Hybrid energy harvesting from the natural wind and magnetic field

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Abstract. This paper proposes a hybrid energy harvester scheme from the natural wind and magnetic field. A prototype is fabricated with a piezoelectric sheet and a Galfenol substrate cantilever. The energy harvester from natural wind not the tunnel wind is simulated and verified by the experiment results. Moreover the performances of hybrid energy harvester with respect to the single energy collection are in-depth investigated. The optimal output criterion is defined and the hybrid output voltages for the optimal parameters can be predicted. The optimal ranges of magnetic field intensity for different wind speeds are presented. Experiment results demonstrate the superiority of the hybrid energy harvester over individual harvesters. Suggestions for the rational design of this hybrid energy harvester are illustrated. This paper provides a feasible solution for the hybrid energy harvester from natural wind and magnetic field, which can be significant for improving the capacity and reliability in energy harvesting.

1. Introduction

Self-power supplies have been investigated explosively in the past years for the development of wireless sensor networks, health monitoring, cardio pacemaker and self-powered sensors due to the limited lifetime of batteries and the requirement of regular replacement or recharging [1-2]. Energy harvesting from ambient wasted energy to generate sustainable electricity for low-power electronic devices is becoming increasingly attractive as an alternative to conventional batteries [3-4]. By integrating energy harvesting technologies into wireless sensor networks, the networks can operate autonomously with insignificant maintenance costs [5]. Generally speaking, energy harvesting methods are categorized into motive and non-motive groups. The motive type contains vibration energy transforming method such as piezoelectric, electromagnetic, electrostatic and magnetostrictive approaches, while non-motive ones include solar, wind, thermal etc [6-7]. Investigations of self-powered sensors through harvesting ambient energy has been developed widely. Among them, extensive work focused on applying piezoelectric materials to convert mechanical vibration energy into electrical power [8-9].

Wind energy is an alternative energy source pervasively available in the environment. However, energy harvesting from light winds has received limited attention. The effective wind energy conversion usually involves aerodynamic instabilities such as vortex-induced vibrations, flutter and galloping [10]. For example, Akaydin et al. [11] investigated the harvesting feasibility of the vortex-induced vibration in circular cylinders. Kwon [12] conducted experiments to convert flutter oscillations induced by a T-shaped cantilever into electricity. Tang et al. [13] proposed a galloping-based piezoelectric energy harvester and presented an equivalent circuit approach. However, the
standard tunnel wind is considered in these publications. In practice, the ambient wind flow is disordered and fluctuating. Therefore much work should be done on these conditions.

As the electronic equipment becoming more and more popular, the ambient magnetic field has great potential to be used as energy sources. However, different from vibration excitation, how to transfer the magnetic field energy to the electrical energy is not easy. Magnetostrictive material which can response to the magnetic field changes is an ideal material for energy harvester from ambient magnetic field. The characteristics studies of magnetostrictive energy conversion are still insufficient and literatures review shows that rare work has been conducted in this specific scope [14].

One of the most important matters in the energy harvester is that the energy density needs to be improved. This paper intends to investigate the energy harvester performances for the natural wind. Moreover, the hybrid energy conversion which includes the wind and magnetic field excitations is explored to examine enhancement behaviors of the joint harvester. The optimal range of magnetic field intensity is provided for different wind speeds and the output voltages can be predicted. This paper will provide a feasible scheme for the hybrid energy harvester from natural wind and magnetic field.}

2. Experiment details

As Figure 1 (a) displays, the proposed energy harvester includes a cantilever beam clamped at one end and subjoined to a tip mass (45mm×25mm×25mm) at the free end (Figure 1 (a)). The beam is composed of a Galfenol substrate (150mm×20mm×0.8mm) and a piezoelectric sheet (40mm×20mm×0.5mm) which is connected to the interface circuit. As shown in Figure 1 (b), the simplified single-degree-of freedom model can be regarded as a mass-spring system with mass $M$, stiffness $K$ and damping $D$. Wind $U$ flows with the angle of attack $\alpha$. The aerodynamic force $F_z$ acting on the bluff body causes it to oscillate in the $z$ direction.

Figure 1 The typical wind energy harvester scheme. (a) Schematic diagram of the structures. (b) Schematic diagram of a bluff body undergoing wind excitation.

