Enhancing Performance of a Piezoelectric Energy Harvester System for Concurrent Flutter and Vortex-Induced Vibration

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Abstract: This paper proposes a novel and efficient energy harvester (EH) system, for capturing simultaneously flutter and vortex-induced vibration. There exists a coupling effect between flexible spring energy harvester (FSEH) and cantilever beam energy harvester (CBEH) in aerodynamic response and output characteristic. Many prototypes of the harvester were manufactured to explore the coupling effect in a wind tunnel. The experimental results demonstrate that FSEH is mainly subjected to flutter-induced vibration and CBEH undergoes vortex-induced vibration. Disturbance of FSEH first takes place, a limited oscillation cycle then occurs, and chaos ultimately happens as airflow velocity increase. Root mean square voltages are more than 11 V for FSEH at beyond 10.52 m/s, which shows the better output performance over the existing harvesters. Vibration response and output voltage of various harvesters are mutually enhanced with each other. An enhancing ratio for FSEH-130-25 is up to 69.6% over FSEH-130-0, while the enhancing ratio for CBEH-130-30 is 198.3% compared to CBEH-0-30. Field application testing manifests that discharging time to power the pedometer is almost twice as long as the charging one for FSEH-130-25 at 14.48 m/s. The current research offers a suggestive guidance for promoting future practical application in micro airfoil aircrafts.

Keywords: nonlinear aeroelastic; vortex-induced vibration; piezoelectric energy harvester; coupling effect; enhancing performance; field application testing

1. Introduction

A vibration-based energy harvester can convert directly vibration energy into electricity via piezoelectric transduction, which owns the enormous advantages of replacing or recharging battery for the sake of sustainably driving low-power monitoring sensor or wireless transmitter usually placed at hard-to-access location for their entire operational life [1–6]. The conversion mechanisms of vibration energy-to-electricity mainly consist of piezoelectric [7–9], electromagnetic [10,11], electrostatic [12], and triboelectric transduction [13], among which piezoelectric transduction has obvious superiority over the others, for example simple structure and high energy density; thus, it has garnered much interest academically and commercially [14–16].

The vibration source types generally include the forced vibration and self-excited vibration; flow-induced vibration as a self-excited form is omnipresent in the environment and reserves enormous energy, for instance vortex-induced vibration (VIV) [17,18], the wake-induced vibration (WIV) [19,20], the galloping-induced vibration (GIV) [21–23], and the flutter-induced vibration (FIV) [24,25]. Capturing Energy from FIV has been widely studied in the last decades [26,27], and the structural types usually include cantilever beam harvester [28–30], fixed airfoil-based harvester [31,32], and mobile airfoil-based
harvester [33,34]. Dowell et al. [35,36] investigated the limit cycle oscillation of a cantilever beam attached to the trailing edge of the fixed airfoil. Shan et al. [37] explored the curved wing panel harvester for aeroelastic vibration. Inman et al. [38,39] proposed a piezoelectric composite wing for energy harvesting and vibration suppressing simultaneously in a small unmanned aerial vehicle. Orrego et al. [40] proposed a flexible membrane harvester called “inverted flag”, which demonstrated that a peak output power of 5 mW/m³ occurred at 9 m/s. In addition, many scholars also have fully investigated the multi degrees of freedom (DOF) airfoil-based flutter piezoelectric energy harvester, consisting of single DOF plunge or pitch motions [41,42], double DOF plunge–pitch motions [43,44], and three DOF plunge–pitch–flap motions [45]. For example, Wu et al. [46] proposed a novel pitch–plunge–lead-lag airfoil-based energy harvester and studied numerically the aeroelastic vibration and output performance. Abdelkefi et al. [47] investigated the impact of aerodynamic loads on the performance of camber airfoil-based harvester.

Furthermore, some improved methods have been adopted to broaden the frequency range and enhance the output performance of airfoil-based flutter harvester, for example introducing free play nonlinearity [48], integrating magnetic force [49], and utilizing hybrid excitation [50,51]. Abdelkefi et al. [52,53] explored the enhancing performance of wing-based piezoelectric energy harvester through free play nonlinearity. Zhou et al. [54] designed a Y-shaped bi-stable energy harvester. Li et al. [55] presented a novel nonlinear magnetic-coupled flutter-based harvester. Sousa et al. [56] investigated the aeroelastic energy harvester of combining cubic hardening stiffness and free play nonlinearities, which reduced the cut-in velocity. Bibo et al. [57] proposed a single vibratory energy harvester integrated with an airfoil to concurrently harness energy from ambient vibration and wind.

