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A broadband E-shaped piezoelectric energy harvester based on vortex-shedding induced vibration from low velocity liquid flow

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This letter presents an E-shaped piezoelectric energy harvester (PEH) based on vortex-shedding induced vibration (VSIV) for achieving broadband and enhanced energy capture from the liquid flow with low velocities. The PEH is realized by introducing two symmetrical vice piezoelectric beams to a traditional structure consisting of a drive sheet and a main piezoelectric beam. By changing the mass blocks on the sheet and vice beams, the first two order resonance frequencies can be tuned to be close enough to obtain a wide bidirectional tunable operating bandwidth. Experimental results demonstrate that the proposed harvester can adapt to a wider fluid velocity spectrum and bring out higher output performances than the conventional PEH. Under the excitation of vortexes from the liquid flow with low velocities (0.15m/s–0.7m/s), the maximum increase in power, efficiency and velocity spectrum over 20μW can be 70%, 326% and 60%, respectively, compared to its conventional counterpart. The total size of the E-shaped harvester is \( L \times W \times H = 90 \text{ mm} \times 70 \text{ mm} \times 5 \text{ mm} \). © 2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5063268

Piezoelectric energy harvesters scavenging flow energy from the ambient environments, as a new meaningful research topic, have attracted great interest in researchers in recent years. Vortex-shedding induced vibration from aerodynamic or hydrodynamic instability phenomena is one of the energy sources for this type of PEHs. Various strategies and mechanisms are proposed in the last years for efficiency improvement of vortex-shedding induced PEHs. Akaydin et al. proposed a flexible PEH with cantilever structure placed in the wake of cylinder at high Reynolds numbers. A cantilevered PEH of adjustable frequency in a heating, ventilation and air conditioning flow was reported by Weinstein et al. Alhadidi et al. represented a broadband bi-stable flow PEH based on the wake-galloping phenomenon. However, all of the aforementioned studies are focus on energy harvesting from air flow with relatively high speed range (0–10m/s). Researches on designing PEHs from vortex shedding-induced vibration in liquid flow are much fewer than that in the air flow. This mainly due to that the liquid medium significantly increases the difficulty of encapsulation, wire leading and test operation of the harvester. Moreover, the velocity of liquid flow in natural and industrial environments (such as in river/ocean and water supply pipes) is commonly at extremely low level (about 0–1m/s) with some fluctuations in most cases. Therefore, the resonance type PEHs are facing many challenges when they are applied to the liquid flow.

Generally, traditional linear vibration PEHs designed as resonators work high efficiently only at its resonant frequency. Therefore, matching the resonance frequency of the PEH with the input frequency of the vibration source has been considered one of the most significant design
requirements for improving the efficiency of these PEHs.\textsuperscript{15} However, the vibration sources in natural and industrial environments for ambient energy harvesting typically have relatively low, broadband and sometimes time variant characteristics of frequency.\textsuperscript{16–18} Facing this dilemma, various frequency matching techniques have been represented in the last decade to realize the optimum design of PEHs for high performance.\textsuperscript{19,20} Based on the operating mechanisms, frequency matching techniques\textsuperscript{16} mainly consist of down-converting device natural frequency strategy,\textsuperscript{21–23} up-converting vibration source input frequency strategy,\textsuperscript{24,25} and broadening bandwidth strategy.\textsuperscript{26,27}

Concerning energy harvesting from vortex-induced vibration (VIV)\textsuperscript{2}, the most known concept is a bluff body which is directly attached to the end of a piezoelectric cantilever beam. However, the vortex-shedding induced vibration (VSIV)\textsuperscript{9} PEH usually consists of a drive sheet, which is attached to the end of a piezoelectric cantilever beam. This sheet with the piezoelectric beam is usually separated from the bluff body and captures the flow kinetic energy from the vortexes shedding from the bluff body.

