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Yaowen Yang, Liya Zhao, and Lihua Tang

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Comparative study of tip cross-sections for efficient galloping energy harvesting

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This letter presents a comparative study of different tip cross-sections for small scale wind energy harvesting based on galloping phenomenon. A prototype device is fabricated with a piezoelectric cantilever and a tip body with various cross-section profiles (square, rectangle, triangle, and D-shape) and tested in a wind tunnel. Experimental results demonstrate the superiority of the square-sectioned tip for the low cut-in wind speed of 2.5 m/s and the high peak power of 8.4 mW. An analytical model is established and verified by the experimental results. It is recommended that the square section should be used for small wind galloping energy harvesters. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4792737]

Development of self-powered sensors by harvesting ambient energy has been researched explosively in the past years due to the inconvenience and high cost of replacement of batteries. Many studies have been conducted on vibration-based energy harvesting. However, small wind energy harvesting has received less attention. Flow-induced vibrations due to vortex shedding, galloping, flutter, and wake galloping can be harnessed using piezoelectric energy harvesters (PEHs). Various designs of PEH have been reported, including a bio-inspired cross-flow piezo-leaf, a flapping wing with airfoil section, a T-shaped piezoelectric cantilever, a self-sustained MEMS wind sensor implementing micro PEH for scavenging turbulence-induced vibrations, a cantilever with a windward cylinder attached to the tip operating through vortex-induced vibrations, and some other designs. Translational galloping is a self-excited aeroelastic phenomenon, giving rise to transverse oscillations normal to the direction of wind flows in structures with weak damping when wind velocity exceeds a critical value. It is a better choice to obtain structural vibrations for energy harvesting purpose compared to the vortex-induced vibrations and flutter, for its advantage of large vibration amplitude and the ability of oscillating in infinite range of wind velocities. Barrero-Gil et al. theoretically analyzed the potential use of transverse galloping to obtain energy using a single-degree-of-freedom (1DOF) model. Different galloping energy harvesters consisting of cantilevers with attached prisms of triangular and D-shape cross-sections have been reported by Sirohi and Mahadik. Abdelkefi et al. theoretically analyzed the influence of load resistance and bluff body cross-section geometry on the onset of galloping and harvested power. However, no experimental comparative study has been reported in the literature.

This letter presents an experimental study on the influence of cross-section geometries (square, rectangles with distinct aspect ratios, equilateral triangle, and D-section) of bluff bodies on galloping piezoelectric energy harvesting in the laminar flow condition. The flow condition is kept the same for all harvesters to ensure fair comparison. A lumped parameter single-degree-of-freedom (1DOF) model integrating electromechanical and aerodynamic formulations is also established and validated.

The proposed galloping energy harvester consists of a piezoelectric cantilever beam clamped at one end, and connected to a rigid prism with a specific cross section at the free end (Fig. 1(a)). Translational galloping was first analyzed by Den Hartog. The simplified SDOF model comprises a bluff body $M$ mounted on a spring $K$ and a damping $C$ as shown in Fig. 1(b). Wind $U$ flows from the right to the left, with the angle of attack $\alpha$. The aerodynamic force $F_z$ acting on the bluff body causes it to oscillate in the $z$ direction. A criterion for galloping is identified as $\partial C_{F_z}/\partial \alpha > 0$, where $C_{F_z}$ is the aerodynamic force coefficient.

Figure 2(a) shows the schematic of the proposed energy harvester. The fabricated prototype device and the experimental setup in the wind tunnel are shown in Fig. 2(b). The joint of the connection between the beam and the tip is detachable. The dimensions of the aluminum cantilever are $L_p = 150$ mm, $B_p = 30$ mm, and $t_p = 0.6$ mm. Two piezoelectric sheets (DuraAct P-876.A12 from Physik Instrumente) are attached to the root of the cantilever beam on both sides, and connected in parallel. Each piezoelectric sheet weighs 7.29 g and 3.5 g, respectively. Consider different values of $\partial C_{F_z}/\partial \alpha$ of various cross sections of the tip body, five cross sections are chosen for comparison, including square, equilateral triangle, two rectangles with different aspect ratios, and D-section. The five tip bodies have equal length of 150 mm and equal area of wind exposure as $40 \times 150$ mm². Dimensions of the tip cross sections are shown in Table I. For a fair comparison, the weights of the five tip bodies are all adjusted to 26.8 g by attaching various steel masses onto their inner surfaces to achieve a constant fundamental frequency for the harvester with different tip bodies.

