Electroaeroelastic Modeling and Analysis for Flow Energy Piezoelectric Harvester

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(Received 18 January 2016; revised 20 February 2016; accepted 5 March 2016)

Abstract: An electroaeroelastic model for wind energy harvesting using piezoelectric generators is presented. The flow field is mapped in detail. The force which the fluid flow exerts on the generator is formulated. The output voltage levels generated from the mechanical strain within the piezoelectric elements are determined. An analytical model is developed with consideration of the interactions between the fluid, solid and electric. Various analytical results are obtained, such as flow velocity contour and pressure contour for the flow, moving trajectories, stress contour and output voltage of the harvester. A prototype is fabricated and tested. The simulation result is close to the experimental result. The model developed in this paper can predict the performance and behavior of different energy harvesters. And it also can be used as a design tool for optimizing the performance of the harvester.

Key words: wind energy harvester; piezoelectric; aeroelasticity; electromechanics

CLC number: TM387 **Document code**: A **Article ID**: 1005-1120(2017)01-0009-06

0 Introduction

In recent years, with the rapid development of wireless network and microelectronic devices, there has been more and more requirement of electrical energy for these devices. Most of the current small electronic devices and wireless sensors are battery-powered. The batteries have a limited life and need frequent charge[1]. In certain situation, when wireless sensors are placed outside of high-rise buildings, battery replacements are money-consuming in maintenance. And it is also one of major bottlenecks for the development of wireless network. Energy harvesting from environmental vibration is one of the promising alternatives, which has been actively explored.

Small wind energy harvesters are divided into two kinds: turbine type and vibration type energy harvester. Bansal et al. developed a micro turbine generator working at a low wind speed[2]. The 12-blade design achieves a generator output power of 4.3 mW at a tunnel flow speed of 10 m/s, and can operate at flow speeds down to 4.5 m/s. Karami et al. presented a new piezoelectric compact wind turbine[3]. The piezoelectric bimorphs are made bi-stable by incorporation of repelling magnetic force. An 80 mm × 80 mm × 175 mm nonlinear piezoelectric wind generator can generate milliwatts of power from wind as slow as 2 m/s.

The vibration type energy harvesters are divided into three categories: electromagnetic vibration, electrostatic vibration, and piezoelectric vibration energy harvesters[4-8]. Zhu et al. developed an electro-magnetic miniature wind harvester[9]. Its permanent magnet is installed on the free end of the cantilever beam. The airflow over the aerofoil causes the cantilever to bend and drives the permanent magnet to swing. Then the magnetic flux is changed and electricity in the coils is produced. The generator can operate at wind speeds as low as 2.5 m/s with a corresponding electrical output power of 470 μW. Kwon de-

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How to cite this article: Zhang Jiantao, Wu Song, Shu Chang, et al. Electroaeroelastic modeling and analysis for flow energy piezoelectric harvester[J]. Trans. Nanjing Univ. Aero. Astro., 2017,34(1):9-14.

http://dx.doi.org/10.16356/j.1005-1120.2017.01.009

veloped a new type of wind energy harvesting[10], which has a "T" shape from the top-view. When the clamped-free cantilever beam is excited by air flow, it will vibrate back and forth in the horizontal direction. And the piezoelectric material is deformed and generates electrical energy.

Piezoelectric harvesting is more effective than electromagnetic harvesting at small scales. It has attracted considerable attention in recent years. In the present work, an analytical model for wind energy harvesting using piezoelectric generators is developed. The interactions between the fluid, solid and electric are analyzed and modelled. A prototype of an energy harvester is fabricated. And the experimental testing results are compared with the computational ones.

1 Analytical Methods and Modeling

Wind energy harvesting using the piezoelectric structure usually performs a two-step energy conversion. Fluid flow kinetic energy is first converted into mechanic vibration energy of the harvesters. Second, the mechanical oscillations of the piezoelectric ceramics are converted into electrical energy. The relationships between fluid-solid-electric interactions are shown in Fig. 1.

