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Study on a piezo-windmill for energy harvesting

Junwu Kan, Chuntao Fan, Shuyun Wang*, Zhonghua Zhang, Jianming Wen, Leshuai Huang

Institute of Precision Machinery, Zhejiang Normal University, Jinhua, 321004, China

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ABSTRACT

A piezo-windmill excited by rotating magnets was presented to harvest energy from wind of low speed and wide range speed. The exciting force exerting on the piezo-windmill is general periodic (inharmonic). An analytical model for performance evaluation was established based on Fourier series as well as superposition principle and simulated to obtain the influence of system parameters on the response of the piezo-cantilever in terms of the number of optimal rotary speeds and the relative amplitude ratio. A prototype was fabricated and tested to prove the analysis results. The research results show that, under other parameters given, there are multiple optimal rotary/wind speeds for the amplitude-ratio/generated-voltage to achieve peak. With the increasing of the number of exciting magnets, the number of the optimal rotary/wind speeds decreases. There is a moderate quantity of exciting magnets for the peak amplitude-ratio/generated-voltage to achieve maximum. Besides, with the increasing of proof mass, the optimal speeds decreases, and the relative amplitude-ratio/generated-voltage increases.

1. Introduction

To provide real-time and endless energy directly for low-power electronics such as wireless sensors, biomedical implantable devices, health monitoring systems and so on, the researches devoted to energy harvesting are increasing rapidly [1–5]. One of the effective methods to obtain electric energy is to harvest and convert various ambient energy by piezoelectric elements [6–9]. Up to now, the developed piezoelectric harvesters can be used to harvest kinds of environmental energy, such as vibration energy [9–12], flow energy (including wind energy and liquid-flow energy) [13,14], ultrasonic energy [15,16], and so on. The studies and experiments mentioned above indicate the feasibility of using piezoelectric energy harvesters as power sources. But the energy-conversion capability and efficiency of piezoelectric harvesters are still too low to be used widely, especially to be used for real-time power supply without energy storage. Thus, the methods to enhance the performance in terms of energy-generating, reliability, and bandwidth of the developed piezoelectric harvesters are still key technologies [17].

Wind energy, as an important kind of renewable energy, has been a wide range of development and utilization from macro-scale to micro-scale due to clean, green and rich advantages. Among power generation technologies using the wind energy, piezoelectric wind energy harvester has gained widespread attention in the field of small-scale alternate power sources. To harvest effectively wind energy, several kinds of piezoelectric wind energy harvesters have been proposed. According to the structures and principles, the proposed piezoelectric wind energy harvesters can be categorized mainly into two groups: (I) the blow-type harvesters based on the vibrations due to aerodynamic instability phenomena such as vortex-induced vibration [18], galloping [19], and flutter [20], and (II) rotary type harvesters utilizing fan blades to capture wind energy (i.e. windmills or turbines) [21–25].

For the blow type harvesters, the piezoelectric transduction elements interact directly with wind. Thus, the piezoelectric elements are apt to breakdown due to unexpected wind of high speeds. Besides, the harvesters achieve maximal energy levels only when the natural frequency of piezoelectric elements is equal to the self-exciting (vortex induce) frequencies, which depend on Reynolds Number, Strouhal number, wind speeds, and structural parameters such as the shape/size of piezoelectric-element/bluff-body/tip-mass. As a result, the effective bandwidth of the blow-type harvesters is narrow. In practical applications, a piezoelectric wind energy harvester should be robust and suitable to large range of wind speed, and especially low wind speed.

Thus, kinds of rotary type piezoelectric harvesters are developed sequentially. They are excited indirectly with mechanical devices rotating with fan blades powered by wind flow. The available exciters for the piezo-windmills are rotating bumps/teeth [21,22],

* Corresponding author.
E-mail addresses: jutkjw@163.com (J. Kan), jutwsy@163.com (S. Wang).

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falling balls [23], and rotating magnets [24,25]. Compared to the blow type harvesters, the advantages of a rotary type harvester are as followings: ① suitable for capturing low-speed wind energy by using multiple blades to offer larger surface area vanes; ② wide bandwidth and the exciting frequency of the piezoelectric elements can be easily adjusted with changing the number of exciters (rotating bumps or magnets); ③ more wind power can be captured with simultaneously exciting multiple piezoelectric elements.

For the previous piezo-windmills, the piezoelectric elements are excited by contact with rotating bumps/teeth/falling-balls [21–23]. Thus, the impact between the piezoelectric elements and exciters inevitably results in energy dissipation, noise, and even damage of piezoelectric elements. On the contrary, for the noncontact piezo-windmills excited by rotating magnets [24,25], there is no contact impact, noise, and breakdown of the piezoelectric element.

