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Energy harvesting from wind by a piezoelectric harvester

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ABSTRACT

A novel wind power harvester using piezoelectric effect is developed. This engineering structure device employs a wind turbine that extracts kinetic energy from the wind and converts it into the rotational motion of a shaft. The rotational shaft is connected to a Scotch yoke mechanism that is used for converting the rotational motion into linear vibrations of two piezoelectricity-levers through springs. A mathematic model is developed to calculate the root mean square value of the generated electric power. The influences of some practical considerations, such as the rotational speed of the wind turbine and the stiffness of the springs, on the root mean square of the generated power are discussed. The research results show that a power up to 150 W can be harvested for a piezoelectric wind turbine with a radius of blades of 1 m at the wind speed of 7.2 m/s, and the designed angular velocity of 50 rad/s.

1. Introduction

The increasingly consumption of traditional energies has caused serious energy crisis and environmental pollution on a global scale. Wind energy has been regarded as one of the most important renewable and green energy sources to solve the above problems [1]. Wind turbines have been used on one of the traditional ways of transferring kinetic energy from wind based on the principle of electromagnetic induction [2,3]. The power coefficient of the wind turbines with output of megawatt has been reported up to 40–45% at the optimal tip speed ratio of 5–7 [4]. However, these large-size turbine generators are always complex, costly, and normally induce a cogging torque which restricts the cut-in speed. For small wind turbines located in areas of unfavorable wind, they are of little practical use except in rare situations [5,6]. As a result, using unconventional approaches such as vortex induced vibration, galloping, flutter, and buffeting to harvest the wind energy have been recently proposed [7–15]. To provide a more efficient energy transfer process, piezoelectric technology is the most prominent candidate for converting mechanical energy to electricity with highest efficiencies and lowest costs owing to their high energy generation density, high voltage generation capability and simple configurations and economic benefits [16–18].

Early works about a piezoelectric windmill were carried in literatures [9,10]. The proposed devices had ten piezoelectric bimorphs arranged along the circumference of a horizontal-axis wind turbine rotor shaft in the cantilever beam form. The oscillating torque to vibrate the bimorphs was generated using the camshaft gear mechanism. A power of 7.5 mW at the wind speed of 10 mph was measured across a matching load of 6.7 kΩ. Authors also addressed some drawbacks of this device and gave an optimized structure made of only plastic parts in the later work [11]. Sirohi et al. [12] developed a piezoelectric energy harvesting device based on a galloping cantilever beam. The harvested wind energy is transferred to a galloping beam which has a rigid tip body with a D-shaped cross section. Piezoelectric sheets were bonded on the top and bottom surface of the beam. During galloping, vibrational motions are induced due to aerodynamic forces on the D-section, which is converted into electrical energy by the piezoelectric (PZT) sheets. Their experimental and analytical investigations of dynamic response and power output have shown that a maximum output power of 1.14 mW was measured at a wind velocity of 10.5 mph on a prototype device of length 235 mm and width 25 mm. Rezaei-Hosseinabadi et al.[13] presented a topology for piezoelectric energy harvesting made of a lift-based wind turbine and a piezoelectric beam with contactless vibration mechanism. The research results showed that a power density of 2 mW/cm^3 at 3.8 V at the wind speeds above 0.9 m/s can be achieved. Kishore et al. [14] designed an ultra-low start-up speed windmill made of a 72 mm diameter horizontal axis wind turbine rotor with 12 alter-

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nating polarity magnets around its periphery and a 60 mm × 20 mm × 0.7 mm piezoelectric bimorph element having a magnet at its tip. This wind turbine was found to produce a peak electric power of 450 μW at the rated wind speed of 4.2 mph. Wu et al. [15] developed an effective and compact wind energy cantilever harvester subjected to a cross wind. Sufficient electrical energy output as high as 2 W was realized by tuning the resonant frequency of the harvester with a proof mass on the tip of the cantilever.

The aforementioned piezoelectric harvester devices have been mainly developed for energy supplies of wireless sensors. Therefore, most of them are small in sizes and the energy outputs are always in the scale of mW. Recent researches have shown that piezoelectric harvesters can harvest power range from several watts to hundreds of megawatts [19–23]. Xie et al. [19,22] developed a novel piezoelectric technology of energy harvesting from high-rise buildings and found that a power up to 432.2 MW can be realized. Viet et al. [23] proposed a floating energy harvester (FEH) using piezoelectric effect to harvest energy from water waves. Based on their simulated results, the root mean square (RMS) of 103 W can be achieved when the wave amplitude is 2 m. Hence, it is imperative to develop harvesters with high power using piezoelectric effect from wind.

In this research, a wind energy harvester using piezoelectric technique is developed. This proposed piezoelectric wind turbine incorporates the advantages of the conventional wind turbines and the piezoelectric harvesters. Wind turbine rotor blades with the shape optimized by aerodynamics and connected to a horizontal shaft are employed as the driving device. The wind-induced rotational motion of the shaft is converted into translation motion of a slotted rod through a Scotch yoke mechanism. Both sides of the slotted rod are linked with a spring used for transferring the linear motion into vibrations of two piezoelectricity-levers. The extracted wind power is directly converted into an applied force on the piezoelectric bars with levers for amplification to achieve a more efficient energy harvesting process. In addition, since only few structural components with small sizes are required, the current engineering structure device is much smaller and lighter than the conventional wind turbines.

