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Incident flow effects on the performance of piezoelectric energy harvesters from galloping vibrations

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Abstract In this paper, we investigate experimentally the concept of energy harvesting from galloping oscillations with a focus on wake and turbulence effects. The harvester is composed of a unimorph piezoelectric cantilever beam with a square cross-section tip mass. In one case, the harvester is placed in the wake of another galloping harvester with the objective of determining the wake effects on the response of the harvester. In the second case, meshes were placed upstream of the harvester with the objective of investigating the effects of upstream turbulence on the response of the harvester. The results show that both wake effects and upstream turbulence significantly affect the response of the harvester. Depending on the spacing between the two squares and the opening size of the mesh, wake and upstream turbulence can positively enhance the level of the harvested power.
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Keywords energy harvesting, galloping oscillations, incident flow effects, experimental measurements

Converting aeroelastic vibrations into electricity has been proposed for energy harvesters design that can be used to operate self-powered small electronic devices or to take the place of small batteries, which have a finite-life span or require expensive and hard maintenance. Depending on the operating wind speed, piezoaeroelastic energy harvesters can be designed and deployed in different locations, such as structure's surface, ventilation outlets, rivers, etc., to power sensors or actuators. Several investigations have focused on harvesting energy from flow-induced vibrations, such as vortex-induced vibrations of circular cylinders,[1–4] flutter of airfoil sections,[5–13] wake galloping,[14,15] and galloping of prismatic structures.[15–22]

The transverse galloping phenomenon has shown a promise for effective energy harvesting. For instance Sirohi and Mahadik[16] reported that at a wind speed of 11.6 mph (1 mph = 0.447 m/s) most of the commercial wireless sensors can be supplied by their proposed piezoaeroelastic energy harvester. To design enhanced galloping-based piezoaeroelastic energy harvesters, Abdelkefi et al.[17–21] studied the effects of the cross-section geometry, Reynolds number, electrical load resistance, ambient temperature on the onset speed of galloping, and the harvested power's lever. Yang et al.[22] experimentally investigated the effects of the cross-section geometry on the performance of galloping-based piezoelectric energy harvesters.

In all of the above studies, the harvesters were subjected to uniform wind speed. In this work,

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we investigate wake and turbulence effects on the performance of galloping-based piezoaeroelastic energy harvester. The tested harvester consists of a unimorph piezoelectric cantilever beam with a square section tip mass, as shown in Fig. 1. The piezoelectric material (PSI-5A4E from Piezo Systems, Inc) is bonded by two in-plane electrodes with negligible thicknesses connected to an electrical load resistance. To investigate the performance of this harvester when placed in the wake of another harvester, we determine its performance for different positions in the wake, as shown in Fig. 2. To investigate the effects of upstream turbulence, we place a turbulence generating mesh upstream of the harvester. Two meshes with different opening sizes as shown in Figs. 3 and 4 were considered.

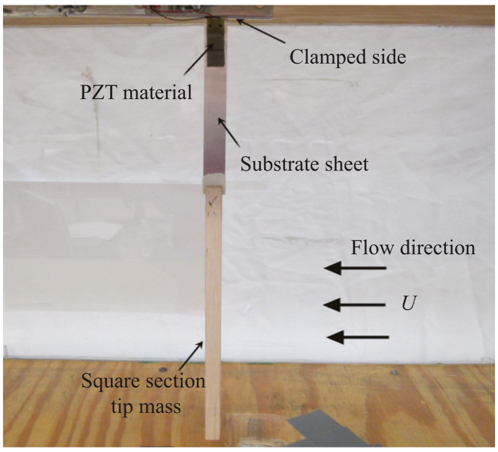

Fig. 1. Galloping-based piezoaeroelastic energy harvester in a wind tunnel: experimental setup.

