HARVESTING ENERGY FROM AIRFLOW WITH MICROMACHINED PIEZOELECTRIC HARVESTER INSIDE A HELMHOLTZ RESONATOR

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Abstract: In this paper we report an airflow energy harvester that combines a piezoelectric energy harvester with a Helmholtz resonator. The resonator converts airflow energy to air oscillations which are converted into electrical energy by the piezoelectric harvester. A Helmholtz resonator with an adjustable resonance frequency has been designed. The resonance frequencies of the resonator and the piezoelectric harvester were matched during harvesting. The aim of the presented work is a feasibility study on using packaged piezoelectric energy harvesters with Helmholtz resonators for airflow energy harvesting. The maximum energy we were able to obtain was 2 μW at 13 m/s.

Keywords: piezoelectric harvester, Helmholtz resonator, airflow, cantilever

INTRODUCTION

The oldest known way to extract energy from airflow is by using wind turbines. Large-scale wind turbines can be highly efficient, but performance of miniature wind turbines is less efficient due to the relatively high viscous drag on the blades at low Reynolds numbers and the bearing losses [1]. Operation at very low flow velocities, about 1m/s, and miniature turbines require very low-friction bearing. For such applications, devices without bearings are a better solution. In recent years harvesters of airflow energy have been developed based on vibration energy harvesters. These airflow harvesters rely on the drag force of the airflow, which causes vibration of a piezoelectric or magneto-electric component, which in turn converts kinetic energy of motion into electricity. Cuadras et al. [2] report a tail- in-a-flow type device – a PVDF film that is actuated by von Karman vortices. Akaydin et al. [3] designed short flexible piezoelectric cantilever beams by the PVDF film and placed them inside turbulent flows, again excited by von Karman vortices. Generally for optimum operation of the devices it is required that the beam and the predominant frequency of the flow match. In order to ensure matching of the resonance frequencies, other authors suggest a Helmholtz resonator as a mediator between the airflow and the piezoelectric harvester [4,5]. The harvester is placed on the bottom of the resonator where it is actuated by the oscillation of the air in the resonator's chamber. The reported energies which were generated by these harvesters are about 10 μW.

In this paper we report an airflow energy harvester which uses a piezoelectric cantilever beam in a Helmholtz resonator. A custom designed Helmholtz resonator with adjustable resonance frequency is used. The piezoelectric harvester is vacuum packaged between two glass covers [6]. In order to harvest air oscillation in the Helmholtz cavity, we complemented the resonator with soft latex membrane on the bottom. The packaged piezoelectric harvester was mounted on top of the membrane. In such way it was possible to harvest the maximum energy that the harvester could produce.

HELMHOLTZ RESONATORS

Helmholtz resonance is the phenomenon of air resonance in a cavity (Figure 1). A Helmholtz resonator can be represented as a simple mass-spring system, where the mass is the volume of the air in the neck of the resonator and the spring is the volume of the air in the cavity of the resonator.

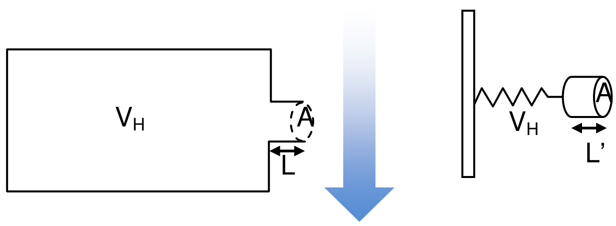


Fig. 1: Helmholtz resonance cavity and a mass-spring representation.

The resonance frequency depends on the volume of the cavity and the volume of the aperture (the neck) of the cavity.

$$f_H = \frac{\upsilon}{2\pi}\sqrt{\frac{A}{V_H L'}} \qquad (1)$$

where υ is the speed of sound in a gas, A is the cross sectional area of the neck, L' is the apparent length of the neck and V_H is the static volume of the cavity. If the aperture is slendering, then A should be considered the average cross sectional area of the neck. The apparent length of the neck includes the actual length of the neck with correction for the extra inertial mass of air around the neck region.

$$L' = L + 1.7r\,, \qquad (2)$$

for a slendering aperture, where r is the inside radius of the neck.