It can be known from the above literature that the flutter-induced piezoelectric energy harvesters with the cantilever beam attached to the fixed airfoil were proposed to investigate the output performance. However, the flutter-induced harvester with attaching the cantilever beam to the mobile airfoil has rarely been reported. In addition, the airfoil-based harvester with a single flexible spring was carried out to investigate numerically the output performance by the authors of [47,56]; however, the important effect of various flexible springs on the vibration response and harvesting performance was ignored. Furthermore, attaching the cylinder to the cantilever beam at the free end has also not been referred. In an incoming airflow, the airfoil can undergo FIV and bluff body can undergo VIV. The hybrid excitation may have a significant effect on their output performance. However, the coupling effect between the cantilever beam energy harvester (CBEH) and the flexible spring energy harvester (FSEH) in the aerodynamic response and the harvesting performance is unclear and very complicated. To this end, the coupling effect of the harvester system still needs to be further explored to improve the output performance of the harvester. In addition, the harvester could stimulate the two DOF plunge–pitch motions, which may be considered for utilization in future micro or unmanned airfoil aircrafts.

Therefore, this paper proposes a novel piezoelectric energy harvester system with the cantilever beam attached to the trailing edge of the mobile airfoil, including FSEH and CBEH, to harvest concurrent FIV and VIV. The VIV generated by the cylindrical bluff body could be acted on the airfoil, and affect largely the aeroelastic response of FSEH. To this end, this paper explores the coupling effect and enhances the output performance of the harvester system. The harvester system for concurrent flutter and vortex-induced vibration is designed in Section 2. The experimental investigations of various harvesters to explore the coupling effect in a small wind tunnel and field application testing for the pedometer carried out to further verify the harvesting performance are presented in Section 3. The significant conclusions of this work are drawn in Section 4.

2. Concept and Design of the Piezoelectric Energy Harvester System

To focus on the two-DOF airfoil-based piezoelectric energy harvester system and take place the plunge–pitch motions, the airfoil is mounted by a span-wise shaft. The shaft is fitted with the bearings
at both ends, which can rotate around the bearing. The spring rod can constrain the rotational motion to emulate the pitch motion to some extent. The flexible spring can produce the bending deformation to stimulate the plunge motion. In addition, the cantilever beam is connected to the airfoil at the fixed end and the bluff body is installed at the free end. When subjected to the incoming airflow, the cantilever beam and the airfoil undergo VIV and FIV in transverse direction, respectively. The hybrid excitation of FIV and VIV is first adopted in the proposed harvester system by attaching a cantilever beam to the trailing edge of the mobile airfoil, as shown in Figure 1, with intent to improve the aeroelastic vibration and enhance the harvesting performance. Because of the great distance between the flexible spring and airfoil, the effect of the fixture and flexible spring on the vibration response of VIV is not considered. This harvester system under consideration mainly consists of an airfoil, two flexible springs, a cantilever beam, and a cylindrical bluff body. Two piezoelectric patches (PZT-5H) are attached to the end of the flexible spring and the cantilever beam, respectively, which are composed of the flexible spring energy harvester (FSEH) and cantilever beam energy harvester (CBEH), respectively.

When the harvester system takes place the aerodynamic vibration, it would produce an alternating strain on the flexible spring and cantilever beam. Meanwhile, the piezoelectric patches cause strain and thus output the alternating electricity. Because of fixing together in the harvester system, the aeroelastic vibration of the airfoil has a significant effect on that of CBEH. On the contrary, CBEH also can affect significantly the vibration characteristic of FSEH. Therefore, there exists the coupling effect between FSEH and CBEH in vibration response.

3. Experimental Investigation on the Aerodynamic Response and Harvesting Performance

3.1. Experimental Setup of the Harvester System

To investigate the aerodynamic response of the piezoelectric energy harvester system, a small wind tunnel experimental setup is fabricated, as illustrated in Figure 2. The total length of the wind tunnel is 3000 mm, and the testing sectional dimension is 300 mm × 300 mm. The airflow velocity range can be adjusted from 0 to 22.73 m/s. The corresponding Reynolds number ranges 0–3.8 × 10^4 for the bluff body. The experimental system consists of a wind channel (made by the Acrylic plate), a super charging blower, a frequency converter, a harvester system, an anemometer, an electricity collecting and storing circuit, and a data acquiring and processing system. The harvester system includes a NI 9229 acquisition card, a PC, an anemometer, and a digital storage oscilloscope (TDS 2012C, Tektronix Inc., Beaverton, OR, USA), which can measure, display, and record the output voltage across the piezoelectric patches in real-time.
collecting and storing circuit, and a data acquiring and processing system. The harvester system is symmetrically and vertically placed by the designed fixture at the testing section. The data acquiring and processing system includes a NI 9229 acquisition card, a PC, an anemometer, and a digital storage oscilloscope (TDS 2012C, Tektronix Inc., Beaverton, OR, USA), which can measure, display, and record the output voltage across the piezoelectric patches in real-time.