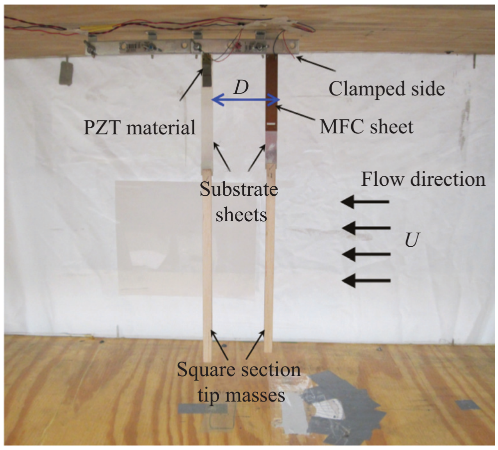

Fig. 2. Wake effects experimental setup of two square cylinders.

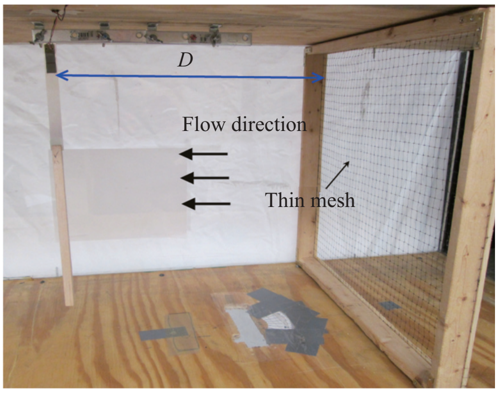

Fig. 3. Experimental setup of the thin mesh for turbulence effects.

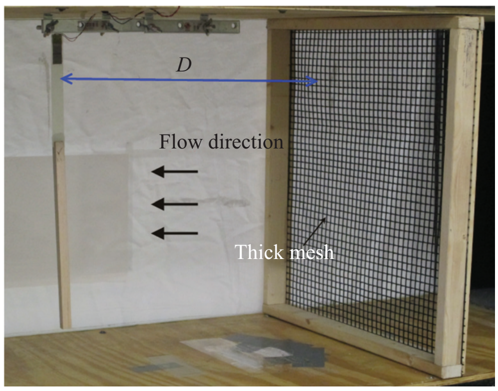

Fig. 4. Experimental setup of the thick mesh for turbulence effects.

The experiments were performed in an open-circuit wind tunnel with a 52 cm$\times$51.5 cm test section. Data acquisition was performed by using an NI 9219 DAQ module. The harvester consists of an aluminum alloy substrate sheet. The active dimensions of this aluminum sheet are 15.24 cm$\times$1.8 cm$\times$0.305 mm (length $\times$ width $\times$ thickness). The length, width, and weight of the wood square cylinder are 26.67 cm, 1.28 cm, and 7.6 g, respectively. The onset speed of galloping of this harvester in uniform form was determined by applying initial displacements and measuring the steady-state output voltage. These tests showed that below a wind speed of 0.3 m/s, all disturbances were damped which resulted in zero output voltage. At higher wind speeds, limit-cycle oscillations with different amplitudes were observed and non-zero output voltage was measured. As such, it was determined that the onset speed of galloping of this harvester is approximately 0.3 m/s. This cut-in speed is the lowest reported value in the literature. For example, in the experimental works of Kwon,[23] Sirohi and Mahadik,[16] and Yang et al.,[22] the cut-in speed of their proposed harvesters are 4 m/s, 3.57 m/s, and 2.5 m/s, respectively.

Figures 5 and 6 show the bifurcation diagram curves of the root mean square (RMS) of the generated voltage and average harvested power for various values of the electrical load resistance and for wind speed values between 0.2 m/s and 3 m/s. The average harvested power was determined from the RMS voltage value by $P_{avg} = V_{rms}^2/R$, where R is the electrical load resistance. It shows that the generated RMS voltage and average harvested power increase as the wind speed increases from 0.3 m/s to 2 m/s. At higher speeds, there is a drastic drop in the level of generated voltage and harvested power. This sudden drop is probably related to the decrease of the damping which is associated with the aerodynamics effects up to the point where the total damping becomes positive (mechanical damping is larger than aerodynamic damping) and causes the harvester to regain stability. This result is well-explained in the work of Abdelkefi et al.[8] Furthermore, it follows from these bifurcation diagram curves that an increase in the electrical load resistance (R) is accompanied with an increase in the level of the generated voltage which stabilizes at higher R ($R > 10^6$ Ω). On the other hand, the variations of the average harvested power as a function of R is not straightforward. In fact, there is an optimum value of R at which the harvested power's level is enhanced. We should note that when increasing and decreasing the wind speed, we obtained the same bifurcation diagram curves without the presence of any hysteresis which is a defining characteristic of a supercritical instability.