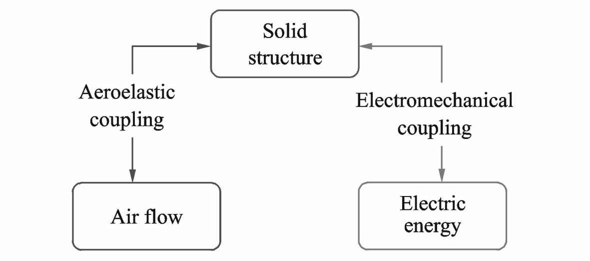


Fig. 1 Relationships between fluid-solid-electric interactions

The k-ε turbulence model is routinely used in computational fluid dynamics (CFD) for its robustness, economy, and reasonable accuracy. It is a semi-empirical model, and the derivation of the model equations relies on phenomenological considerations and empiricism. It gives a general description of turbulence by means of two transport equations[11-12]. It is used to simulate the fluid flow conditions. The k-ε model include two extra transport equations to represent the turbulent properties of the flow. The turbulent kinetic energy k[11-12] describes the energy in the fluid flow field, given by

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right]+2\mu_t E_{ij}E_{ij}-\rho\varepsilon \tag{1}$$

The turbulent dissipation ε[11] describes the rate of dissipation of the fluid kinetic energy, given by

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho\varepsilon u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij}-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{2}$$

where u_i is the velocity component in the corresponding direction, E_{ij} the component of rate of deformation, μ_t the eddy viscosity, $\mu_t=\rho C_\mu k^2/\varepsilon$, and σ_k, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$ are the adjustable constants.

The interactions between the fluid and the solid domains are modeled according to the Newton's third law[13-14].

When the load is transferred from the fluid to the solid, the action-reaction force can be expressed as

$$\int_{V_\mathrm{f}} F_\mathrm{sf}^\mathrm{f}\,\mathrm{d}V=\int_{V_\mathrm{s}} F_\mathrm{sf}^\mathrm{s}\,\mathrm{d}V \tag{3}$$

When the load is transferred from the solid to the fluid, the action-reaction force can be expressed as

$$\int_{V_\mathrm{s}} F_\mathrm{fs}^\mathrm{s}\,\mathrm{d}V=\int_{V_\mathrm{f}} F_\mathrm{fs}^\mathrm{f}\,\mathrm{d}V \tag{4}$$

where V_s and V_f are the volumes of the solid domain and fluid domain, respectively; F_sf^f, F_sf^s are the cellular action-reaction forces when projecting the load from the fluid to the solid mesh; and F_fs^s, F_fs^f the cellular action-reaction forces when projecting the load from the solid to the fluid mesh.

The harvester is mounted as a cantilever beam and its piezoelectric element is poled along the thickness direction. The vibrations of the harvester exist mainly along the thickness direction. Therefore, the piezoelectric material is assumed to experience a one-dimensional state of stress along the length direction. The constitutive equations for the linear piezoelectric element are

$$\begin{aligned} S_1 &= s_{11}^{E} T_1 + d_{31} E_3 \\ D_3 &= d_{31} T_1 + \varepsilon_{33}^{T} E_3 \end{aligned} \tag{5}$$

where S_1, T_1 are the strain and stress along the length of the beam, and D_3, E_3 the electric displacement and the electric field in the thickness of piezoelectric element, respectively. s_{11}^{E} is the compliance at constant electric field. d_{31}, ε_{33}^{T} are the piezoelectric coefficient and the permittivity at constant stress, respectively.

The 3D k-ε model of the harvester is simulated using the finite element model in FLUENT (Ansys, Inc.). The analytical model comprises the fluid domain and solid domain, as shown in Fig. 2. The air enters from the inlet and exits from the outlet of the cavity. In the inlet, two plates are used to form a trapezoidal channel, which would increase the wind flow speed and improve the vibration amplitude of the harvester. It is known that the harvesting efficiency is dependent on the vibration amplitude and frequency of harvester. The harvester is composed of piezoelectric element and metal elastic layer. One end of the harvester is fixed and the other is free. When the harvester vibrates as it is subject to the excitation of the aerodynamic pressure, the piezoelectric element generates a voltage.

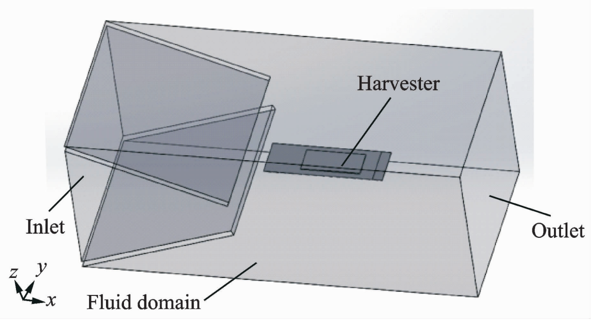
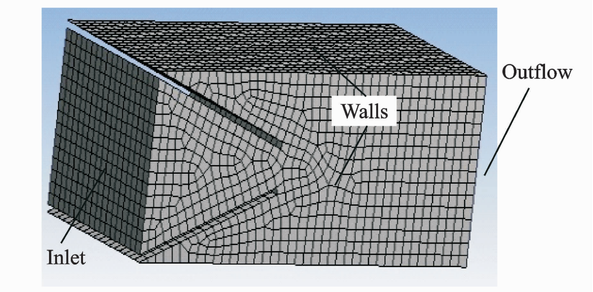
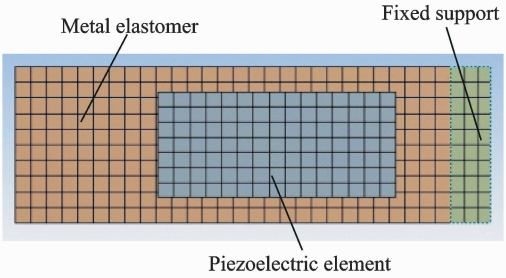