It is necessary to utilize an excellent frequency matching technique for the PEHs based on VSIV to make them work effectively. In this study, for extremely low velocity liquid flow application, we developed a broadband PEH based on vortex-shedding induced vibration (Fig. 1(c)). Through a motion coupling effect of multiple piezoelectric beams connected by a drive sheet, the proposed PEH is able to achieve wider bandwidth and higher power generation than the traditional counterpart from the low-level and low-frequency excitations of vortexes. Fig. 1(a) depicts the structure and working principle of the proposed E-shaped PEH system. The structural and material parameters of the harvester are illustrated in Table S1 in the supplementary material. When this system works, the inlet flow is firstly stabilized by the aluminum honeycomb cores as a flow straightener to generate the steady coming flow. A series of vortexes shedding from the cylinder in the coming flow produce periodically changeable pressure fields on both sides of the drive sheet, leading to continuous vibration of the E-shaped PEH in the y-direction. The proposed E-shaped PEH based on VSIV mainly consists of a drive sheet, a main bimorph beam and two vice bimorph beams, as shown in Fig. 1(c). The piezoelectric material of the functional layers of these bimorph beams is lead zirconate titanate (PZT). The total size of the E-shaped PEH is $L \times W \times H = 90 \text{ mm} \times 70 \text{ mm} \times 5 \text{ mm}$. Under the excitation of vortexes, the piezoelectric materials in the main and vice beams utilize the positive piezoelectric effect to transform the vibration deformation from the flow kinetic energy into the electric energy consumed in the electrical device. Compared with the conventional PEH (Fig. 1(b)) that has the

![FIG. 1. Schematic of (a) the proposed PEH system; (b) a conventional PEH; and (c) an E-shaped PEH.](image-url)
same working principle and a similar structure without the vice beams, the proposed E-shaped PEH (Fig. 1(c)) is able to make much more efficiently use of the space behind the cylinder and the energy from the vortexes. The attachment of the two vice bimorph beams is beneficial, as the total output power of the harvester can be significantly improved. Besides, the frequency bandwidth of the PEH can be effectively broadened by these additional beam structures.

In order to analyze the vibration modes and compare the output performance of the E-shaped PEH and the conventional PEH under the same excitation condition, the vibrating control system and the circular flow experimental system are built respectively as depicted in Figs. 2(a) and 2(b). The vibrating control system consists of a vibrating controller, power amplifier, shaker, accelerometer, oscilloscope and PC. The voltage output of each piezoelectric beam is detected and recorded by an independent single channel of the oscilloscope. Thus, the resonance frequencies of all three beams on the E-shaped PEH are obtained from the frequency response test in this system. The components, experimental setup and test methods of circular flow experimental system have been introduced in our previous work.28

The frequency responses of the main and vice beams on the E-shaped PEH under base excitation with acceleration of 0.02g are shown in Figs. 3(a) and 3(b). The research method is to change the heights of tip mass on the vice beams to adjust their resonance frequency while the tip mass on the main beam remains the same. In this case, the resonance frequency of main beam is set as about 5.35Hz whilst the ones of vice beams are set as 3.41Hz (Fig. 3(a)) and 7.84Hz (Fig. 3(b)) successively. The experimental results show that a new voltage peak of the main beam (4.86V in Fig. 3(a) and 4.31V in Fig. 3(b) on the red line) is generated by the vibration of vice beams at their resonance frequency (3.41 Hz in Fig. 3(a) and 7.84 Hz in Fig. 3(b)). On the other hand, a lower voltage peak of the up and down vice beams (2.47 V in Fig. 3(a) and 1.47 V in Fig. 3(b) on the pink and green line)
is also produced by the vibration of main beam at its resonance frequency of about 5.35 Hz. That is to say, the vice beams make the main beam vibrate effectively at the resonant frequency of the vice beams, and vice versa.