![Experimental setup: (a) harvester system; and (b) enlarged figure of the harvester.](image)

To improve output performance and decrease the overall weight of the harvester system, the utilized materials of the flexible spring, the cantilever beam, and the bluff body are a spring steel, copper, and acrylic, respectively. Because of high piezoelectric constant and low fabricating cost, Lead Zirconate Titanate (PZT-5H, Baoding Hongsheng Acoustic Electronic Equipment Co. Ltd., Baoding, China) is selected as the piezoelectric patch. The structural parameters and materials of the flexible spring and the spring rod are selected based on the flutter characteristic, as listed in Table 1. The fixed structural parameter of the cantilever beam is adopted, and this manuscript does not consider the effect of the structural parameters of the cantilever beam on the VIV.

| Properties            | Flexible Spring | Piezoelectric Patch | Cantilever Beam | Bluff Body         |
|-----------------------|-----------------|---------------------|-----------------|--------------------|
| Materials             | Spring steel    | PZT-5H              | Copper          | Acrylic            |
| Density, $\rho$ (kg/m$^3$) | 7850            | 7500                | 8900            | 1190               |
| Modulus, $E$ (GPa)    | 210             | 66                  | 105             | 30                 |
| Poisson’s ratio, $v$  | 0.29            | 0.3                 | 0.35            | 0.39               |
| Length, $l$ (mm)      | 130 to 180      | 40                  | 100             | 100                |
| Width/Diameter, (mm)  | 30              | 20                  | 30              | 20 to 30           |
| Thickness, $h$ (mm)   | 0.5             | 0.2                 | 0.25            | -                  |
| Mass, $m$ (g)         | 16 to 21        | 5                   | 14              | 44 to 84           |

**Figure 2.** Experimental setup: (a) harvester system; and (b) enlarged figure of the harvester.
Table 1. Dimensions and materials parameters of the harvester system.

| Properties                        | Flexible Spring | Piezoelectric Patch | Cantilever Beam | Bluff Body |
|-----------------------------------|-----------------|---------------------|-----------------|------------|
| Materials                         | Spring steel    | PZT-5H              | Copper          | Acrylic    |
| Density, $\rho$ (kg/m$^3$)        | 7850            | 7500                | 8900            | 1190       |
| Modulus, $E$ (GPa)                | 210             | 66                  | 105             | 30         |
| Poisson’s ratio, $\nu$            | 0.29            | 0.3                 | 0.35            | 0.39       |
| Length, $l$ (mm)                  | 130–180         | 40                  | 100             | 100        |
| Width/Diameter, (mm)              | 30              | 20                  | 30              | 20–30      |
| Thickness, $h$ (mm)               | 0.5             | 0.2                 | 0.25            | -          |
| Mass, $m$ (g)                     | 16–21           | 5                   | 14              | 44–84      |
| Permittivity, $\varepsilon$ (nF/m) | -              | -                   | -               | -          |
| Piezoelectric, $d_{31}$ (C/N)     | -               | -274                | -               | -          |

A standard NACA 0012 airfoil is adopted. Table 2 lists the airfoil dimensional parameters. It is manufactured by 3D printer. PZT-5H is pasted on the clamped end of the flexible spring and cantilever beam by using the epoxy resin.

Table 2. Airfoil dimensional parameters.

| Properties               | Airfoil |
|--------------------------|---------|
| Materials                | PLA     |
| Density, $\rho$ (kg/m$^3$) | 1250    |
| Modulus, $E$ (GPa)       | 3.5     |
| Harvester mass, $m_T$ (g) | 540     |
| Airfoil mass, $m$ (g)    | 380     |
| Span, $s$ (mm)           | 100     |
| Semi-chord, $b$ (mm)     | 126     |

For convenience of description of various harvesters in the following analyses, it is first necessary to name the harvester system according to the structural parameters of the flexible spring and the bluff body. For example, FSEH-180-20 represents the flexible spring energy harvester (FSEH) with the length of the flexible spring of 180 mm and the diameter of bluff body of 20 mm attached to the trailing edge of the mobile airfoil, as listed in Table 3. CBEH-180-20 refers to the cantilever beam energy harvester (CBEH). In addition, FSEH-180-0 only shows FSEH with the length of the flexible spring 180 mm and without bluff body. CBEH-0-20 denotes CBEH with the diameter of the bluff body of 20 mm attached to the fixed airfoil. FSEH-*-20 represents FSEH with various lengths of the flexible springs, where the * denotes the flexible spring length.