To investigate the performance of this harvester when placed in the wake of an upstream harvester, we place two harvesters at different spacing distances (D), as shown in Fig. 2. The

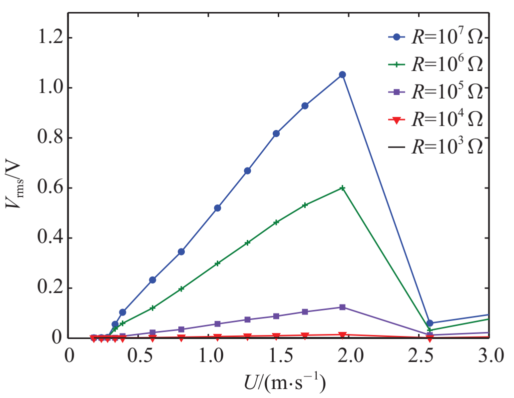

Fig. 5. Bifurcation diagrams of the RMS generated voltage for different electrical load resistances when the harvester is placed by itself in the wind tunnel.

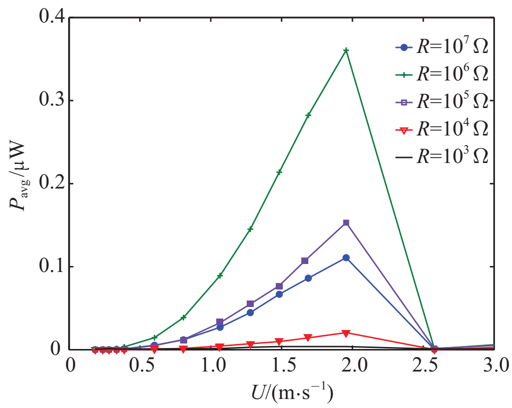

Fig. 6. Bifurcation diagrams of the average harvested power for different load resistances when the harvester is placed by itself in the wind tunnel.

dimensions of the upstream harvester are the same as that of the tested harvester.

The curves in Fig. 7 show the variations of the RMS generated voltage as a function of the spacing distance D for three different wind speeds ($U = 1.27$ m/s, 1.96 m/s, and 3.05 m/s). To determine the wake effects, we also plot, for each wind speed, the RMS generated voltage value when the harvester was placed by itself in the wind tunnel. It shows from Fig. 7 that for $U = 1.27$ m/s and $U = 1.96$ m/s the level of generated voltage strongly depends on the spacing distance. At $U = 1.27$ m/s, there is a transitory spacing distance, $D = 16$ cm, at which the harvester starts oscillating with high amplitudes. At smaller values ($D < 16$ cm), there are some fluctuations in the RMS generated voltage. The level of the RMS generated voltage is always smaller than that obtained from the single harvester. It is also noted that increasing the spacing distance is accompanied by an increase in the associated RMS generated voltage. At $U = 1.96$ m/s, the harvester has the same tendency and critical spacing distance as in the case when $U = 1.27$ m/s. On the other hand, a slightly higher RMS generated voltage is obtained when the spacing distance is larger than 36 cm. At $U = 3.05$ m/s, the harvester does not generate any power when placed by itself in the wind tunnel. However, when placed in the wake of an upstream harvester, there is a critical spacing distance $D = 18$ cm, at which high values of the RMS generated voltage are obtained. Clearly, the performance of the harvester is significantly impacted when placed in the wake of an upstream harvester. We can conclude that the presence of an unsteady wake flow may result in an increase in the aerodynamic damping and then the harvester always remains unstable with higher oscillation amplitudes.