Fig. 2 3D analytical model

The finite element models of the computational domain are built as shown in Fig. 3. The fluid domain has 14 998 elements and the solid domain has 415 elements. To simulate the interactions between the fluid, solid and electric, each domain is solved separately and the coupling information between the domains is exchanged periodically. This approach can save computation time and has enough accuracy in dealing with many complex non-linear problems[15].



(a) Fluid domain



(b) Solid domain

Fig. 3 Finite element model

2 Computational and Experimental Results

2.1 Computational results

The wind velocity of the inlet is set as 3 m/s. Fig. 4 shows the wind velocity contours in the fluid domain. The wind velocity around the harvester is about 6.5 m/s. It is shown that the convergent component can effectively amplify the wind velocity. Fig. 5 shows the pressure contour in the fluid domain. It can be seen that the pressure in trapezoidal channel is higher.

Fig. 6 shows a vibration period of the harvester. The flow direction is from left to right; and the beam is fixed at its right end. It can be seen that the harvester oscillates up and down under the force of the fluid flow. The maximum vibration amplitude of the harvester is 0.15 mm.

The equivalent stress of the harvester is shown in Fig. 7. It is shown that the stress of the

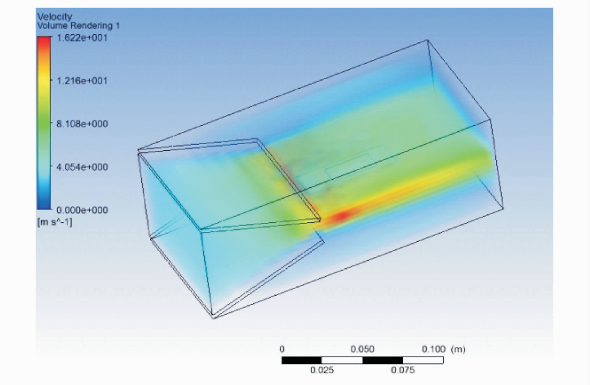


Fig. 4 Wind velocity contour for the flow

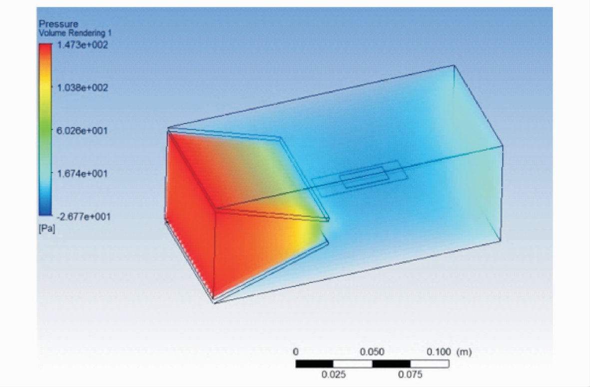


Fig. 5 Pressure contour for the flow

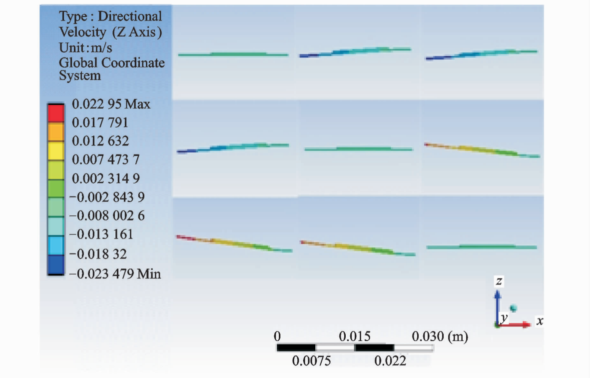


Fig. 6 Nine consecutive images of the vibrating beam in the period

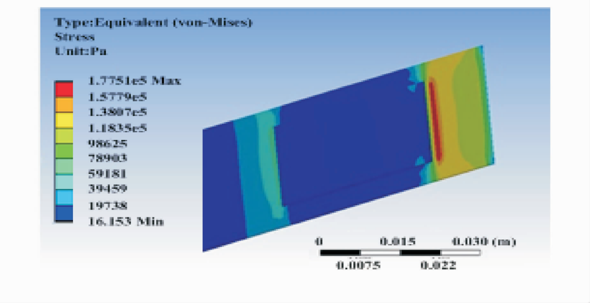


Fig. 7 Stress contour of the harvester

right part is bigger than that of the others. Fig. 8 shows the open circuit voltage output of the harvester. The curve of voltage output to time is similar to a sinusoidal curve. The output voltage is about 1.7 $V_{\text{p-p}}$.

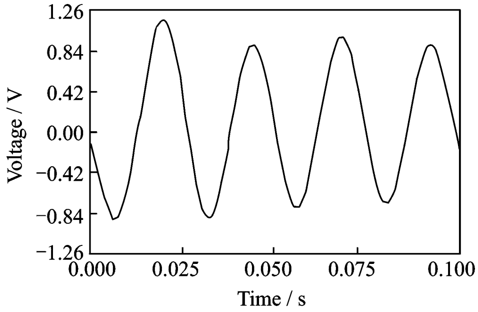


Fig. 8 Open circuit voltage output of the harvester

2.2 Experimental results