Table 3. Names of different harvesters.

| Names                        | FSEH-180-20 | FSEH-180-0 | CBEH-180-20 | CBEH-0-20 |
|------------------------------|-------------|------------|-------------|-----------|
| Length of flexible spring    | 180         | 180        | 180         | -         |
| Airfoil motion pattern       | Mobile      | Mobile     | Mobile      | Fixed     |
| Diameter of bluff body       | 20          | -          | 20          | 20        |

3.2. Aerodynamic Vibration Response of the Harvester System

When undergoing the incoming airflow, the harvester system can undertake aerodynamic response. To analyze quantitatively the aeroelastic response of the harvester, output voltage may be a better way in this paper. The output voltage can only represent the vibration response in plunge degree of freedom. The airflow velocity is an import parameter that affects the vibration characteristic. Figure 3 illustrates the time history, power spectral density, and phase portrait of output voltage for FSEH-130-20 at 5.42, 9.90, 11.76, and 14.48 m/s.
As shown in Figure 3(a1,a2), that when subjecting to the lower airflow velocity, 5.42 and 9.9 m/s, FSEH-130-20 shows the poor output performance. It could generate a higher and quasi-periodic output voltage at 11.76 and 14.48 m/s, and hence the peak-to-peak voltage is up to 20 V at 14.48 m/s. The power spectral density obtained by Fast Fourier Transform (FFT) indicates that the fundamental oscillation frequency slightly decreases and the frequency domain amplitude increases rapidly with the airflow velocity. However, the fundamental and secondary oscillation frequencies of 1.313 and 2.35 Hz occur unexpectedly at 5.42 m/s, which shows the chaotic vibration, as confirmed by Figure 3(c1). With further increasing of the airflow velocity, the vibration response for FSEH-130-20 becomes gradually stable and quasi-periodic. When exceeding the flutter onset of velocity, 9.90 m/s, the quasi limit cycle oscillation also appears at 11.76 m/s. However, the phase portrait observed in Figure 3(c3) cannot express an approximate single circle and the chaos occurs at 11.76 and 14.48 m/s. The reason is that the harvester system possesses the lower stiffness and has not enough ability to resist the larger aerodynamic force generated at the higher airflow velocity. In addition, the assembly accuracy and clearance error in the harvester system also affect largely the occurrence of chaos. Furthermore, as for 14.48 m/s, increasing further the airflow velocity augments correspondingly the aerodynamic force and thus causes the
unstable vibration, as indicated in Figure 3(c4). Therefore, Figure 3(a2) demonstrates that the vibration response at the peak voltage is very complex and irregular.

To further investigate the coupling effect of various structural parameters on the vibration response of FSEH, Figure 4 illustrates the time history, power spectral density, and phase portrait of output voltage for FSEH-130-0, FSEH-130-25, FSEH-180-0, and FSEH-180-25 at 10.52 m/s.

Comparing with FSEH-130-0 and FSEH-180-0, Figure 4(a1,a2) shows that the output voltages of FSEH-130-25 and FSEH-180-25 are enhanced by CBEH. As a result, the peak-to-peak voltages increase from 9.49 to 15.96 V and from 11.97 to 14.12 V, respectively. The enhancing performance is also verified, as observed in Figure 4(b1–b4). The fundamental oscillation frequency of 1.221 Hz for FSEH-130-25 decreases mildly over 1.373 Hz for FSEH-130-0. The frequency of FSEH-180-0 is equivalent to FSEH-180-25. In addition, as for FSEH-130-25 and FSEH-180-25, the vibration response gradually turns into unstable and complex compared to FSEH-130-0 and FSEH-180-0, and the phenomenon is also observed in Figure 4(c2–c4). This is because when CBEH is fixed at the airfoil, the cylindrical bluff body could take place VIV in airflow, and it could be acted on the airfoil and further intensify
the unstable vibration response. Therefore, when subjecting to FIV and VIV, the larger aerodynamic force would further deteriorate the harvesting performance. Therefore, the output performance of the harvester with the shorter flexible spring outperforms that of the longer one. Because of the inherent characteristic of the harvester system, the FIV and VIV show self-limiting oscillations.

The coupling effect is mutual in the harvester system, and it could exert a vital influence on CBEH. Figure 5 illustrates the time history and the power spectral density of output voltage for CBEH-130-30 at 5.42, 9.90, 11.76, and 14.48 m/s.

As shown in Figure 5(a1,a2), the output voltage rapidly increases and then decreases gradually with the increase of the airflow velocity. It should be noted that the vibration response turns into unstable and irregular at 5.42 and 14.48 m/s, while it clearly shows better vibration at 9.90 and 11.76 m/s. This is because the vibration of the airfoil is relatively minimal at the lower airflow velocity and it causes the small disturbance of CBEH-130-30. However, for the higher velocity, i.e., 14.48 m/s, the airfoil could generate the larger aerodynamic force and similarly cause the unstable vibration. Due to the interference of the airfoil, the cylindrical bluff body could not take place the actual VIV.