The overall layout of the experiment is shown in Figure 2. The cantilever is placed in the center of the Helmholtz coil which produces the magnetic field. The wind generator is used to provide the wind flow, and the hand-held anemometer (type UT363) is applied to measure the output wind speed. The circular table connected to the wind generator outlet can reduce the cross-sectional area of the wind flow to increase the maximum wind velocity. The maximum wind speed that the wind generator can provide is 9m/s through measurements. By changing the area of the wind blow, the wind speed can be lowered and adjusted. A cuboid is fixed at the end of the beam as a bluff body for the easier vibration of the cantilever. The bluff body is an internal hollow structure and a mass block can be added to adjust the natural frequency of the cantilever. The piezoelectric sheet is directly connected to the oscilloscope signal input port. The voltage outputs under the combined effects of the wind and magnetic field are observed. The root mean square (RMS) of the output voltage is observed and recorded for results discussion.
3. Results and Discussion

First, the effects of magnetic field on this energy harvester is ignored. The governing equation of coupled lumped parameter model can be written as

\[
\begin{align*}
&M\ddot{w}(t) + D\dot{w}(t) + Kw(t) + \Theta V(t) = F_z(t) \\
&\frac{V(t)}{R_L} + C_p \dot{V}(t) - \Theta\dot{w}(t) = 0
\end{align*}
\]

where \(w\) is the tip displacement in the direction normal to the wind flow. \(V\) and \(R_L\) are the generated voltage and load resistance respectively. \(C_p\) is the total capacitance of the piezoelectric sheet in parallel connection and \(\Theta\) is the electromechanical coupling coefficient. The coupling coefficient \(\Theta\) is given by

\[
\Theta = \sqrt{(\omega_{no}^2 - \omega_{ns}^2)MC_p}
\]

where \(\omega_{no}\) and \(\omega_{ns}\) 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 expressed as

\[
F_z(t) = \frac{1}{2} \rho_a SU^2 C_F \tilde{w}
\]

where \(\rho_a\) and \(S\) are the air density and area facing the wind flow, respectively. \(C_F\) can be expressed as a polynomial function of the attack angle \(\alpha\).

\[
C_F = \sum_{i=1}^m A_i (\alpha)^i + \sum_{j=2}^k A_j (\alpha)^j \frac{\tilde{w}}{|\tilde{w}|}
\]

\[
\alpha = \frac{\tilde{w}}{U} + w'(L)
\]

where \(A_i\) and \(A_j\) are the empirical coefficients and \(w'(L)\) represents the rotation angle of the beam at the free end due to the bending deformation. Herein \(L\) is the length of the beam.

When a region has a stable wind speed distribution, the two-parameter Weibull distribution fits the wind frequency curve well and it is close to actual wind conditions. Therefore the corresponding probability density function is suitable for the simulation of wind frequency distribution. The two-parameter Weibull distribution can be expressed as

\[
F(U) = \frac{k}{c} \left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^k\right]
\]

where \(k\) and \(c\) are the scale and shape parameters, respectively.

The responses of the harvester can be simulated by the derived analytical model. The short circuit and open circuit natural frequencies for the proposed harvester are measured to be 59.74 Hz and 59.78 Hz under base excitations, respectively. The electromechanical coupling coefficient \(\Theta\) is calculated to be \(1.58 \times 10^{-4} \text{N/V}\) by Eq. (2) with the parameters \((M=28.2\text{g} \text{ and } C_p=186\text{nF})\). The damping ratio is
measured utilizing the logarithmic decrement technique. The coefficients \( A_i \) and \( A_j \) are obtained according to the methods in the reference [15]. The average wind speed and variance of the wind are respectively 5m/s and 10m\(^2\)/s\(^2\) for the local wind conditions. Thus the scale and shape parameters are determined (\( k=30.1762 \) and \( c=1.4273 \)).

The wind speed and energy harvester results versus time are illustrated in Figure 3. The local wind is adopted as the wind flow in the experiments. As can be observed, the RMS of output voltages for the experiment and simulation are 276.32mV and 269.87mV, respectively. The error is just 2.33%. At the same time, some discrepancies exist between the calculated and measured voltages. It can be attributed to that the inaccurate damping used in the simulation. In practice, the damping is not constant but amplitude-dependent. On the other hand, the coefficients \( A_i \) and \( A_j \) are fixed when adopting the methods in the reference. However they vary with wind speed in fact. In general, this energy harvester scheme for nature wind is verified.

![Figure 3](image-url)

**Figure 3** Energy harvester performances for the wind excitation. (a) Wind speed versus time. (b) Experimental and theoretical results for the wind energy harvester. Solid line-experiment results and dotted line-theoretical results.

