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Piezoelectric Windmill: A Novel Solution to Remote Sensing

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This study demonstrates a technology, "Piezoelectric Windmill", for generating the electrical power from wind energy. The electric power-generation from wind energy is based on piezoelectric effect and utilizes the bimorph actuators. Piezoelectric Windmill consists of piezoelectric actuators arranged along the circumference of the mill in the cantilever form. Using the camshaft gear mechanism an oscillating torque is generated through the flowing wind and applied on the actuators. A working prototype was fabricated utilizing 12 bimorphs ($60 \times 20 \times 0.5\,\mathrm{mm}^3$) having a preload of 23.5 gm. Under a nominal torque level corresponding to normal wind flow and oscillating frequency of 6 Hz, a power of 10.2 mW was successfully measured across a load of 4.6 kΩ after rectification. Combined with the wireless transmission, this technology provides a practical solution to the remote powering of sensors and communication devices. [DOI: 10.1143/JJAP.44.L104]

KEYWORDS: piezoelectric, energy harvesting, bimorph, windmill, transducer, remote sensing

There has been continuous focus on developing small-integrated-smart structures for energy harvesting in various defense and civil applications. Research efforts in this arena have focused on present generation unmanned aerial and water vehicles, hybrid automobiles, smart pocket computers, audio and video devices. Previously, solar energy, hydrogen fuel cell, thermoelectric devices and photostrictive materials have been used as the alternative methods for generating electric energy. However, integration of these methods with the intended platform of "small-range", "energy-on-demand" is expensive, tedious and technology driven. The most attractive alternative is utilizing wind flow to generate electricity. Practically, on-site small scale successful harvesting of electrical energy from wind energy can solve various existing challenges and evolve new applications. The letter addresses this specific issue and demonstrates a technology for harvesting electric energy from wind energy using piezoelectric bimorph actuator.

There are three main steps in electric power generation using piezoelectric: (a) trapping of the mechanical AC stress from available source and applying it to piezoelectric transducer (b) conversion of the mechanical energy into electrical energy using direct piezoelectric effect and (c) processing and storage of the electrical energy. Normal vibration sources in the environment are random and difficult to control. However, wind flow provides a constant source of mechanical energy.

Engines and electrical motors in many common usage machines are other sources for tapping the vibrations to produce electricity. A car delivers vibration between 50–120 Hz with force of 500 kgf while a farmhouse feeder provides vibrations of 10–15 Hz with a vertical oscillation load of 350 kg. Previously, Kim *et al.* have demonstrated the capability of harvesting the electrical energy from mechanical vibrations in dynamic environment through a "Cymbal" piezoelectric transducer.[1,2] The mechanical vibrations were in the range of 50–150 Hz with force amplitude of the order of 10 N. The experiments performed at the frequency of 100 Hz on a cymbal with 29 mm diameter and 1 mm thickness under force of 7.8 N showed that 39 mW power was generated from the cymbal measured across a 400 kΩ resistor.[1,2] A DC–DC converter was designed which allowed transfer of 30 mW power to a low impedance load of 5 kΩ with a 2% duty cycle and a switching frequency of 1 kHz.[2] This approach is not suitable for harvesting power from low magnitude force of 1–2 N and at low frequencies of 1–10 Hz. Further, the requirement of DC–DC converter makes the energy harvesting circuitry quite complicated and results in loss of power.

MIT media labs developed a piezoelectric unimorph transducer shoe insert and the associated electronic circuitry for scavenging electrical energy during walking.[3] A power level of 8–10 mW was realized in these experiments. This method suffers from several drawbacks including: (i) difficulty in incorporation of piezoelectric transducer and circuit into the shoes without disturbing the human action, (ii) limitation on the power level that can harvested, and (iii) expensive. Ocean Power Technologies utilizes the mechanical flow energy in oceans and rivers to convert to electrical energy by using piezoelectric polymer (PVDF) actuators.[4] This research is still in very early stages and is facing challenges associated with circuit for storing the electrical energy. The aim of this study is to investigate the electric energy harvesting using piezoelectric bimorph transducers which has significant advantages over these previous approaches.