The phase relationship of voltage between the main and vice beams is then studied. Fig. 3(e) shows the phase difference of voltage between the main beam and vice beams when the driving frequency ranges from 2Hz to 10Hz. At the beginning, the results indicate that the phase difference of voltage remains at 180° and then starts to decrease rapidly. When the driving frequency approaches the resonance frequency of the vice beams, the phase difference is tending to 0°. However, the phase difference is rapidly turning to 180° when the driving frequency is moving away from this point. Based on this law of change in phase difference, the main and vice beams can be wired reasonably to form the total output of the harvester if the driving frequency is fixed as a special constant. Figs. 3(c) and 3(d) illustrate the comparison of voltage output between the E-shaped PEH and the traditional counterpart. Obviously, the harvester has one more peak of voltage wave than the traditional counterpart, resulting in much wider bandwidth. The peak value of the structure of PEH at the resonant frequency of the main beam is also significantly larger than that of the traditional structure of PEH under the same excitation condition. The broadband and performance improvement of the E-shaped PEH are distinct advantages over the conventional PEH, attributing to the contribution of the coupled motions caused by the vice bimorph beams. Furthermore, both the positions of the peak point and bandwidth of the E-shaped PEH can be adjusted by changing the mass blocks on the drive sheet and vice beams.

The frequency of the vortex shedding from one side of the cylinder in Fig. 1(a) can be expressed as

$$f = S_f \times \frac{U}{D}, \quad (1)$$

where $S_f$ is the Strouhal number, $U$ is the fluid velocity, and $D$ is the diameter for the cylinder.

The velocity of liquid flow in usual natural and industrial environments is commonly at a low level. Therefore, 0.25m/s and 0.5m/s that cover the range of interest in research, corresponding to shedding frequencies of 2.63Hz and 5.25Hz according to Eq. (1), are set as experimental conditions for testing the performance and characteristics of the proposed E-shaped PEH. Then, the structure of PEH as shown in Fig. 3(c) is selected out to fabricate a prototype because it has obvious advantages in low velocity environment compared with the one in Fig. 3(b).

The distance $d$ between the drive sheet and cylinder has a remarkable influence on the output voltage of PEH. Based on previous studies, there exists an optimal location area in the flow field for the harvester. Figs. 4(a) and 4(e) illustrate the experimental results in average amplitude of open circuit voltage (peak-to-peak) of the main and vice beams on the E-shaped PEH under different scale factor $d/D$ with velocities of 0.25m/s and 0.5m/s. This figure presents that the voltage firstly increases...
FIG. 4. Comparison of experimental results in output performance of main and vice beams on the E-shaped PEH at velocities of 0.25m/s and 0.5m/s: (a) and (e) open circuit voltage (peak-to-peak) amplitude versus the scale factors; (b) and (f) open circuit voltage variations in 1.5s; (c) and (g) voltage versus the load resistance; (d) and (h) power versus the load resistance; (b)-(d) and (f)-(h) $d/D = 2$.

and reaches the peak, and then decreases with the increasing scale factor. Thus, the optimum position for the E-shaped PEH in the flow filed with low velocities is around $d/D = 2$. In this position, the voltage variations of the main and vice beams in 1.5s for each velocity condition are demonstrated in Figs. 4(b) and 4(f). Under the condition of 0.25m/s, the voltage phase of vice beams is gradually approaching that of main beam because the vortex shedding frequency at this velocity is close to the resonance frequency of the vice beams. However, three beams have the same phase when the velocity is 0.5m/s due to that the vortex shedding frequency in this condition is near the resonance frequency of main beam. A resistance $R$ as the load circuit is respectively connected with these bimorph beams to do impedance matching for optimizing the output performance of this system. Figs. 4(c), 4(g), 4(d), and 4(h) show the voltage and power of the main and vice beams versus the different load resistances. The voltages of these beams increase continuously and then tend off with the increasing load resistances. The voltage generated from each vice beam is nearly close to half of that of the main beam in each condition, resulting in the PEH total output voltages of 9.47V and 18.90V at velocities of 0.25m/s and 0.5m/s. Besides, the power initially increases with increasing load in each condition. The power of main beam then peaks at 8.65$\mu$W and 29.65$\mu$W, whilst the power of up and down vice beams peak at 2.64$\mu$W and 8.39$\mu$W when the load resistance is about $10^5$ $\Omega$ which is considered as the best load matching value. This optimum load resistance shows that all three piezoelectric beams have a same dimension (i.e., internal capacitance). The power generated from each vice beam is about a third of that of the main beam. Generally, the up and down vice bimorph beams as the additional optimized structure bring about notable improvements for the performance of the proposed E-shaped PEH.