Then experiments are implemented in the static air environment to achieve the wind speed adjustment of the wind generator. We conducted some more experiments aiming to find some consistent characterizations of the output voltages. However the waves in the oscilloscope do not behave obvious and common features. It may be attributed to the unstable wind velocity. Although the measured wind speed is 9m/s, this value is just the average speed within a period of time. Therefore, the wind speed denotes the average speed. On the other hand, the export of the wind generator is not rectified to be constant like the wind tunnel. The disordered output wave comes into being due to the disordered wind flow. In actual working conditions, the natural wind is also disordered. Under the conditions of 5m/s, the experiment results produced by the wind generator are in consistent with those by the natural wind. Therefore, this disordered flow field condition is closer to the actual working conditions than the tunnel wind. And it can be regarded as the natural wind situation. The advantage is that the wind speed can be adjusted to conduct more research, while the local natural wind cannot be controlled.

Experiments under the condition of high (9m/s) and low (3m/s) wind speed are further studied. In the longest period that can be recorded by the oscilloscope, the amplitude of the voltage changes with no regularity. The frequency of the waveform under the influence of the wind excitation is measured and the frequency maintains about 60 Hz regardless of the wind speed condition. This is exactly the first-order natural frequency of the cantilever. Therefore, one of the characteristics of wind-induced energy harvester is that the frequency of output voltage is independent of the wind flow and related to the natural frequency of the cantilever itself, which may be helpful for subsequent experiments. In addition, the higher the wind speed, the more energy the piezoelectric cantilever can intercept from the wind field in our experiments. Even the individual waveform do not show obvious laws, voltages generated by the cantilever under the high wind velocity are overall higher than those at low wind speeds.
The wind energy harvester actually converts the wind energy into vibrational energy and then collects it through the piezoelectric sheet. Therefore, some principles concerning the joint collection of vibration energy are also applicable to the combined harvester of wind and magnetic field energy. When the magnetic field is also applied, priority is given to whether the voltage produced by the single magnetic field and the voltage generated by the wind are at the same magnitude level. First, a magnetic field of the same magnitude (hereinafter referred to as a weak magnetic field, \( M_w \)) is applied, and then a stronger magnetic field (hereinafter referred to as a strong magnetic field, \( M_s \)) is adopted. The superposition results are observed.

Since the voltage waveform generated by wind-induced vibration is not a stable harmonic wave, the results of the final superposition are also unstable. Results show that the strengthening or weakening effects are obvious. The energy harvester performances for different combinations of wind speed (high speed \( U_h \) and low speed \( U_l \)) and magnetic field intensities (\( M_w \) and \( M_s \)) are investigated. In each case, multiple waveforms are inspected and the RMSs of the waveform are marked in Figure 4. Ten groups of waveform are intercepted from the hybrid output voltages successively and they are defined from cycles 1 to 10.

![Figure 4](image_url)

**Figure 4** Output voltages of the combined wind and magnetic field excitations. (a) \( U_h \) and \( M_s \). (b) \( U_h \) and \( M_w \). (c) \( U_l \) and \( M_s \). (d) \( U_l \) and \( M_w \). Blue line-wind, green line-magnetic field and red line-hybrid effects.

In Figure 4(a), although the voltage generated alone by the wind fluctuates, the average result (301.42mV) of ten cycles are much lower than that (933.57mV) of the magnetic field. Even the combined RMSs for different cycles are not completely equal, it can be seen that the scope of change is within 882mV and 967mV. The hybrid output voltages are basically in the vicinity of those produced by the magnetic field alone. Similar results are observed in Figure 4(c). The voltages generated only by the magnetic field are similar to the case of single wind excitation in Figure 4(b) and Figure 4(d), in which combined effects of the fluctuations are much more pronounced than Figure 4(a) and Figure 4(c). The hybrid results are higher than those of either the wind or magnetic field excitation.

The characteristics of the results in Figure 4 can be summarized as follows: (1) when the energy harvested by the magnetic field is much stronger than that of the wind, the hybrid results do not show obvious advantages. No significant enhancement effects can be produced, nor any obvious weakening influences. (2) When the level of energy collected by the magnetic field is equal to the wind energy, the hybrid harvester is apparently effective. Although there exist weakening situations, the probability of enhancing effects is greater. The hybrid output voltages are generally greater than the voltages of single excitation.