As shown in Figure 5(b1–b4), the fundamental oscillation frequency of CBEH-130-30 is the same, while the frequency domain amplitude first increases, and then decreases with the airflow velocity. In addition, the voltage change curves are very complex at the peak, which is because the low stiffness and assembly clearance of the harvester system can cause disturbance, and even buffeting.

Because of being fixed together in the harvester system, the mobile airfoil could also have a significant influence on the vibration characteristic of CBEH compared to the fixed one. Figure 6 illustrates the time history and the power spectral density of output voltage for CBEH-0-20, CBEH-130-20, CBEH-0-30, and CBEH-130-30 at 10.52 m/s.
Figure 6. Time history and power spectral density of output voltage for CBEH-0-20, CBEH-130-20, CBEH-0-30, and CBEH-130-30 at 10.52 m/s: (a) time history; and (b) power spectral density.

Figure 6(a1,a2) shows that the output voltage of a CBEH attached to the mobile airfoil, i.e., CBEH-130-20 and CBEH-130-30, is superior to that attached to the fixed one, e.g., CBEH-0-20 and CBEH-0-30. This reason is mainly because the thickness of the airfoil NACA 0012 is near 30 mm, and the maximum diameter of bluff body we utilize in this paper is 30 mm. It could produce the low-pressure area at the tail; the cylindrical bluff body is just placed at the area, and the bluff body is not subjected to the actual VIV. Therefore, the vibration response of the bluff body is not very smooth. However, when the harvester is attached to the mobile airfoil, it will generate the larger lateral vibration accompanying with the airfoil, and it thus escapes from the low-pressure area and undergoes the VIV. The synchronized pitch of the airfoil in the harvester system also can enhance VIV. Therefore, the vibration response of CBEH-130-30 outperforms than that of CBEH-130-20. As a result, a maximum output voltage of CBEH-130-20 and CBEH-130-30 increases from 1.42 to 3.80 V and from 2.34 to 7.12 V over CBEH-0-20 and CBEH-0-30, respectively. However, it should be noted that the fundamental oscillation frequencies of CBEH-130-20 and CBEH-130-30 decrease accordingly compared to CBEH-0-20 and CBEH-0-30.

Focusing on showing more directly the coupling effect on the vibration characteristic of FSEH, Figure 7 illustrates the variation of output voltage with time for FSEH-130-0, FSEH-130-30, FSEH-180-0, and FSEH-180-30. Time refers to the actual measured time instance, and without any treatment.

As shown in Figure 7a,b, the output voltage of FSEH-130-30 is higher than that of FSEH-130-0 when exceeding 10.52 m/s. The phenomenon is opposite at the lower velocity. The flutter onset of velocity at 10.52 m/s for FSEH-130-30 is greater than that 9.9 m/s for FSEH-130-0. However, attaching CBEH to the airfoil can enhance the output characteristic. As a result, the maximum output voltage of FSEH-130-30 increases from 13 to 24 V compared to FSEH-130-0 at 14.48 m/s. For FSEH-180-0, the output voltage of FSEH-180-30 is also reinforced, and increases from 10.6 to 14.6 V.
results in improving the vibration response of FSEH, while it could also cause the unstable vibration at
the higher airflow velocity, as observed in Figure 7b,d.

(a)  

(b)  

(c)  

(d)  

Figure 7. Variation of output voltage with time at various airflow velocities for different harvesters: (a) FSEH-130-0; (b) FSEH-130-30; (c) FSEH-180-0; and (d) FSEH-180-30.

The coupling effect also has an important influence on the fundamental oscillation frequency. Figure 8 shows the frequency of various harvesters as a function of the length of the flexible spring at 10.52 m/s.

Figure 8a demonstrates clearly that increasing the length of the flexible spring is followed by a decrease of the fundamental oscillation frequency of FSEH. The frequency of the harvester without bluff body is higher than that with one. In addition, it also decreases slowly with the increase of diameter of the cylindrical bluff body. When the bluff body is attached to the cantilever beam, which leads to intensifying the vibration of FSEH, which correspondingly increases the overall weight of the harvesting system. As shown in Figure 8b, the frequency of CBEH attached to the mobile airfoil is distinctly lower than that attached to the fixed one. Furthermore, because of fixing together the harvester system, the frequency of FSEH is the same as CBEH. When carrying out the modal analyses by using the simulation method, the obtained natural frequency is 6.28 Hz. The mode shape is rotated around the airfoil shaft. The oscillation frequency ranges 0.8–1.5 Hz, which is lower than the natural frequency of the harvester system. The reason is perhaps that the assembly accuracy and clearance error in the experimental setup decreased the overall stiffness and thus resulted in the lower oscillation frequency.
Through analyses of aerodynamic vibration response, FSEH and CBEH could mutually enhance the vibration response. The disturbance of FSEH first takes place, the limit oscillation cycle then occurs, and chaos ultimately happens with the airflow velocity. When attaching CBEH to the mobile airfoil, it could reduce the flutter onset of velocity and improve the vibration response of FSEH. It is also enhanced over that attached to the fixed one.

