Research on Piezoelectric Energy harvesting from Multi-Direction Wind-Induced Vibrations

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Abstract. Micro electric devices have been widely applied in outdoor field work, but the battery power limits its performance. Piezoelectric energy harvesting from wind-induced vibration is an attractive power solution for the micro electric devices in field work. Its output characteristics of proposed system is analysed under different wind speed and direction. Experimental results show that the proposed system can harvest more energy if the incoming flow is parallel to the piezoelectric plate. Its output voltage increases from 2.5V to 10.3V when the wind speed ranges from 9m/s to 21m/s. The output voltage can achieve 8.5V, if the flow direction is vertical to the piezoelectric plate. But the proposed harvesting system outputs very small voltage in case the flow direction from the top. These results show that the piezoelectric energy harvesting system can collect the wind energy from multi-direction, and have potential application to power the micro electric devices.

1. Introduction

In recent years, micro electric devices have been developed rapidly and widely applied in outdoor field work, such as bridge structure monitoring, forest fire prevention, etc. A major limitation of the outdoor application is the power supply, and most of classic choice is the chemical battery. Due to the limited capacity and large size, the batteries have to be frequently replaced with a new one, and cause the environment pollution. Piezoelectric energy harvesting from wind-induced vibration is an attractive power solution for the micro electric devices in field work. It can collect the energy from environment, and do not need to replace the battery.

Inspired by the swinging leaves, piezoelectric energy harvesting system was designed with piezoelectric film. Its maximum output power is 296uW at the wind speed of 8m/s [1]. With a piezoelectric ceramic plate and piezoelectric films, a tree-shape device is developed to harvest the wind energy [2]. The accumulation of output power from the piezoelectric leaves was more than 1mW. In Ref [3], a cantilever beam is designed with piezoelectric ceramic plate, and blunt body, and its output voltage achieved 20V, in the wind tunnel experiment. A wind-induced vibration piezoelectric wind power generation device combined with resonator design is proposed by Ref [4]. The self-excited vibration will be generated, when the wind blows into the resonator, and the vibration energy will be transformed into electric energy through the piezoelectric cantilever beam at the bottom of the resonator. Most of these researches focus on improving the output power and voltage of the energy harvesting system, and effect of wind flow direction is less reported. However, the wind can come from any direction in
practical application, hence it is necessary to research on piezoelectric energy harvesting from multi-direction wind-induced vibration. In this paper, a piezoelectric energy harvesting system of simple structure and small size is designed with piezoelectric plate and blunt body. Experimental research on the proposed energy harvesting system was performed in different wind direction. The output power and load characteristics were analysed with energy interface circuit.

2. Principal analysis and structural design

As shown in Fig.1, the wind-induced vibration device was designed with a blunt body fixed on the end of piezoelectric cantilever. When the wind flow passes the blunt body, it will be acted by the aerodynamic force that bends or vibrates the piezoelectric cantilever. The electric energy generated by the piezoelectric effects can be collected by certain energy interface circuit.

When the incoming flow towards the blunt body, there will be an elastic deformation with static balance angle on piezoelectric cantilever. In the air flow, the Karman vortex street occurs behind the blunt body. Due to the shedding of vortexes, a periodic force will be generated on the blunt body, which excites the piezoelectric cantilever. With a suitable energy interface circuit, the mechanical energy from the wind is converted into the electric energy. If the frequency of vortexes shedding is close to the natural frequency of wind-induced vibration device, it will resonate which can maximize output power of the proposed piezoelectric energy harvesting system.

![Fig.1 diagram of wind-induced vibration devices](image)

The piezoelectric cantilever was designed with a copper substrate covered by piezoelectric plate. Because the strength-to weight ratio is better than most of the metals, the blunt body is made of wood. With a certain mass and structure, there is enough aerodynamic and inertial force on the blunt body, so that the piezoelectric cantilever can be deformed and vibrated to convert the energy. When the piezoelectric cantilever is bent under the aerodynamic force of blunt body, its output voltage can be expressed as [5]:

\[ V_s = \frac{3\lambda_h (1-\lambda_h) \lambda_{33} E_p}{4K \left(1 - \lambda_h + \lambda_h \lambda_E \right)} \left( \frac{h}{l} \right)^2 F. \]  