However, the excitation forces of the proposed piezo-windmills are almost the harmonic. In this case, there is only one optimal exciting frequency (matched with the natural frequency of piezoelectric element) for a windmill to achieve maximal energy. Namely, the effective wind-speed range where the windmill can generate electric energy is limited. Besides, the previous researches on piezo-windmills focus mainly on the experiments to verify the feasibility of proposed devices. No analysis model was established to investigate the influence of system parameters (such as wind speeds and the number of magnets/teeth) on energy-generation performance in terms of voltage waveform and voltage-frequency characteristics.

In this work, a piezo-windmill excited non-harmonically by general periodic force of rotating magnets was presented to harvest wind energy. Compared to the windmills based on harmonic excitation, its advantages are multiple resonant frequencies for the piezoelectric elements to achieve peak values of voltage/power. So multiple optimal wind speeds can be obtained for the windmill to generate peak voltage. The range of wind speed where the proposed piezo-windmill can harvest wind energy is obviously increased. The above characteristics are important and even indispensability for harvesting energy from winds of low speed and wide-range speed. An analytical model based of Fourier series and superposition principle is developed to match the experiments and investigate the influence of wind speeds as well as the number of magnets on energy-generation performance in terms of time domain (waveform) and frequency domain (amplitude-frequency) characteristic.

2. Structure and working principle of the piezo-windmill

As shown in Fig. 1, the presented piezo-windmill consists generally of piezo-cantilever traducers consisting of a substrate plate and piezo-membrane bonded to it, exciting magnets rotating with rotary disk, excited magnets, fan blades, and tubulate framework. The piezo-cantilevers are fixed on the outside of tubulate framework with the excited magnets attached on their free-end. The rotary disk together with fan blades is installed inside of the tubulate framework. The exciting magnets are fixed on the flange of rotary disk. The fan blades provide torque for the rotary disk to rotate.

The piezo-cantilevers are excited by the interactive repulsive force between the exciting magnet and excited magnet to avoid the impact of exciting magnets against framework. As shown in Fig. 2(a), with the exciting magnet rotating from location A to location B, and then to location C, the change of excitation force can be treated as a general periodic triangular wave as shown in Fig. 2(b). Here $T = 60/(nn_0)$ is the period, n is rotating speed of the rotary disk and excited magnets, n_0 is the number of the exciting magnets, $T_m = 60l/(\pi nR)$ is the exciting time, l is the arc length of the exciting magnets (equal to the length of the exciting magnets), h is the exciting distance between the exciting magnets and excited magnets, R is the radius of the rotary disk, and F_m is the amplitude of excitation force depending on the structure/configuration/property parameters of the exciting/excited magnets.

According to Fig. 2(b), the excitation force can be written as

$$F(t) = \begin{cases} F_m \dfrac{2t}{T_m}, & \text{for } 0 < t < \dfrac{T_m}{2} \\ F_m \dfrac{2(T_m - t)}{T_m}, & \text{for } \dfrac{T_m}{2} < t < T_m \\ 0, & \text{for } t > T_m \end{cases} \tag{1}$$

For any periodic function of time can be represented by Fourier series as an infinite sum of sine and cosine terms, the Fourier series representation of Eq. (1) can be given by Ref. [26].

$$F(t) = \frac{a_0}{2} + \sum_{j=1}^{\infty} \left[a_j \cos(j\omega t) + b_j \sin(j\omega t) \right] \tag{2}$$

where $\omega = 2\pi/T = nn_0\pi/30$ is the fundamental frequency and a_0, a_j,

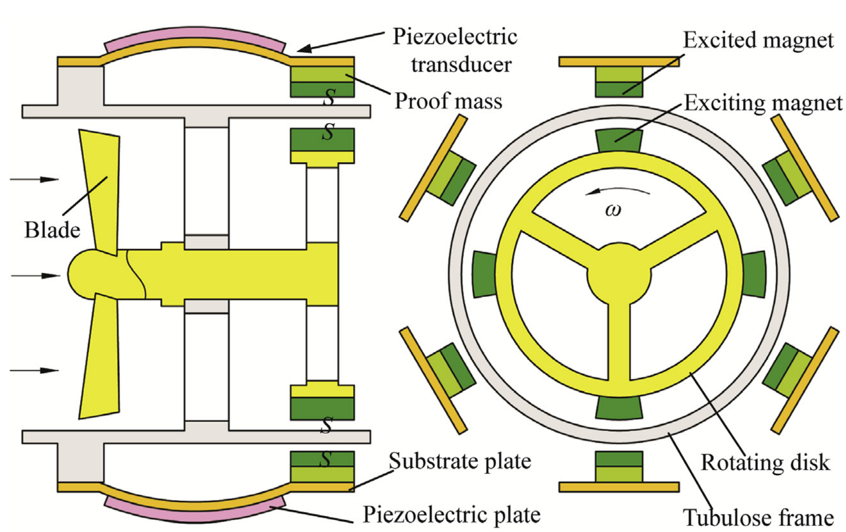

Fig. 1. Structure and working principle of the piezo-windmill.