3.3. Harvesting Performance of Various Harvesters

The influences of the structural parameters of the flexible spring and the bluff body on the vibration response of various harvesters are obtained in the above analyses. The output performance of FSEH and CBEH was fully investigated by experiments to uncover the coupling characteristic, which are presented in this section. Figure 9 shows the variation of the root mean square open-circuit output voltage with the airflow velocity for various harvesters.

**Figure 8.** Fundamental oscillation frequency of various harvesters as a function of the length of the flexible spring at 10.52 m/s: (a) FSEH; and (b) CBEH.

**Figure 9.** Variation of output voltage with airflow velocity for various harvesters: (a) 130 mm; (b) 140 mm; (c) 150 mm; (d) 160 mm; (e) 170 mm; and (f) 180 mm.
As shown in Figure 9a–f, when the flutter onset of velocity is exceeded, the output voltage of the harvester increases rapidly, attains to a maximum value, then flattens gradually, and ultimately decreases slowly with the airflow velocity. It is noted that, as the length of the flexible spring is increased, the effect of FIV on the output voltage gradually weakens for various harvesters. However, FSEH demonstrates clearly the poor output performance with the length of the flexible spring increase, and the obvious decreasing trend occurs at the higher velocity for the longer FSEH. The root mean square output voltage of FSEH is distinctly improved compared to the systems without the bluff body attached to the trailing edge of the airfoil, for example FSEH-130-0 and FSEH-150-0. That is because the VIV generated by the cylindrical bluff body can augment the aerodynamic force to act on the airfoil, and then it is transferred to FSEH by the holder. It is noteworthy that the output performance of FSEH with the diameter of the bluff body of 25 mm is better than that of 20 or 30 mm. In addition, when the bluff body is attached to the airfoil, the airflow velocity bandwidth corresponding to the better harvesting performance is obviously broadened and the flutter onset of velocity is reduced correspondingly. When exceeding 10.52 m/s, better output voltage can be achieved, and hence the peak voltage is up to 17.94 V for FSEH-140-25 at 13.69 m/s.

In addition to the effects of the bluff body on the output voltage of FSEH, CBEH can be greatly impacted by the flexible spring. Figure 10 illustrates the variation of output voltage of CBEH with the airflow velocity under different flexible spring lengths: (a) 20 mm; (b) 25 mm; and (c) 30 mm.

Figure 10 shows that attaching CBEH to the trailing edge of the fixed airfoil results in the poor performance of CBEH-0-20, CBEH-0-25, and CBEH-0-30 compared to the mobile one. This is mainly because the wake field of the airfoil can affect the vibration of the bluff body. The phenomenon is also verified in Figures 5 and 6. It should be noted that the output voltage of CBEH with the shorter flexible spring outperforms than that with the longer one, for instance CBEH-130-20, CBEH-130-25, and CBEH-130-30. The longer flexible spring may not possess enough ability to resist the aerodynamic force and thus results in the poor output performance, as described in aerodynamic response analyses. As the diameter of the cylindrical bluff body increases, the VIV gradually enhances, and it thus improves the output performance for various harvesters. In addition, when increasing the length of the flexible spring, the airflow velocity corresponding to the peak voltage shifts to left (lower airflow velocity range) under the same bluff body. The longer the flexible spring is, the lower the critical frequency is, and the more likely VIV is to happen. Furthermore, there are no effects of the structural parameters of the flexible spring on the output voltage at less than 5 m/s, while the effects are further intensifying with the increase of airflow velocity. A maximum output voltage of 5.93 V can be obtained for CBEH-130-30 at 11.76 m/s.

When CBEH is attached to the airfoil, it can reduce the flutter onset of velocity, broaden the airflow bandwidth, and thus enhance the output voltage of FSEH. The bluff body of 25 mm has better...
performance than those of 20 and 25 mm for FSEH. The output voltages of FSEH are more than 11 V at over 10.52 m/s.

3.4. Coupling Effect Analyses

The flutter-induced vibration and vortex-induced vibration can occur at the airfoil and bluff body, respectively. Because of the connection at the end of cantilever beam, there exists a coupling vibration between FSEH and CBEH. The output performances of the harvesters are mutually enhanced by each other. The effect of CBEH attached to the trailing edge or without on the output voltage of FSEH is first investigated. Figure 11 illustrates the variation of output voltage and enhancing ratio of FSEH with the length of the flexible spring at 14.48 m/s.

![Graph](attachment:figure11.png)

**Figure 11.** Variation of output voltage and enhancing ratio of FSEH with the length of the flexible spring: (a) output voltage; and (b) enhancing ratio.