2. Design and modeling methods

Design of a horizontal piezoelectric wind turbine is depicted in Fig. 1(a and b). Three blades with a radius of R are attached to a shaft that is used to link the internal piezoelectric device. As seen in Fig. 1(b), the main piezoelectric harvester consists of a Scotch yoke mechanism, two springs with stiffness coefficient of k_1, and two piezoelectric levers. The Scotch yoke, shown in Fig. 2, is a reciprocating motion mechanism, converting a rotational motion into a linear motion [24]. A slotted rod is used to make sure the motion is only in the direction perpendicular to the axis of the shaft by a cylindrical slider attached to a wheel. When the wheel rotates at an angular velocity, ω, the end points of the slotted rod are displaced from their initial position by an amount z_s (in time t) given by $z_s = Y\sin\omega t$, where Y is the amplitude, i.e. the distance between axles of the cylindrical slider and the shaft.

The piezoelectricity-lever device, shown in Fig. 3(a), consists of a lever with a long moment arm L_2 and a short moment arm L_1, a fixed-hinge for restricting linear displacements of the lever, and a piezoelectric bar with a Young's modulus, width, length, and height of E_P, a, b, and h, respectively. Since the piezoelectricity-lever devices are connected to the slotted rod by two springs, the harmonic motion is then converted into a spring force $F(t)$. The force location is at the point C and magnified n times at the point A on the piezoelectric bar by the lever mechanism, where n is the ratio of the length of the long moment arm to that of the short moment arm, $n = L_2/L_1$. Consequently, the electric power is generated by the piezoelectric-lever design.

In order to estimate the spring force $F(t)$, one of the piezoelectric lever is used as an example and is simplified as a damped single-degree-of-freedom (spring-mass) system, shown in Fig. 3(b) [23,25]. The equivalent mass m_e, spring stiffness k_e, and damping coefficient c can be derived from the material properties and dimensions of the lever and piezoelectric bar.

In the proposed design, the piezoelectric bar is firmly bonded on the lever at the region of point A. Due to the high tensile/compression stiffness of the piezoelectric bar in the force direction, the lever is supposed to be fixed throughout points A and B and equivalently transformed into a cantilever beam with a length of L_2. Hence, the equivalent mass m_e can be calculated as $m_e = \rho_l A_l L_1 n$, where ρ_l and A_l are material density and cross-section area, respectively. In this work, the lever is made of steel, and its cross-section is rectangular in shape with a width and height of s_1 and s_2, respectively. The dimensions of the lever face are selected as $s_1 = 0.015$ m and $s_2 = 0.004$ m, unless otherwise noted.

Since the applied force at point C induces an elastic deflection of the cantilever and axial deformation of the piezoelectric bar, the equivalent spring stiffness, k_e in Fig. 3(b) can be yielded as [26]:

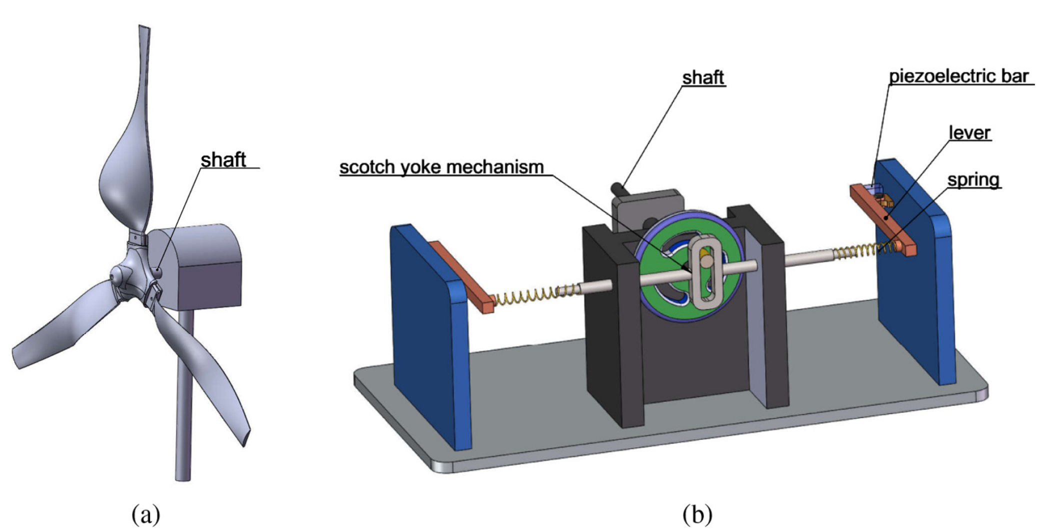

Fig. 1. Schematic diagram of a horizontal piezoelectric wind turbine: (a) an overview of the device, and (b) an internal structure of the device.