 12 m/s.

1. Introduction
Piezoelectric vibration energy harvesters (PVEHs) have been widely studied as promising power sources for battery-free wireless sensor nodes. Conventional PVEHs are usually composed of simple cantilever structure with piezoelectric materials (bulk ceramic and thin film form), and the electric power is generated from the external mechanical vibration of cantilevers. Therefore, PVEHs have to be used in environments where relatively-large vibrations exist.

In recent years, airflow energy harvesters (AFEHs) have attracted attention as a novel type of PVEH [1-5]. The AFEHs generate electric power from the vibration induced by continuous airflow, whereas conventional PVEHs generate electric power from mechanical vibration or kinetic motion. Therefore, the AFEHs are expected to extend the range of application of PVEHs. It is known that a self-excited vibration is induced by airflow when the wind speed is above a critical value (cut-in wind speed) [6]. In the practical use of AFEHs, they are placed in airflows with higher wind speed than cut-in wind speed. However, there are no detailed studies about the mechanism responsible for self-excited vibration for MEMS-scale AFEHs, and clear design theory for the MEMS-AFEHs has not been established yet.

In this study, we fabricated PVEHs of Pb(Zr,Ti)O₃ (PZT) thin films as AFEHs driven by self-excited vibration in an airflow. We used thin stainless steel foils as base cantilevers in order to obtain a large displacement of self-excited vibration without breakdown of the AFEHs. We measured the vibration characteristics of the AFEHs and examined the effect of the various parameters (wind speed and angle of attack, etc.) to optimize the design of the MEMS-AFEHs.
2. Experiments

2.1. Device fabrication
Figure 1 shows a schematic illustration of our AFEH. We used 30-μm-thick stainless steel (SS304) foils (20 × 20 mm²) as base cantilevers. After sputtering deposition of Pt/Ti bottom electrodes, the PZT thin films were then directly deposited onto the SS304 cantilevers by radio-frequency (rf) magnetron sputtering. Since PZT-sputtering on SS304 foils inevitably caused large initial bending due to the thermal stress, we deposited counter PZT layers on the opposite side of PZT/SS304 foils to make flat PZT/SS304 cantilevers. Subsequently, the Pt top electrodes were prepared through a shadow mask. One end of the PZT/SS304/PZT foils was fixed by a clamping jig that then looked something like a flag.

![Figure 1. Schematic illustration of the AFEH.](image)

2.2. Frequency response and optimal resistance
Prior to the evaluation of the self-excited vibration in airflow, we measured the frequency response of the output voltage and the displacement to determine the resonance frequency of the AFEHs. The AFEHs were mounted on a vibration exciter and swept the excitation frequency at an acceleration of 1.0 m/s². We also measured the load resistance dependence of the output power in an external load resistance at the resonance frequency of 1.0 m/s² acceleration. The effective electric power $P$ was calculated using

$$P = \frac{V_{p-p}^2}{8R}$$

where, $V_{p-p}$ and $R$ are the peak-to-peak output voltage and the load resistance, respectively.

2.3. Power-generation performance of AFEHs
Figure 2 shows the measurement setup for the power generation characteristics of AFEHs in airflow. The airflow was generated in an air channel by a fan, and the wind speed was tuned by voltage from a DC power supply. The AFEH was set at the outlet of the air channel and the angle of attack (AOA) was defined by the angle between the AFEH and the airflow direction as shown Figure 2 (c). We measured the output voltage by oscilloscope, while the cantilever displacement of the AFEHs was observed using a high speed camera. The measurements were conducted in various airflow conditions with wind speeds (0 ~ 12 m/s) and the AOA (0 ~ 180°). In order to examine the vibration mode of the AFEHs in detail, we analyzed the frequency spectrum of output voltage by fast Fourier transformation (FFT). Subsequently, we measured the effective electric power generated at the optimal load resistance and the optimal AOA.
3. Results and discussion

Figure 3 shows the frequency response of the output voltage and the cantilever displacement at an acceleration of 1.0 m/s². The resonance frequency of the AFEH was measured to be 124 Hz. Figure 4 shows the output power and voltage as functions of load resistance. The maximum output power was obtained at a load resistance of 7.5 kΩ. This value is in good agreement with the theoretical value of optimal load resistance of 8.1 kΩ.