The piezoelectric material has a great impact on the achievable performance of the transducer. Under an applied force ($F = X \cdot A$, where X is the stress and A is the area), the electric power available under the cyclic excitation is given by eq. (1):

$$P = \frac{1}{2} CV^2 \cdot f$$
$$P = \frac{1}{2}\frac{d}{\varepsilon_0\varepsilon^X} \cdot F^2 \cdot \frac{t}{A} \cdot f = \frac{1}{2}(d.g) \cdot F^2 \cdot \frac{t}{A} \cdot f \qquad (1)$$

where t is the thickness of the ceramic, g is the piezoelectric voltage coefficient, d is the piezoelectric constant, ε is the dielectric constant and C is the capacitance of the material. Above relationship shows that under given experimental conditions, *for a given material of fixed area and thickness, the generated electrical power under the AC force F is dependent upon the ratio* d^2/ε^X *(or d.g) of the material*. In order to obtain high performance at low frequencies far from

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Table I. Piezoelectric constants of the hard and soft ceramics.

Properties	APC 840	APC 850	APC 855
$\varepsilon_{33}^{X}/\varepsilon_o$	1000	1750	3250
$\varepsilon_{11}^{X}/\varepsilon_o$	1100	1594	3465
$-d_{31}$ (pC/N)	93	175	270
d_{33} (pC/N)	218	400	580
g_{33} (10^{-3} m^2/C)	24.6	26	19.5
$-g_{31}$ (10^{-3} m^2/C)	9.5	12.4	8.8
$g_{33}.d_{33}$ (10^{-15} m^2/N)	5362.8	10400	11310
$g_{31}.d_{31}$ (10^{-15} m^2/N)	883.5	2170	2376
Q_m	500	80	75

the resonance a piezoelectric material with high figure of merit (*d.g*) was selected. Table I shows the material constants for the conventional hard and soft ceramics. It can be clearly seen from this table that soft materials have higher figure of merit and consequently APC 855 was selected as the transducer material.

Piezoelectric bimorph transducer structure was selected because of the following advantages in terms of suitability for windmill:

1. Bimorphs have enough mechanical strength in the high vibration conditions of frequency 1–10 Hz. In this limit the applied load on the bimorph can be of the order of few newtons. Laboratory scale measurements have shown that a bimorph vibrating under a force of 2 N at low frequencies of 10 Hz do not suffer from any mechanical degradation.
2. The piezoelectric voltage coefficient of bimorph is high so the charge developed under fully loaded condition is high.
3. The maximum displacement of the bimorph is significant due to the high level of bending force that can be applied. Hence, the mechanical energy that can be transferred to the bimorph is high.
4. The manufacturing cost of bimorph is very low.

Figure 1 shows the picture of the fabricated windmill. Twelve bimorph transducers were arranged around the circumference of the center shaft as shown in Fig. 2 in a pipe of diameter 114 mm and width 60 mm. Each bimorph was adjusted such that it just touches the tip of the triangular stopper. The dimensions of each individual bimorph were $60 \times 20 \times 0.6\,\text{mm}^3$ with a free length of 53 mm. The resonance frequency and capacitance for this size of bimorph was measured to be 65 Hz and 170 nF respectively. The displacement of the bimorph under the maximum torque was equal to the gap between the stoppers and thus it oscillates between these gaps. As the bimorph is pressed against the stopper it produces charge through direct piezoelectric effect. Thus, continuous back and forth oscillation of bimorph between the two stoppers will continuously generate electricity. The transducer bearings were designed to be with very low friction. The structure shown in Fig. 2 was mounted on a central windmill shaft as shown in Fig. 3(a). The windmill shaft was rotated by the motion of the wind using the camshaft mechanism as shown in Fig. 3(b). The wind flow causes the fan to rotate. The torque generated from the rotation of the fan is transferred to the windmill shaft by using a cam of height equal to the circumferential distance between the two stoppers and a hanging weight of 23.5 gm in the form of beam. Thus, rotation of the fan results in generation of the oscillatory motion of the weight (similar to pendulum) and this motion is transferred to the windmill shaft which oscillates the stoppers.

