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Electromagnetic resonant cavity wind energy harvester with optimized reed design and effective magnetic loop

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ABSTRACT

We demonstrate a new electromagnetic resonant cavity wind energy harvester combined with dual-branch reed and turning fork vibrator to harvest wind energy for wireless sensor nodes. Compared with electromagnetic structures in the past, the proposed magnetic circuit has a better linearity and a magnetic loop that more effectively increases the rate of the change of magnetic flux. Moreover, the motion of the free magnet is directed vertically to the direction of the magnetic pole for a zero resistance startup mode and a compact construction. We also designed a tuning fork-like reed structure to reduce system losses. To achieve maximum output power, we defined a virtual resistance to deal with the decrease of the electromotive in the circuit caused by the Lorentz force between the magnet and the induced magnetic field of the coils when the circuit is turned on. The dimensions of the wind inlet were 60 mm × 60 mm. The maximum output power and conversion efficiency can reach 56 mW at wind speed of 20.3 m/s and 2.3% at wind speed of 4 m/s, respectively, with wind speed from 3.2 m/s to 21.2 m/s. The experiments show that this electromagnetic wind energy harvester has high output power and wide wind speed range.

1. Introduction

Methods to harvest ambient energies for portable electronics or wireless sensor nodes have been extensively investigated in recent years [1]. These methods can harvest energies from photovoltaic, temperature gradients, fluid flows, pressure variations, and mechanical vibrations [2,3]. With advances in microelectronics and micro manufacturing technologies, power consumption of electronic devices has been reduced to only a few hundreds of microwatts or even less [4,5], which means that the development of self-powered electronic devices become achievable by harvesting energies from ambient environment. Thus, these renewable ambient energies will provide useful sources of electrical power to replace or supplement traditional batteries which have limits in capacity, heavy size, lifespan and environmental friendliness [4].

As a universal environmental existence, wind energy is clean and abundant, and is especially suitable in some remote places where sunlight is inaccessible. With piezoelectric or electromagnetic conversion principle, many mechanical structures have been developed and tried to convert wind energy to electrical power simply and efficiently. These converting structures include wind turbines, windmills, windbelts, piezoelectric cantilevers, and wind cavities. Peirs et al. [6] and Howey et al. [7] proposed small turbines to generate electricity by rotating electromagnetic coils with wind. Although the turbine structure has high conversion efficiency and high output power in huge size, its efficiency and output power reduces heavily in small size due to the increased proportion of bearing friction losses and the reduced area of blade surfaces. Priya et al. [8,9] developed micro windmills to generate electricity from vibrated piezoelectric bimorphs. The size of windmills can be miniaturized to centimeter-scale. However, the inner structure is complex and the conversion is inefficient at present. Fei et al. [10,11] reported flexible wind-flutters to harvest wind energy from windbelts. This technology has a good performance at low wind speeds (7 mW at 2.8 m/s), but it has a complex fabrication process and a high production cost. Sirohi and Mahadik [12] and Kwon [13] presented piezoelectric cantilever reed placed in the wake of a cylinder to harness energy from air flows through the vibration caused by the passage of vortices shedding. Inspired from the flow-induced self-excited oscillation in a harmonica, Ji et al. [14] and Clair et al. [15] developed resonant cavity structures to harvest wind energy using piezoelectric reeds. Although wind cavities provide a promising candidate to harvest wind energy due to their simple, compact, and reliable structures, the conversion efficient of the existing prototypes is still low.

In general, wind energy harvesters are based on wind-induced rotations or vibrations, which means that they should first convert wind energy into mechanical energy as mentioned above, and then convert mechanical energy into electrical energy. There are three main approaches can be used to convert mechanical energy into electrical energy: electrostatic, piezoelectric, and electromagnetic [16]. For electrostatic generators, Meninger et al. [17] and

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Lee et al. [18] proposed a MEMS-based electrostatic energy converter with two opposite electrostatic charge signs, this is not commonly used for its low output power and requiring a separate voltage source to begin the conversion cycle. For piezoelectric wind energy harvesters, piezoelectric cantilevers are often adopted, including unimorph and bimorph structures. In fact, harvesting vibration energy by piezoelectric cantilevers are widely used and investigated in recent years for their simple, durable and cheap structures. Ovejas and Cuadras [19] and Robbins et al. [20] used flexible piezoelectric materials to generate electricity. Oh et al. [21], Priya et al. [8,9], and Jing et al. [22] utilized piezoelectric bimorph vibration to convert energy. For electromagnetic wind energy harvesting, it appears various kinds of forms and structures. Apart from traditional turbine structures [6,7] and the commonly used ones comprising a fixed helical coil and a moving axial magnet [23,24] or a fixed magnet and a moving axial helical coil [25], many new designs with optimized magnetic loop to improve the coupling effect of electromagnetic energy harvesters have been proposed in recent years. Dayal et al. [26] developed a structure with one helical coil and two repulsive moving magnets to generate more electricity. Further, Kwon et al. [27] and Cepnik et al. [28] presented repulsively stacked multilayer moving magnets to effectively improve the electromagnetic coupling. Fei et al. [10,11] developed a structure with two coils and one moving magnet to increase the generated electricity. Beeby et al. [29] and Glynne-Jones et al. [30] designed a optimized magnetic loop with four magnets for one moving coil. Roundy and Takahashi [31] and Liao et al. [32] demonstrated a structure with a multi-pole magnetic plate and a multipolar hard magnet ring for vibration energy harvesting. The piezoelectric and electromagnetic energy harvesters have their own advantages. Sometimes, the piezoelectric and electromagnetic mechanisms can be combined together to enhance the efficiency of mechanical energy harvesting [33].