Figure 11a shows that FSEH-*-0 without the CBEH demonstrate poor output performance. However, when it is attached to the airfoil, the output voltage of FSEH could be enhanced. The reason is mainly that the vortex-induced vibration produced by the bluff body can strengthen the aerodynamic force of the airfoil, and improved the output performance of FSEH. In addition, the diameter of the cylindrical bluff body also has a vital effect on the output voltage of the harvester. Therefore, there exists the large difference in output voltage for various cylindrical bluff bodies, especially at the longer flexible spring. The enhancing voltage of the harvester attaching to 25 mm outperforms than that of 20 and 30 mm. Based on the output voltage of FSEH-*-0, Figure 11b shows the enhancing ratio of FSEH-*, FSEH-*, and FSEH-*. The output performance of all other FSEH is improved over FSEH-*-0. A maximum enhancing ratio of 69.6% can be obtained for FSEH-130-25, while the minimum ratio is also at least 10.7% for FSEH-140-20.

In addition to the effect of CBEH on the output voltage of FSEH, the enhancing performance of CBEH is greatly impacted by the mobile or fixed airfoil. Figure 12 illustrates the output voltage and enhancing ratio of CBEH as a function of the length of the flexible spring at 14.48 m/s.

When the airfoil is fixed by the designed fixture in wind tunnel, it cannot produce the vibration of the airfoil and thus cannot affect output voltage of CBEH. Figure 12a indicates that output voltages of 0.99, 1.38, and 1.48 V, respectively, are obtained for CBEH-0-20, CBEH-0-25, and CBEH-0-30 at 14.48 m/s. However, when it is attached to the mobile airfoil, the harvesting performance of CBEH is largely enhanced by the vibration of the mobile airfoil. The enhancing voltages are up to 1, 1.88, and 2.94 V for CBEH-130-20, CBEH-130-25, and CBEH-130-30, respectively. Except for the slight decrease of CBEH-160-25, the output voltage of CBEH is improved via the mobile airfoil. When the airfoil produces the flutter-induced vibration, it further enhances the vibration of the bluff body. Therefore, the bluff
body may escape from the lower-pressure area and thus amplify the vibration response of CBEH. Figure 12b shows that an enhanced ratio of output voltage is obviously observed for CBEH-130-20, CBEH-130-25, and CBEH-130-30. A maximum enhancing ratio of 198.3% is achieved for CBEH-130-30. Furthermore, a decrease in the enhancing effect is followed by an increase in the length of the flexible spring, and the ratio of 31.48% is only obtained for CBEH-180-30.

![Figure 12. Output voltage and enhancing ratio of CBEH as a function of the length of the flexible spring: (a) output voltage; and (b) enhancing ratio.](image)

By exploring the coupling effect between FSEH and CBEH, they can mutually enhance the output performance for various harvesters. The enhancing ratio is decreasing with the length of the flexible spring increase, and peak enhancing ratios of 69.6% and 198.3%, respectively, are acquired for FSEH-130-25 and CBEH-130-30.

### 3.5. Field Application Testing of the Harvester System

The aerodynamic response and output performance of the harvester are obtained in the above analyses, respectively. The output power of the harvester is still to be further investigated for the sake of determining the optimal resistance, collecting electricity, and considering the future practical application. The harvesters of FSEH-130-0 and FSEH-130-25 were chosen to assess quantitatively the field application testing characteristic and the enhancing performance. Figure 13 shows the variation of root mean square output voltage and power of the harvester with the external load resistance at 10.52, 11.76, and 14.48 m/s.

![Figure 13](image)

Figure 13a indicates that an increase in the external load resistance is followed by an increase in the output voltages of FSEH-130-0 and FSEH-130-25 for all considered airflow velocities. The output voltage of the harvester of FSEH-130-25 is obviously superior to that of FSEH-130-0, which fully means that CBEH results in enhancing the output performance of FSEH. Figure 13b demonstrates that the output power of FSEH first increases rapidly, attains a maximum value, and then decreases slowly with the resistance. Because of the electric current shuttle effect, the output power has fluctuations to some extent under various resistances at 10.52 m/s. The optimal resistance range of FSEH is found to be from 300 to 500 kΩ, at which the harvester power is maximum. Therefore, the external load resistance of 400 kΩ is adopted to collect and evaluate the electricity in the following analyses.

Figure 14a illustrates the experimental device of the energy collecting and storing circuit. An energy collecting and storing circuit includes the resistances, a rectifier (GBU 406), a capacitor (6.3 V, 1000 μF), and a pedometer (initially powered by a 1.5 V cell button battery, capacity of 80 mAh). When the harvester is connected to the circuit, the electricity generated by the harvester can be rectified by the rectifier, stored via the capacitor, and then drive the low-power electronic equipment. The pedometer
that exists a suitable application prospect is adopted to estimate quantitatively the output power of the harvesters of FSEH-130-0 and FSEH-130-25. Figure 14b shows the variation of the capacitor voltage with time for the pedometer testing.