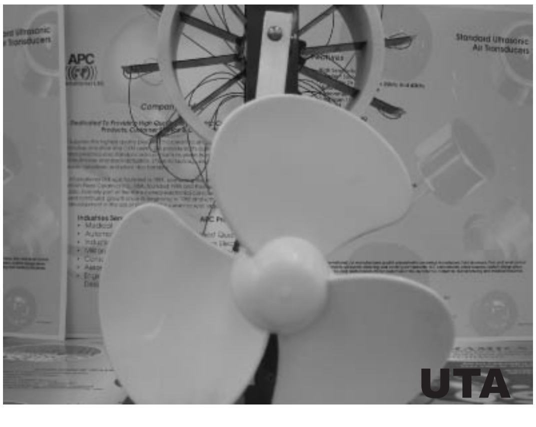

Fig. 1. Picture of the fabricated prototype "Piezoelectric Windmill".

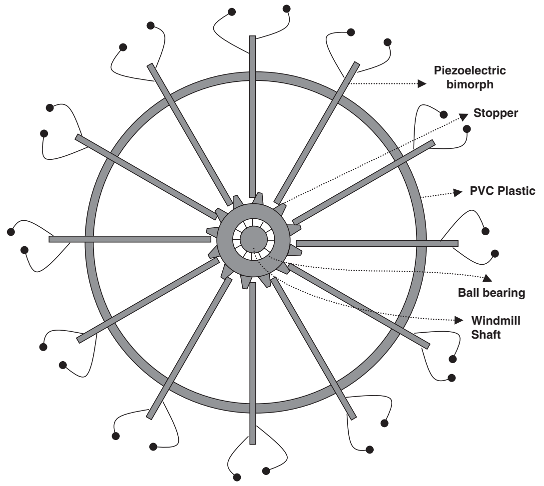

Fig. 2. Schematic of the piezoelectric bimorph arrangement in the windmill and the method for applying oscillatory stress.

The working prototype shown in Fig. 1 was evaluated for its performance. After the completion of the windmill assembly it was found that one of the bimorph had an electrode delamination and other eleven were fully functional. Hence, these eleven bimorphs were used for the measurement. Before the operation of the windmill, the bimorphs were pre stressed to have a bending of 1.77 mm at the tip touching the stopper. The output power increases with the prestress level however the rotation of the fan becomes proportionately difficult. Thus, the pre stress level was adjusted such that the fan could be rotated easily in the normal wind flow conditions. Figure 4(a) shows the signal waveform generated from the windmill at the frequency of 4.2 Hz measured across the 4.6 kΩ resistor. A peak voltage of 3.75 V was obtained in this case. Figure 4(b) shows the frequency dependence of the rectified output voltage. The rectification circuit used for the measurement is shown in Fig. 5. The peak voltage increases with frequency of the oscillation which is expected as more electrical energy is

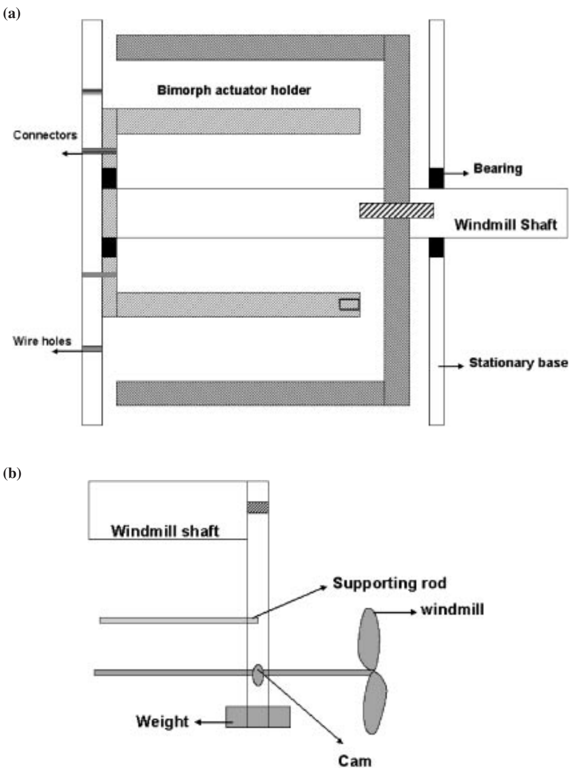

Fig. 3. Schematic drawing of the windmill structure. (a) Bimorph actuator holder and method of mounting the whole assembly on a rotating shaft. (b) Cross-section of the fan-assembly along with the hanging weight and cam-shaft mechanism used for generating the oscillatory motion from the wind flow.