Generally the cavity has several resonance frequencies, lowest of which is the Helmholtz resonance. The pressure in the cavity is relatively uniform, and the air in the neck oscillates as a single mass [7].

AIRFLOW ENERGY HARVESTER

Custom Helmholtz resonator

If one would like to use a Helmholtz resonator combined with a pressure driven energy harvester to harvest energy from airflow, one should place the energy converter at the bottom of the Helmholtz resonator [7]. In order to shield the harvester from unwanted viscous influence and provide only vibration excitation to the device, we suggest using a packaged piezoelectric harvester. An additional advantage of vacuum packaging is the increased power output and the robustness of the device. Thus the amplitude of the excitation depends on the amplitude of vibration of the packaging. The latter is a coupled result of the oscillation of the air in the cavity and the consequent vibration of the bottom of the Helmholtz resonator. The amplitude of vibration increases with the airflow velocity.

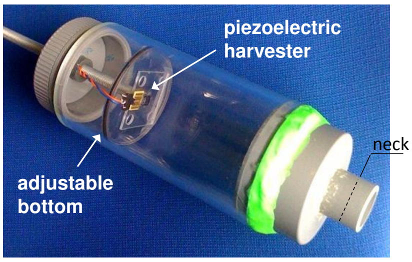


Fig. 2: Photograph of the Helmholtz resonator with the piezoelectric cantilever harvester in it.

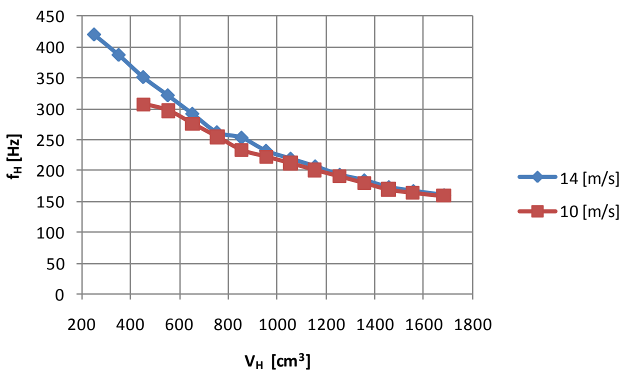
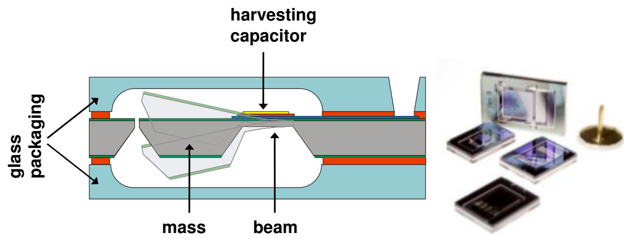


Fig. 3: Dependence of the frequency of the custom Helmholtz resonator on the volume of the cavity at constant airflow velocity. Measured with Helmholtz resonator presented in Fig 2.

Figure 2 shows the custom Helmholtz resonator with adjustable resonance frequency that we have designed for our feasibility study. The resonator oscillates in the frequency range of 160 Hz to 400 Hz. Figure 3 shows the dependence of the frequency of the custom Helmholtz resonator on the volume of the cavity. One can notice a small frequency shift between the two constant airflow velocities. This shift comes from the shift of the optimal angle at which the airflow enters the neck of the resonator.

Piezoelectric energy converter

We have fabricated piezoelectric cantilever energy harvesters with different beam and mass dimensions to cover a frequency range from 200 up to 1200 Hz [6,8]. The footprint of all devices is smaller than 1 cm^2 in order to allow integration with miniaturized wireless sensor nodes. Aluminium nitride (AlN) was chosen as piezoelectric material.



a) b)

Fig. 4: a) Vibration energy harvester packaged in between glass substrates. The mass can move up- and downwards; b) Photograph of various piezoelectric energy harvesters.

The energy harvester uses a MEMS cantilever structure with a seismic mass attached to the free end of the cantilever, as shown on figure 4 a). This structure is fabricated from silicon by a combination of wet and dry etching techniques. A piezoelectric patch, consisting of a platinum bottom electrode, the piezoelectric material and a top aluminum electrode, is fabricated on top of the beam. The beam and AlN thickness were 25 ± 0.5 µm and 400 nm respectively. The harvesters were packaged in between two glass substrates. Cavities with a depth of 400 µm were etched into these glass substrates to allow the mass to oscillate. Electrical power is dissipated in a resistive load which is connected to the piezoelectric patch.