The analytical model of the proposed harvester should take into account the electromechanical coupling effect, as

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where \( w \), \( C \), and \( K \) are the tip displacement in the direction normal to the wind flow, the damping coefficient, and the stiffness of the harvester, respectively; \( V \) and \( R_L \) are the generated voltage and applied load resistance, respectively; \( C_P \) is the total capacitance of the piezoelectric sheets in parallel connection; \( \Theta \) is the electromechanical coupling coefficient; and \( M_{\text{eff}} \) is the effective mass expressed by 
\[
M_{\text{eff}} = \frac{33}{140}M_b + M_{\text{tip}} \text{ with } M_b \text{ and } M_{\text{tip}} \text{ being the mass of the cantilever and the tip body, respectively. The coupling coefficient } \Theta \text{ is obtained as }
\]
\[
\Theta = \sqrt{(\omega_{\text{noc}}^2 - \omega_{\text{nsc}}^2)M_{\text{eff}}C_P} \tag{2}
\]
where \( \omega_{\text{noc}} \) and \( \omega_{\text{nsc}} \) are the fundamental natural frequencies of the harvester for the open circuit and short circuit conditions, respectively. The aerodynamic model established here is based on the quasi-steady hypothesis. The aerodynamic force is given as
\[
F_Z = \frac{1}{2} \rho_a h L_{\text{tip}} U^2 C_{Fz} \tag{3}
\]

where \( \rho_a \), \( h \), \( L_{\text{tip}} \), and \( U \) are air density, frontal dimension facing the wind flow (Fig. 2(a)), length of the tip body, and wind velocity, respectively. \( C_{Fz} \) can be expressed as a polynomial function of the angle of attack \( \alpha \)

\[
C_{Fz} = \sum_{i=1}^{m} A_i (\alpha)^i + \sum_{j=2}^{k} A_j (\alpha)^j \left[ \frac{\dot{w}}{|\dot{w}|} \right] \tag{4}
\]

where \( \dot{w} \) is the vibration velocity of the tip body; \( A_i \) and \( A_j \) are the empirical coefficients; and \( w'(L_{\text{tip}}) \) denotes the rotation angle of the beam at the free end due to the translational motion. The first sum in the expression of \( C_{Fz} \) involves odd integers \((i, m)\) and the second involves even integers \((j, k)\).

The root of the beam is clamped using a metal support during the wind tunnel test. Wind velocity is measured using a pitot tube and a manometer. Voltage data are acquired through the NI 9229 DAQ module. The average output power is calculated by \( P = \frac{V_{\text{RMS}}^2}{R_L} \), where \( V_{\text{RMS}} \) is the root mean square (RMS) voltage across \( R_L \).

Figure 3(a) shows the output power measured over a range of load resistances at different wind velocities for the proposed harvester with a square-sectioned tip. The optimal load resistance is around 105 k\( \Omega \) and hardly changes with the wind velocity (in our testing range). Here, the optimal load resistance refers to the one when the output power is the maximum. For galloping energy harvesters with different tip bodies, the optimal \( R_L \) is obtained at a specific wind velocity and applied to all wind velocities.

Figure 3(b) shows the measured output power versus load resistance at a wind velocity of 6 m/s for the five cross sections. It is observed that the optimal \( R_L \) for the five cross sections are almost the same, which are all around 105 k\( \Omega \). This is reasonable. The oscillation frequency due to galloping is always consistent with the fundamental frequency of the harvester, which is equal for the five harvesters since the tip masses are the same and the axial force on the beam due to wind is negligible. Hence, equal optimal \( R_L \) is achieved, which can be approximated by \( R_L = 1/\omega_{\text{nsc}}C_P \).

The measured voltage and output power at different wind velocities with optimal \( R_L \) are plotted in Figs. 3(c) and 3(d), respectively. It is obvious that the square section generates the largest voltage and power, with a peak output power of 8.4 mW measured at 8 m/s, which is also higher than the peak power achieved in the literature (e.g., 4 mW in Ref. 11, 2.2 mW in Ref. 7, 1.14 mW in Ref. 21). Moreover, the square section starts to oscillate at a wind velocity of 2.5 m/s, which is lower than the other harvesters in our test and other previously reported ones (e.g., 4 m/s in Ref. 11, 8 mph (3.576 m/s) in Ref. 20). This could be attributed to the largest value of \( \partial C_{Fz}/\partial \alpha \) for the square section according to the criterion of galloping instability. Power outputs for the

**TABLE I.** Dimensions of tip cross sections.

<table>
<thead>
<tr>
<th>Dimension h x d (mm)</th>
<th>40 x 40</th>
<th>40 x 60</th>
<th>40 x 26.7</th>
<th>40 (side)</th>
<th>40 (dia.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectangular</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circular</td>
<td></td>
<td></td>
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</table>