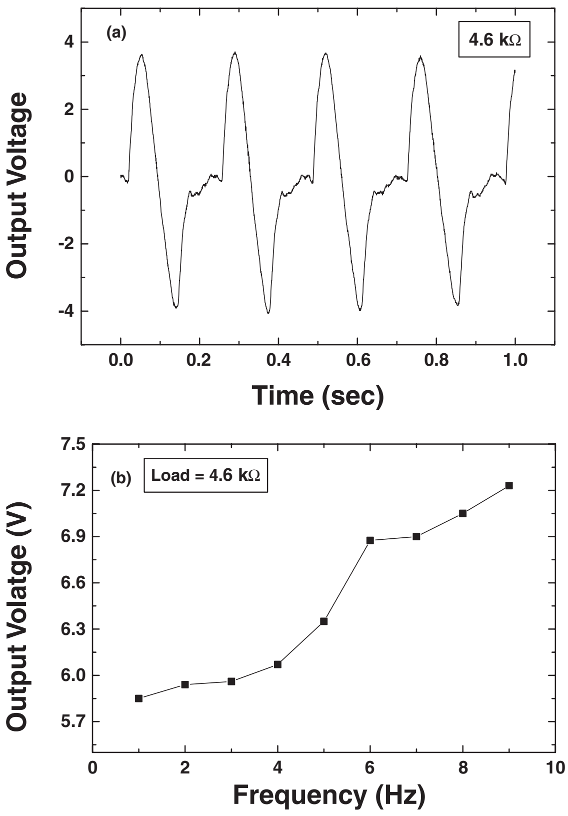

Fig. 4. Output of the windmill with eleven bimorphs connected under controlled wind flow. (a) Output voltage waveform across a 4.6 kΩ load and frequency of 4.2 Hz. (b) Rectified output voltage as a function of the frequency at a frequency of 6 Hz and load of 4.6 kΩ.

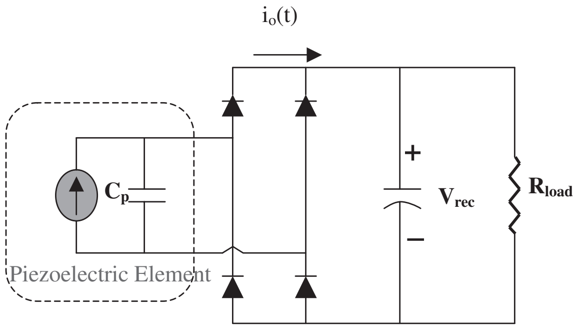

Fig. 5. Rectifier circuit used for measuring power.

available during each cycle.

The figure of merit for designing the transducer is electromechanical efficiency. In the 31 mode the charge generated on the piezoelectric plate is given by:

$$Q/V = \frac{d_{31}LW}{g_{31}T} = \frac{\varepsilon_{31}^{T}\varepsilon_{0}LW}{T} = C_{31} \tag{2}$$

where C is the capacitance of the material. Above relationship shows that at low frequencies a piezoelectric plate can be assumed to behave like a parallel plate capacitor. The electric power available from the cyclic excitation is given by:

$$P_{\mathrm{elec}} = \frac{V_{\mathrm{peak}}^{2}}{R_{\mathrm{load}}} \tag{3}$$

At the frequency of 6 Hz and load of 4.6 kΩ, the peak voltage of the windmill was found to be 6.875 V which gives the electrical power as 10.2 mW.