Figure 5 shows the output voltage in the open-circuit state versus wind speed at an AOA of 0° to 180°. When the free end of the AFEH faced windward, we observed large output voltage at AOA of 10° to 40° (figure 5(a)). When the AOA was 20° and 30°, the output voltage rapidly increased at the wind speed above 8 m/s, which is the cut-in wind speed of the AFEH. The output voltage reached 1.4 V_p-p (30°) at a wind speed of 12 m/s. One the other hand, when the free end of the AFEH faced leeward (AOA was over 90°), the output voltage was less than 50 mV_p-p (figure 5(b)). From these results, we considered that the AFEHs whose free end faced windward induced large self-excited vibration due to the unstable condition of the cantilever in the airflow.
Figure 6 shows the tip displacement (peak-to-peak amplitude) at AOA of 20° and 30° as a function of wind speed. The displacement curve is in good agreement with output voltage curve in figure 5. The tip displacement reached to 14 mm at the AOA of 30° in the wind speed of 12 m/s, however we could find no damage on the AFEHs under such large vibration. Figure 7 shows the optical images of vibrational motion of the AFEHs at the AOA of 20°. Clear vibration was not observed at wind speeds up to 8 m/s, however, large self-excited vibration was generated at the wind speeds of more than 8 m/s.

Figure 8 shows FFT spectrum of the output voltage in the open-circuit state at the AOA of 20°. With increasing the wind speed from 6 m/s to 12 m/s, the vibration frequencies of the AFEH were reduced from 119.1 Hz to 99.1 Hz. Because the vibration frequencies of the AFEH were almost the same as the resonance frequency of the AFEH measured by vibration exciter, the stable self-excited vibration was generated by the airflow. The decrease of vibration frequency with the wind speed was attributed to the softening effect of the large vibration of the cantilevers.
Figure 9 shows the output power versus wind speed. When the AOA was 20° or 30° under wind speeds of 12 m/s, the maximum output power reached 12 μW (20°) and 19 μW (30°), respectively. These output powers are sufficiently large to drive MEMS devices such as wireless sensor nodes [7]. Table 1 compares the performance of our AFEH with other studies. Note that the volumes in Table 1 were calculated from the data of the references. In terms of the power density, our AFEH is comparable to that of other larger scale AFEHs. Those results indicate that MEMS-AFEHs composed of PZT thin films on metal cantilevers are an effective way to obtain large displacement from a continuous airflow.

![Figure 9. Output power as a function of wind speed. The load resistance was 7.5 kΩ.](image)

| Study                  | Piezoelectric material | Effective volume [mm³] | Wind speed [m/s] | Output Power [μW] | Power density [μW/mm³] |
|------------------------|------------------------|------------------------|------------------|-------------------|------------------------|
| D. St. Clair (2010) [2]| PZT [3]                | 266 [3]                | 12.9             | 880               | 3.3                    |
| S. Li (2011) [4]       | PVDF                   | 472                    | 8                | 615               | 1.3                    |
| H. D. Akaydin (2012) [5]| PZT                 | 255747                | 1.192            | 100               | 4 × 10⁴                |
| This study             | PZT                   | 10                     | 12               | 19                | 1.9                    |

4. Conclusion
In this study, we developed AFEHs of metal-based PZT thin films, and evaluated their power-generation characteristics. At AOA of 20° and 30°, we observed large vibration at wind speeds above 8 m/s, while we could not find any damage or breakdown of the AFEH. At the wind speed of 12 m/s, the maximum displacement reached 14 mm at an AOA of 30°. FFT analysis of output voltage revealed that a stable self-excited vibration was generated. The maximum output power at an AOA of 30° reached 19 μW at wind speeds of 12 m/s. The AFEH in this study showed that it could generate power of comparable density to conventional large-scale AFEHs.

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