(1)

where \( l \) and \( d \) are the length and width of piezoelectric plate, respectively. \( K \) and \( F \) are the Equivalent stiffness and equivalent force on the free end of piezoelectric cantilever. \( \lambda_{33} \) is piezoelectric voltage coefficient and \( h \) is the sum of thickness of copper substrate and piezoelectric plate,

\[ h = h_p + h_m \]  

(2)

where \( h_p \) and \( h_m \) are the thickness of copper substrate and piezoelectric plate, respectively. \( \lambda_h \) is the thickness ratio.

\[ \lambda_h = \frac{h_m}{h} \]  

(3)

\( \lambda_E \) is elastic modular ratio,
\[
\lambda_E = \frac{E_m}{E_p} \quad (4)
\]

where \(E_m\) and \(E_p\) are the elastic modulus of the copper substrate and the piezoelectric plate, respectively.

If the frequency of the wind-induced vibration is \(f_s\), the maximum output power of the proposed piezoelectric energy harvesting system is

\[
P = \frac{C_f V_x^2}{2 f_s} \quad (5)
\]

where

\[
C_f = \frac{\eta_1 (1 - \lambda_p + \lambda_E \lambda_E) d l}{(1 - \lambda_n) \beta_{33}^T \eta_n h} \quad (6)
\]

in which \(\varepsilon_{33}^T = 1300 \varepsilon_0\) is the dielectric constant, and \(\beta_{33}^T = 1/\varepsilon_{33}\) is the dielectric isolation rate. The parameters \(\eta_1\) and \(\eta_2\) are

\[
\eta_1 = \lambda_n^4 (1 - \lambda_E)^2 - 2 \lambda_n \left( 2 h_n^2 - 3 \lambda_n + 2 \right) (1 - \lambda_E) + 1 \quad (7)
\]

\[
\eta_2 = \eta_1 (1 - \lambda_n + \lambda_E \lambda_n) \left( 1 + K_{31}^2 \right) - 3 \lambda_n^2 (1 - \lambda_n) \lambda_E^2 K_{31}^2 \quad (8)
\]

where

\[
K_{31}^2 = \frac{E_p S_{31}^2}{\beta_{33}^T} \quad (9)
\]

3. Experiments

The proposed piezoelectric energy harvesting system was fixed on the platform, and the air blower targeted the centre of the blunt body. An oscilloscope measured the voltage on the load with an energy interface circuit. In the experiment, the air blower at a chosen wind speed ran for a period of time, which waits the system to a stable state. The oscilloscope recorded the output voltages of 50 seconds, and then the RMS voltage was calculated.

3.1. First Experiment

Fig. 2 shows the direction of incoming flow which is parallel to the piezoelectric plate. Experimental results shown in Fig. 3 indicates that the output voltage of proposed harvesting system increases with the wind speed. It increases from 2.5V to 10.3V, when wind speed is from 9m/s to 21m/s.
3.2. Second Experiment
In the second experiment, the incoming flow direction is vertical to the piezoelectric plate as shown Fig.4. Wind speed is also chosen between 9m/s to 21m/s, and the results are shown in Fig.5. It can be found that the output voltage of the proposed harvesting system is very small and almost no change with the increasing of wind speed.

3.3. Third Experiment
As shown in Fig.6, the incoming flow was from the free end of piezoelectric plate, and the third experiment was also performed during wind speed of 9m/s to 21m/s. the results in Fig.7 show that the output voltage increases from 2.8V to 8.5V with the increasing wind speed.
4. Conclusion
A piezoelectric energy harvesting system is developed to gather the energy from multi-direction wind-induced vibration. Its output characteristics of proposed system is analyzed under different wind speed and direction. Experimental results show that the proposed system can harvest more energy if the incoming flow is parallel to the piezoelectric plate. Its output voltage increases from 2.5V to 10.3V when the wind speed ranges from 9m/s to 21m/s. the output voltage can achieve 8.5V, if the flow direction is vertical to the piezoelectric plate. But the proposed harvesting system outputs very small voltage in case the flow direction from the top. These results show that the piezoelectric energy harvesting system can collect the wind energy from multi-direction, and have potential application to power the micro electric devices.

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