Figure 6(a) shows the peak rectified output voltage and corresponding power calculated using eq. (3) as a function of the output load for the windmill with eleven bimorphs connected together. It can be seen from this figure that the power reaches maximum of 10.2 mW at an optimum matching load of 4.6 kΩ. The magnitude of the matching load is dependent on various parameters including the damped output capacitance, capacitance change with prestress, dielectric loss factor, impedance of the rectification circuit and changes due to structural assembly. Neglecting all the other factors the matching load can be approximated as:

$$\text{Theoretical matching load} = 1/2\pi f \cdot C_{\mathrm{damped}} \tag{4}$$

Figure 6(b) shows the variation in electrical power and matching load as a function of the number of the bimorphs. The theoretical load was calculated using the eq. (4) and is also plotted in Fig. 6(b) as a function of the number of bimorphs. It is evident from this figure that the power increases with the number of bimorphs while the matching load decreases. For a single bimorph the maximum power of 0.935 mW was obtained at the load of 120 kΩ while for 11 bimorphs connected in the windmill, 10.2 mW power can be obtained across the 4.6 kΩ load. The calculated matching load shows similar functional dependence however the magnitude is higher than measured value. The enhancement in the magnitude of the power by increasing the number of bimorphs is due to the increment in the magnitude of the charge generated. However, it should be noted here that the stress required to oscillate the bimorphs also increases with

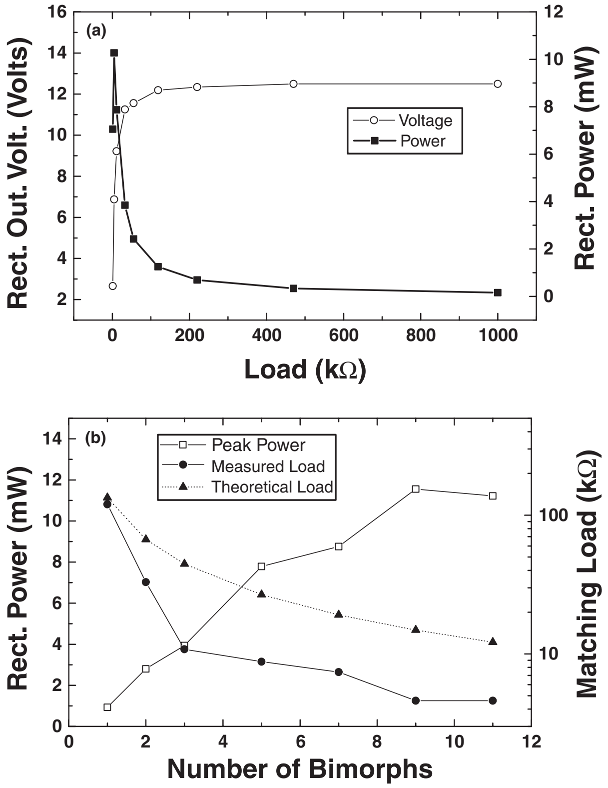

Fig. 6. Characterization of the windmill as a function of load and number of bimorphs. (a) Rectified output voltage and power as a function of the load and (b) Output power and matching load as a function of the number of bimorphs.

the number of bimorphs.

Previous work on energy harvesting has focused on the development of circuitry which maximizes the energy harvested under certain assumptions, such as fixed-frequency AC excitation.[5,6] The circuit consists of a diode rectifier and a DC–DC converter. DC-to-DC converter circuit was used to amplify the output power at the low impedance. The impedance of applications such as charging a battery and lighting a bulb is of the order of few hundred ohms while the matching load of the single bimorph or piezoelectric transducer is of the order of ~100 kΩ. The addition of the DC–DC converter was shown to improve energy harvesting by a factor of 4 and its efficiency has been shown to be between 74 to 88%.[6] However, the technology provided in this paper simplifies the energy harvesting circuitry dramatically. The matching load is decreased by ~100 times and it can be further reduced by increasing the number of bimorphs in the windmill.

In conclusion, this study demonstrates a methodology for harnessing the power from freely available wind on mass scale. This electrical energy generated can be stored in the capacitor or miniaturized Li-batteries and can be transmitted wirelessly to power various remote devices including sensors for weather monitoring and structural health monitoring, accelerometers, strain gages, thermal sensors, switches and alarms which require power in the range of 10–50 mW. The power can be easily controlled by adjusting the number of bimorphs in the windmill.

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