MEASUREMENTS WITH THE AIRFLOW ENERGY HARVESTER

The resonance frequency of the piezoelectric device was measured beforehand: f_p= 309 Hz. The optimum load resistance of the piezoelectric device was determined as R_0 = 3.3 MΩ. The maximum energy that the piezoelectric device can generate is determined by the maximum displacement of the cantilever in the packaging. In our case this was 400 µm deep cavities above and below the cantilever. The maximum power from this device was 2 µW.

The next step was to mount the harvester at the bottom of the Helmholtz resonator and to subject it to constant airflow. By changing the resonance frequency of the Helmholtz resonator by changing the volume of the cavity we obtained the characteristic curve of the piezoelectric cantilevers (figure 5).
In order to enhance the vibration of the packaging of the piezoelectric harvester, we have mounted the harvester on top of a flexible membrane. The membrane was consequently placed on the bottom of the Helmholtz resonator. The latex membrane had natural resonance frequency of 49 Hz.
The vibration of the membrane enhanced the vibration of the piezoelectric harvester 20 times. In this way, at higher airflow velocities we could obtain the maximum energy which the piezoelectric harvester was capable of generating (figure 6).

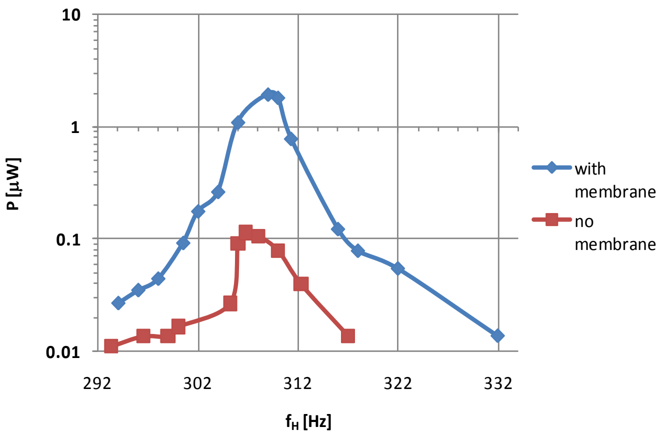


Fig. 5: Power generated by the piezoelectric harvester at R_0 = 3.3 MΩ, constant airflow velocity of 13 m/s and changing volume of the cavity of the Helmholtz resonator.

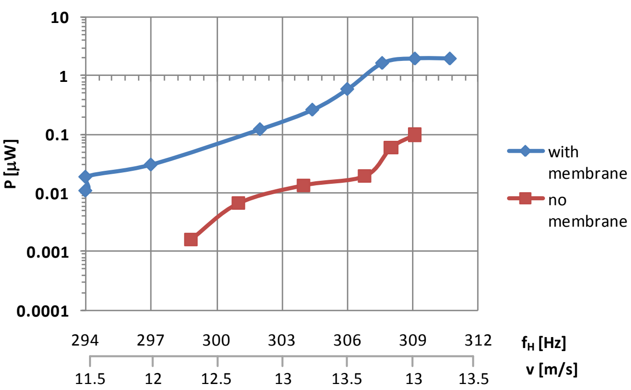


Fig. 6: Power generated by the piezoelectric harvester at R_0 = 3.3 MΩ, constant volume of the cavity of the Helmholtz resonator and different airflow velocities.

Figure 7 shows the sinusoidal signal shape from the harvester. Its amplitude is not fully constant due to fluctuations in the harmonic pressure oscillation inside the Helmholtz resonator.