The average power and conversion efficiency of the harvester can be expressed as follows, respectively:

$$P = \frac{V^2}{8R}, \quad (2)$$

$$\eta = \frac{P}{\left(\rho A U^3 / 2\right)}, \quad (3)$$

where $\rho$ is the density of water and $A$ is the cross section of the harvester presented to the coming flow. Based on Eqs. (2) and (3), the power and efficiency can be calculated from the voltage generated by the harvester from the vortexes. Fig. 5 shows the comparison of experimental results in output performances between the E-shaped PEH and conventional PEH versus velocities in the range of 0.15m/s to 0.7m/s. In general, the power and efficiency of the structure of PEH are significantly improved compared with the traditional one, as illustrated in the green mesh area. From the red curve in Fig. 5(a), there are two power peaks at velocities of 0.3m/s and 0.55m/s, respectively, corresponding to vortex shedding frequencies of 3.2Hz and 5.8Hz according to Eq. (1). The first strong peak is considered to the resonant result of the vice beams and the 3.2Hz vortexes, whilst the second one is considered to the resonant result of the main beam and the 5.8Hz vortexes.
At the velocity of 0.55 m/s, the power increases from 51.20 µW for a conventional PEH to 86.97 µW for the proposed E-shaped PEH, an increase of 70%. Furthermore, the velocity bandwidth over 20 µW of the harvester increases by 60% compared with the traditional harvester without the vice beams. On the other hand, there are also two efficiency peaks on the red curve at the same positions of the horizontal axis in Fig. 5(b). The dramatic increase of 326% occurs when the velocity is 0.3 m/s, at which the efficiency increases from 1.94% for a conventional PEH to 8.26% for the E-shaped PEH. It is mainly because the resonance motion of the up and down vice beams at this velocity drives the main beam to vibrate effectively through the drive sheet. As a result, the mutual coupling of motion between the main and vice beams not only improves the power and efficiency, but also broadens the velocity bandwidth for this system. Another interesting phenomenon is the discrepancy of peak point position between the power and efficiency. It is mainly due to the different influence factors of these two performance indexes as illustrated in Eqs. (2) and (3). From an energetic standpoint, this phenomenon can also be attributed to that the increase of the input power of this system is greater than the increase of the output power when the velocity varies from 0.3 m/s to 0.55 m/s.

In summary, an E-shaped PEH with the structure of folded beams has been studies for application in liquid environment with low velocities. By tuning the mass blocks on the drive sheet and vice beams, the first two order resonance frequencies of the proposed harvester can be adjusted to be close to each other as needed. Therefore, the harvester exhibits the excellent ability of broadening the frequency
operating bandwidth with two adjacent power peaks. Because of the coupling interaction between the main beam and two vice beams, the space and energy in the flow filed behind of the cylinder are efficiently utilized, which significantly increases the output voltage, power and efficiency of the harvester. Compared with the conventional PEH based on VSIV, the maximum increase in power and efficiency of the E-shaped PEH can be 70% and 326%. Besides, the velocity spectrum over 20µW of the harvester has been increased by 60%. We believe the E-shaped PEH proposed in this paper could be applied to supply energy for the low-power MEMS sensors and actuators in the environment of liquid flow with low velocities.

See supplementary material for the structural and material parameters of the PEH.

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