The optimal load resistance at a wind velocity of 6 m/s for the five cross sections are almost the same, which are all around 105 k\( \Omega \).
rectangle \((40 \times 26.7 \text{ mm}^2)\), D-section, and equilateral triangle are quite low. The reason for the first two sections is the failure to meet the criterion of galloping instability in the laminar flow (which is the case for our test), as \(\partial C_{Fz}/\partial \alpha\) equals to 0 for the rectangle \((40 \times 26.7 \text{ mm}^2)\) and −0.1 for the D-section, respectively.\(^{24}\) However, in the turbulent flow, the value for the D-section becomes positive (i.e., \(\partial C_{Fz}/\partial \alpha = 0.79\) for turbulence intensity \(T_u = 11\%\)), which enables the D-section to undergo self-excited oscillation as presented by Sirohi and Mahadik.\(^{21}\) They blew the D-section with an axial fan that generated turbulent flow and obtained a stable output power around a wind velocity of 5.5 mph. For equilateral triangle, the predicted cut-in wind velocity is around 8.5 m/s, which is beyond our testing range. The minor peaks for the rectangle \((40 \times 26.7 \text{ mm}^2)\) and equilateral triangle are caused by the resonance at the first torsional mode due to the vortex shedding (Figures 3(c) and 3(d)). Slight irregular torsional deflections were observed during the wind tunnel test when the wind velocity reached 5.5 m/s. These deflections increased to the maximum (resonance) at 6.5 m/s and then disappeared over 7.5 m/s, as the vortex shedding frequency increased with the wind velocity.

The responses of the harvester with preferred square-sectioned tip can be predicted by simulation with the derived analytical model. The short circuit and open circuit natural frequencies for the proposed harvester are measured to be 6.84 Hz and 6.89 Hz under base excitations, respectively. The electromechanical coupling coefficient \(\Theta\) is then determined to be 0.000373 N/V by Eq. (2). The damping ratio \(\zeta\), which is expressed as \(\zeta = C/(2M_{eff} \omega_{res})\), is measured using the logarithmic decrement technique. The harvester is first excited at 6.84 Hz at the unity RMS acceleration and then the shaker is suddenly shut down to obtain the attenuation curves of short circuit current, from which \(\zeta\) is calculated to be 0.0148. The coefficients \(A_i\) and \(A_j\) for square cross section are shown in Table II.\(^{24}\)

Using the above parameters, the output power versus wind velocity is calculated by numerical integration (Fig. 4(a)). Obvious discrepancy between the calculated and measured power is observed. This should be attributed to the inaccurate damping ratio used in the simulation. In practice, the damping is amplitude-dependant, i.e., not constant. When the energy harvester is subjected to the low-speed wind flow in our test, the oscillation amplitude is much smaller than that in the logarithmic decrement test. For a more rational simulation, after a few trials, a modified damping ratio of 0.005 is used for the voltage and power prediction. The calculated output power versus load resistance agrees well with the measured results as shown in Fig. 4(b). The calculated voltage and output power at 105 kΩ are plotted in Figs. 4(c) and 4(d), respectively. Again, the results match well with the measured data except for the hysteresis region between 2.8 m/s and 3.8 m/s. Theoretically, when wind velocity increases from zero to 3.8 m/s, the power should increase along line 1, then jump to the upper line 2 increasing along it till 8 m/s. When the wind velocity reduces from 8 m/s to 2.8 m/s, the power should decrease along line 2, and then drop to line 1 at 2.8 m/s. However, the experiment does not

<table>
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<tr>
<th>Coef.</th>
<th>(A_1)</th>
<th>(A_2)</th>
<th>(A_3)</th>
<th>(A_4)</th>
<th>(A_5)</th>
<th>(A_6)</th>
<th>(A_7)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>2.69</td>
<td>0</td>
<td>(1.684 \times 10^2)</td>
<td>0</td>
<td>(6.27 \times 10^3)</td>
<td>0</td>
<td>(5.99 \times 10^4)</td>
</tr>
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to capture this hysteresis phenomenon. Sources for these discrepancies may include the use of constant damping in simulation, the vortex shedding from the tip body, and the difference between the operating condition such as Reynolds number in our test and that used in Ref. 24 to get the aerodynamic coefficients.

In summary, this letter presents a comparative study of galloping energy harvester with different cross-section tips. Experimental results confirm the superiority of square cross-section tip over the others used in the literature. A peak output power of 8.4 mW is achieved which is sufficient to power small sensors. An analytical model is established and verified by experimental results. It is recommended that the tip of square section should be used for galloping-based small wind energy harvesting.


FIG. 4. Simulation results for square section: (a) Power versus wind velocity at 105 kΩ; (b) power versus load resistance at 6 m/s; (c) voltage versus wind velocity at 105 kΩ; (d) power versus wind velocity at 105 kΩ. (a) Use the initial ω, (b)–(d) use the modified ω.