A prototype of an energy harvester is fabricated. The experimental setup is shown in Fig. 9. The convergent component and the piezoelectric harvester are fixed in a wind tunnel. The wind speed in the wind tunnel can be adjusted. Wind velocity is measured by a digital anemometer (TASI-8818). The output voltage of the harvester is measured by a digital storage oscilloscope (TBS 1102). When the wind speed around the harvester is 7 m/s, the output voltage of the energy harvester is measured. The open-circuit voltage is shown in Fig. 10. The output voltage is

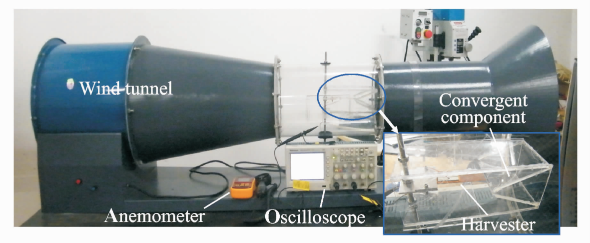


Fig. 9 Experimental setup

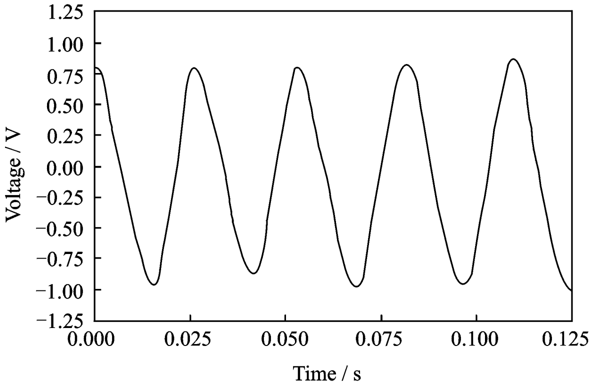


Fig. 10 Experimental open-circuit voltage of the energy harvester

about 1.8 $V_{\text{p-p}}$, the period is 0.027 7 s, and the frequency is 36 Hz, approximately. The simulation result is close to the experimental result.

3 Conclusions

This paper presents an analytical model for wind energy harvesting using piezoelectric generators. The model has taken the interactions between the fluid, solid and electric into account. In the model, the flow field is mapped in detail. The force which the fluid flow exerts on the generator is formulated. The output voltage generated by piezoelectric cantilever harvester is investigated. Various analytical results are obtained. A prototype of an energy harvester is fabricated and experimental testing results are compared with the computational ones. The model developed in this paper can be used as a tool for optimizing and predicting the performance of different energy harvesters. The further study may focus on improving the harvesting efficiency and developing the electric circuit for energy harvesting and storage.

Acknowledgements

This work was supported by the National Natural Science Foundations of China (Nos. 51305248, 51577112), Shanghai Natural Science Foundation of China (No. 13ZR1416900), and the Training Project for Young Teachers in Shanghai Colleges and Universities (No. ZZSD13051).

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(Executive Editor: Zhang Tong)