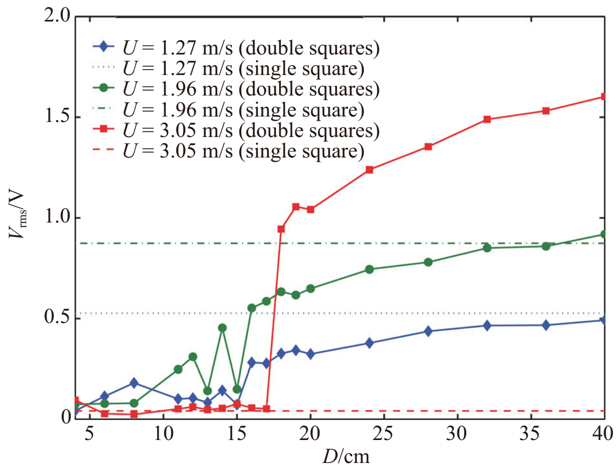

Fig. 7. Variations of the RMS generated voltage as a function of the spacing distance D and comparison with the single PZT harvester for three different wind speeds and $R = 10^7$ Ω.

Another set of experiments was performed to investigate the effects of the mesh-generated turbulence on the performance of the harvester. Two different meshes were used to generate upstream turbulence. The first one (referred to thin mesh shown in Fig. 3) has a larger opening than the second one (referred to thick mesh shown in Fig. 4). The curves in Fig. 8 show the variations of the RMS generated voltage as a function of the spacing distance D between the harvester and the grid mesh sheet (thin or thick) for two different wind speeds and when the

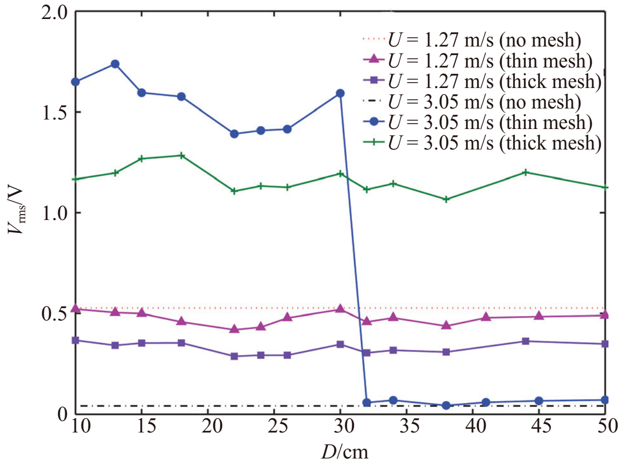

Fig. 8. Variations of the RMS generated voltage as a function of the spacing distance D between the square and grid mesh sheet and comparison with the single PZT harvester for two wind speeds and $R = 10^7\ \Omega$.

electrical load resistance is set to $10^7\ \Omega$. We also plot, for each wind speed, a line describing the RMS generated voltage value when the harvester is placed in a smooth flow. At $U = 1.27$ m/s, the presence of the mesh negatively affects the performance of the harvester. This result is expected because the presence of the mesh decreases the wind speed and hence a decrease in the harvested power is obtained. However, the harvester perform better when using a thin grid mesh. We can conclude that an increase in the thickness of the opening size of the mesh results in a decrease in the harvested power. At $U = 3.05$ m/s, a high RMS generated voltage is observed for both grid meshes. We shall note that at this speed, the harvester does not generate energy in smooth flow. The presence of these high amplitudes of the generated voltage is probably due to the presence of the turbulent flow which results in an increase in the aerodynamic damping. We also note that there is a critical spacing distance $D = 30$ cm at which the influence of the thin grid mesh vanishes. This is explained by the fact that the turbulence generated by the mesh dissipates over this distance and does not affect the harvester's response. For smaller spacing distances, $D < 30$ cm, higher values of RMS generated voltage are obtained when using the thin grid mesh. Clearly, performance of the harvester can be enhanced, in some situations, when it is placed in a turbulent flow, and this enhancement is strongly dependent on the turbulence scales.

In this paper, galloping-based piezoaeroelastic energy harvester's performarce is investigated when it is placed in the wake of an upstream harvester or in turbulent flows. These incident flows result in the presence of unsteady wake effects which can change the aerodynamic damping and initial conditions in the system. The results show that the wake effects of an upstream harvester or the opening size of the mesh can be beneficial in many situations in terms of enhancing the harvested power's level.

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