In this paper, we developed the resonant cavity wind energy harvester with electromagnetic coupling structure. Compared with the piezoelectric cantilevers, the electromagnetic design has a much higher energy storage density [16] and is more suitable for low-frequency and medium-scale applications [34,35]. To improve the efficient of the energy harvester, we optimize the reed with dual-branch and tuning fork designs and present a new design of magnetic loop. In the following sections, we will first describe the working principle of the harvester. Then, analyses of the reed with dual-branch and tuning fork structures will be conducted. The design of new magnetic loop will also be investigated. Tests and discussions of a prototype harvester are then presented. Finally, we will give our conclusions and recommendations for future work.

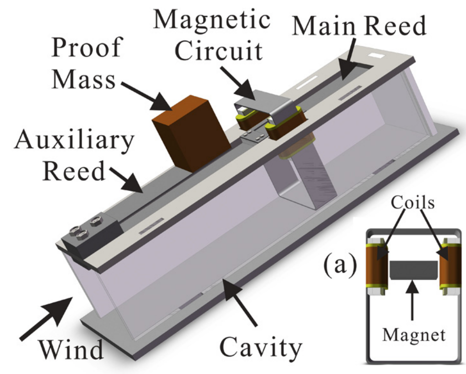

Fig. 1. Diagram of the electromagnetic wind energy harvester.

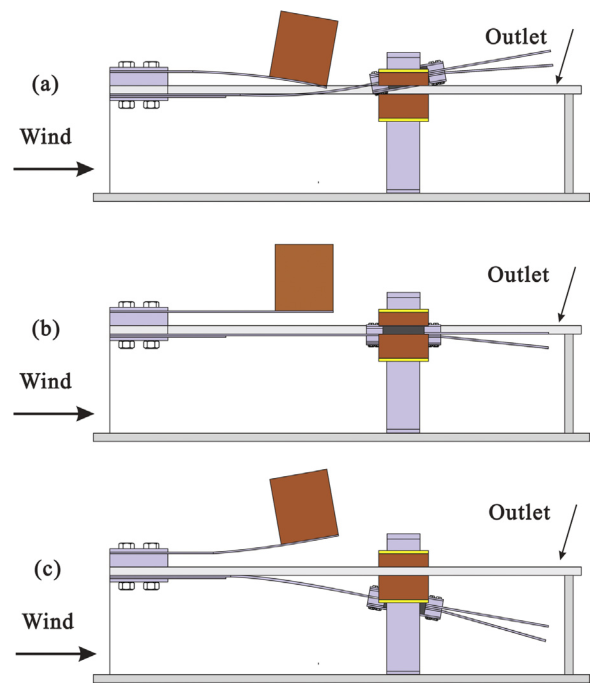

Fig. 2. Working process of the electromagnetic wind energy harvester.

2. Description of the proposed wind energy harvester

2.1. Working principle of the wind energy harvester

The proposed electromagnetic wind energy harvester is based on the principle of wind-induced self-excited vibration. The vibration energy is converted into electrical energy by Faraday's law of induction. Fig. 1 shows an overall view of the energy harvester, which consists of a flow of rectangular cavity that mimics the vibration of the reeds in a harmonica and a cantilever structure with a permanent magnet glued on. The permanent magnet is glued on the center-front of the reed with a branch and the coils are fixed on the sidewall of the cavity. To reduce the viscous forces of the wind, the width of the gap between the cavity and the reed is set to 1 mm. Fig. 1(a) shows the magnetic circuit structure of the electromagnetic wind energy harvester.

The working principle of the harvester is simple. Wind blows into the cavity to increase air pressure and destabilize the balance of the reed. The increased air pressure bends the reed and opens an air path between the cavity and the environment. Thereafter, the air passes through the aperture, which rapidly increases velocity. In turn, the pressure in the cavity decreases, the mechanical restoring force pulls the reed back to decrease the aperture area, and then the process is repeated. As the wind continues blowing, the reed is excited, and self-excited oscillation is generated. This phenomenon is known as a self-excited or self-sustained oscillation [15,36]. The branch of the reed blocks the outlet when the reed is up or down to bestow the reed with further bending ability and stronger vibration. We take the reed with a branch reed as the dual-branch reed in this paper. In the whole process, the permanent magnet vibrates with the reed to produce an alternate magnetic field. Then, according to the principle of Faraday's law of electromagnetism, electricity is generated in the related coils.

Fig. 2 shows the working process of the electromagnetic wind energy harvester. Fig. 2(a) shows the reed was moving upside and the outlet was open. Fig. 2(b) shows the reed was staying in the equilibrium position and the outlet was closed. Fig. 2(c) shows the reed was moving downside and the outlet was open. The process is repeated and the reed keeps vibrating to generate an alternating