![Figure 13](image1.png)

**Figure 13.** Variation of output voltage and power of the harvester with the external load resistance at 10.52, 11.76, and 14.48 m/s: (a) output voltage; and (b) output power.

![Figure 14](image2.png)

**Figure 14.** Experimental device of the energy collecting and storing circuit, and the variation of the capacitor voltage with time for the pedometer testing at various velocities: (a) energy collecting and storing circuit; and (b) capacitor voltage for pedometer testing.

When the harvester is connected to the storing circuit, the capacitor is first required to be charged 120 s by the rectified voltage and then powers the pedometer. Figure 14b indicates that the working times to drive the pedometer via the harvester of FSEH-130-0 are up to 118, 173, and 202 s at 10.52, 11.76, and 14.48 m/s, respectively, while the times via the harvester of FSEH-130-25 are 147, 192, and 209 s, respectively. Therefore, the discharging times via FSEH-130-25 have lengthened correspondingly 29, 19, and 7 s compared to FSEH-130-0. The field application testing for the pedometer fully suggests that the harvester can drive the pedometer and the output performance of FSEH can be reinforced via CBEH. In addition, the discharging time to power the pedometer is almost twice as long as the charging time for FSEH-130-25 at 14.48 m/s. The high efficiency energy harvesting circuit will be adopted for meeting the future field application in micro or unmanned airfoil aircrafts.
3.6. Comparative Analyses

To show further the better output performance of the proposed harvester, a comparison with similar harvesters is conducted to evaluate quantitatively the harvesting characteristic, as shown in Table 4. The compared harvesters adopt the piezoelectric and electromagnetic–piezoelectric mechanisms, but they are all subjected to the incoming airflow. It should be noted that the power densities are defined as $P_{\text{ave}}/A_m$ and $P_{\text{ave}}/V_m$, where $P_{\text{ave}}$ represents the average output power of the harvester; $A_m$ denotes the maximum side area of the entire harvester; and $V_m$ is the maximum volume of the harvester. The power densities of the proposed harvesters are 2.41 and 0.48 μW/cm$^2$, respectively, which demonstrates the superior harvesting performance over the other ones.

Table 4. Comparison of output performance between the previous and proposed harvesters.

| Reference        | Mechanism              | Airflow Velocity (m/s) | Average Power (μW) | Power Density $\mu W/cm^2$ | Power Density $\mu W/cm^3$ | Configuration |
|------------------|------------------------|------------------------|--------------------|--------------------------|---------------------------|---------------|
| Abdelkafi et al. [52] | Piezoelectric          | 12.59                  | 300                | -                        | -                         |               |
| Iqbal et al. [51]  | Electromagnetic–piezoelectric | 6                     | 11.2               | 0.16                     | 0.04                      |               |
| Cheng et al. [58]  | Piezoelectric          | 42.4                   | 13.06              | -                        | -                         |               |
| Erturk et al. [59] | Piezoelectric          | 15                     | 7                  | 0.04                     | -                         |               |
| This work         | Piezoelectric          | 14.48                  | 154                | 2.41                     | 0.48                      |               |

4. Conclusions

This paper presents a novel piezoelectric energy harvester system for concurrent FIV and VIV, which explores mainly the coupling effect between FSEH and CBEH. A small wind tunnel was designed and many prototypes of the harvester were manufactured to investigate experimentally the vibration response and the output characteristic. Some important conclusions are drawn as follows:

- As for FSEH, the longer the flexible spring is, the lower the flutter onset of velocity and critical frequency are, the more likely FIV is to happen, while the VIV easily takes place for CBEH.
- The vibration response and output performance of various harvesters are mutually enhanced with each other, and the enhancing ratio decreases as the length of the flexible spring increases. The enhancing ratios are up to 69.6% and 198.3% for FSEH-130-25 and CBEH-130-30, respectively.
- The output voltage of the harvester first increases rapidly, then flattens gradually, and ultimately decreases with the airflow velocity. As a result, a maximum output voltage of 17.94 V can be harvested for FSEH-140-25 at 13.69 m/s, which is superior to the existing harvesters.
- The field application testing indicated that, when the capacitor charged 120 s via FSEH-130-25 at 14.48 m/s, the discharging time to power the pedometer was up to 207 s, which provides an important experimental guidance for further promotion in the future of practical applications in micro or unmanned airfoil aircrafts.
Author Contributions: X.S. and H.T. designed the model and carried out the experiment; T.X. and X.S. provided guidance; and H.C. provided experimental assistance. All authors have read and agreed to the published version of the manuscript.

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