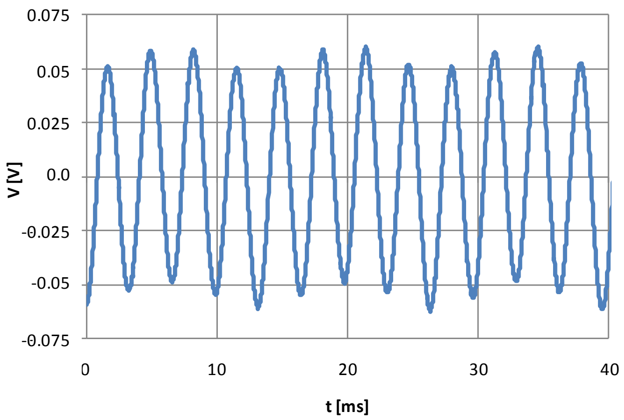


Fig. 7: Output voltage in time of the piezoelectric harvester mounted in the Helmholtz resonator with membrane, at R_0 = 3.3 MΩ, f_p= 309 Hz, airflow velocity of 13 m/s.

ANALYSIS AND CONCLUSIONS

We have proved the feasibility to use Helmholtz resonators combined with piezoelectric energy harvesters to harvest energy from airflow. We were able to harvest 2 µW at 13 m/s airflow velocity with a custom designed harvesting system. We have used a packaged piezoelectric cantilever energy harvester, in order to remove the viscous influence of the air in the Helmholtz cavity and guarantee only vibration excitation of the harvester. In order to enhance the amplitude of vibration excitation, we have mounted on the bottom of the Helmholtz cavity a latex membrane. The membrane vibrated at the resonance frequency of the Helmholtz resonator. Its amplitude of vibration was sufficient to enhance the amplitude of vibration of the piezoelectric cantilever harvester.

Our Helmholtz resonator was a fairly bulk design with a large diameter of the aperture, which led to unwanted frequency shift at different airflow velocities. A slendering aperture would reduce this effect.

From the theory of Helmholtz resonators is known that they are fairly easy down scalable. It is possible to design a small airflow energy harvester for the needs of wireless sensor systems (figure 8).

Major drawback of the Helmholtz resonators is the strong dependence of their resonance frequency on the speed of sound in air, thus the airflow temperature. See equation (1) and figure 9. In a limited temperature range of 10ºC the frequency shift is about 6 Hz, depending on the size of the resonator's cavity. This means that the application of the airflow energy harvesters would be limited to environments with fairly stable temperature, like air-conditioning pipes. Other option is to use an automatic frequency tuning integrated with the piezoelectric cantilever energy harvester or multiple piezoelectric devices in the same resonator's cavity.

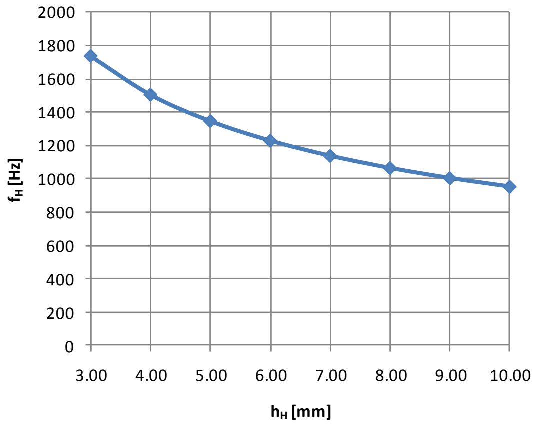


Fig. 8: Dependence of the frequency of the Helmholtz resonator on the height of the cavity h_H at fixed temperature 25ºC. The neck has dimensions 5 mm x ∅ 3mm. The cavity has diameter ∅ 2cm.

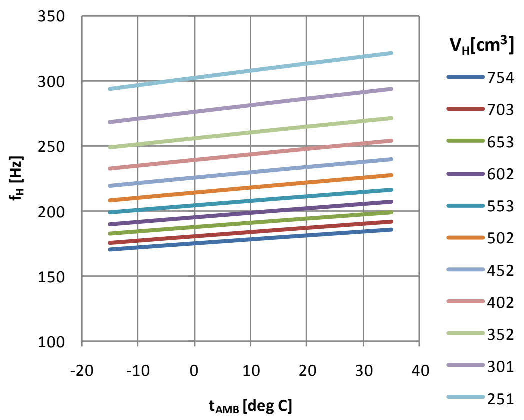


Fig. 9: Dependence of the frequency of the Helmholtz resonator on the temperature of the air at fixed volume of the cavity. Calculated using eqn. (1).

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