The above discussion reveals that the combined results may be more effective if the energy generated by magnetic field excitation and wind excitation is similar. If the average wind speed is
determined, the range of optimal magnetic field intensity is the key point to ensure the excellent performances of hybrid energy harvester. Figure 5 displays the combined output voltages for different magnetic field intensities under the low speed and high speed of the wind, respectively.

Figure 5 Output voltages for different magnetic field intensities under different wind speeds: (a) 20A/m, (b) 70A/m (c) 120A/m, (d) 170A/m, (e) 220A/m, (f) 270A/m, (g) 320A/m and (h) 370A/m. (a), (b), (c) and (d) - low wind speed. (e), (f), (g) and (h) - high wind speed. Blue line - wind, green line - magnetic field and red line - hybrid effects.

When the magnetic field intensity is 20A/m, the output voltage remains 21.37mV. The average voltage for the low wind speed is 53.52mV and the average of the hybrid voltage is 55.08mV. The combined effects is not very obvious. However when the magnetic field intensity is 70A/m, the average hybrid voltage is 132.73mV which is much larger than either the single wind case (53.52mV) or magnetic field case (108.26mV). As illustrated in Figure 5(c) and Figure 5 (d), when the magnetic field increase continuously, the combined voltages are almost equal to those excited by the magnetic field, which means the hybrid energy performances are not remarkable and the effects of wind are wasted. Furthermore, as Figure 5 (e) to Figure 5(h) demonstrate, the cases for high wind speed are explored. The average output voltage for single wind excitation is 276.45mV. When the magnetic field intensity is 220A/m, the average voltages for the single magnetic field excitation and combined excitations are 308.72mV and 401.14mV, respectively. The output voltage for higher magnetic field intensity (270A/m, as illustrated in Figure 5(f)) are 404.36mV, while the average hybrid voltage is only 451.19mV. The superposition effects are slight. Therefore, the magnetic field intensity range needs to be determined to achieve the optimal hybrid energy harvester for different wind speeds. In addition, it can be concluded that the average combined output voltages are larger than those of the single excitation.

In order to determine the optimal magnetic field intensities for different wind speeds quantitatively, the following definitions are proposed:

\[ V_o = 1.2 \max \{V_w, V_m\} \]

where \(V_w\) and \(V_m\) are the average output voltage for the wind and magnetic field, respectively. The increment is 20% which can be adopted to restrict the range of the magnetic field intensity for optimal energy harvesting under the conditions of different wind speeds. This formula limits the magnetic field intensity scope in which hybrid energy harvester will be strengthened greatly. The experiment results are displayed in Figure 6.
Figure 6 The optimal range of the hybrid energy harvester for different wind speeds: (a) optimal magnetic field intensity and (b) hybrid output voltages.

As has been discussed, the output voltages increase when the magnetic field intensity or wind speed increases. There exist the high intensity and low intensity limits for specific wind speed. As a result, the combined voltages also display this characteristic. It can be observed from Figure 6 (a) that when the wind speed is below 3m/s, the optimal magnetic field intensity does not exist. The difference between the high intensity (78.15A/m) and low intensity (59.47A/m) in the case of $U=3$m/s are 18.68A/m. However, when the wind speed is 9m/s, the difference is 39.21A/m. It indicates that the range of magnetic field intensity increases with the wind speed. The magnetostriction saturation of Galfenol may have influences on the range with the increasing of magnetic field. This range provides a feasible selected scope for the magnetic field intensity. Similar results are presented in Figure 6 (b). The combined voltages also increase nonlinearly with the wind speed. The slope of the output voltages becomes large gradually. The reason may be two aspects. On the one hand, the voltages itself generated by the wind increase as the wind speed increases. And on the other hand, the amplitude of voltages produced by the magnetic field are similar to those by wind. This Figure can be applied to predict the optimal output voltages of the hybrid energy harvester system.

4. Conclusions

A hybrid energy harvester scheme from the magnetic field and natural wind was proposed in this paper. The energy harvester of natural wind is theoretical modeled and verified by the experiments. When the magnetic field energy harvested is far stronger than wind energy, the hybrid results do not show obvious advantages and will not produce significant enhancement or weakening effects. When the energy harvested separately from the magnetic field and wind field is equivalent, the superiority of hybrid energy harvester is obvious. Overall, the joint output is greater than the individual output. When the wind speed is determined, the optimal range of magnetic field intensity can be provided. Moreover the optimal hybrid output voltage can be predicted. This work provides a feasible scheme for the hybrid energy harvester from natural wind and magnetic field, which may be benefit for the capacity and reliability in energy harvesting.

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