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Meso-scale piezoelectric energy harvester for low-frequency rotational motion

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ABSTRACT

Wind energy has been seen as a most potential renewable energy. However, in shore environments, the wind turbine usually suffers constantly impact of sand and strong wind speed, which causes the surface deteriorate: cracks may appear. To reduce the wind turbine operations and maintenance (O&M) cost, assembling a self-powered surface condition monitoring system (SCMS) becomes the most important measures. In this paper, a meso-scale piezoelectric energy harvester (PEH) was fabricated, based on a tapered cantilever beam to scavenge the rotational energy to power SCMS. The advantages are to increase its output power density and its lifetime comparing to the traditional rectangular cantilever beam. A frequency up-conversion method was adopted to accommodate PEH to working under variety of rotational speed by using two opposing magnets. With different distances between two magnets, the output voltage and the daily output energy of the PEH were investigated under 5 rpm – 30 rpm rotational speed. The maximum output voltage is 2.7 V, 9.1 V and 13.6 V when the magnets spacing is 3 mm, 2 mm and 1 mm, respectively. For the magnet spacing of 1 mm, the daily output energy of the PEH was estimated to be 5.26 J under periodic magnetic plucking at 30 rpm, much higher than the 0.2 J of SCMS's daily energy consumption, making this harvester an excellent solution for the abovementioned needs.

Keywords: frequency up-conversion, piezoelectric energy harvesting, wind turbine, magnetic plucking

1. INTRODUCTION

In recent years, the demand for electric energy has increased year by year. To the countries who heavily rely on the imported fossil fuels will cost huge economic and environmental burden. Among them, Taiwan is one of the countries in that situation. Fortunately, the consultancy company 4C Offshore reported that Taiwan possess 80% of the world best wind field which is located on Taiwan strait [1]. The government makes a big push to extract international investment on the development of wind energy technology especially after the Fukushima disaster highlighted the risks of using nuclear power in the region prone to earthquake. However, because of the geographical location and narrow coastal terrain, wind turbines frequently suffer strong wind containing high sand concentration in summer. Both of them are the risks to destroy wind turbine blade. As time goes on, the destruction of the wind turbine may occur starting from its surface of the blade. To reduce the operations and maintains (O&M) cost, assembling a self-powered surface condition monitoring system (SCMS) becomes the most important task. With the help of SCMS, we can monitor the surface condition of the wind turbine blade and schedule the maintenance in advance. For the proposed self-powered SCMS shown in Figure 1, a meso-scale piezoelectric energy harvester (PEH) with its interfacing circuit are responsible to generate sufficient electric energy to supply the ultrasonic transducer of SCMS. Finally, the data from SCMS will be transferred back to information center through a wireless module.

In this paper, we will focus on the design, fabrication and the validation of the PEH in energy harvesting system.

Since wind turbines have varying and low rotational speed (5 rpm to 20 rpm) depending on the wind condition, the widely used resonant type of PEH is not available for this application. Band broadening and frequency up-conversion method are

the common solutions to accommodate PEH working at its off-resonant frequency. There are some researchers using direct impact [2] or nonlinear magnetic plucking [3] to improve the performance of PEH at low rotational speed. H. Fu. et al. presented theoretical and experimental validation of bi-stability and frequency up-conversion mechanism of a rotational PEH by using two external repelling magnets [3]. The unimorph PEH is 33.5mm in length, 2mm in width and 0.25 mm in thickness direction. The results indicate the maximum power in double-wall mode is around $54\mu\text{W}$ at around 11 Hz rotational frequency. P. Pillatsh et al. designed a $\varnothing 30$ mm package containing a rotational PEH with dimension of $19.5\text{ mm} \times 1\text{ mm} \times 0.37\text{ mm}$ for human body application [4]. The PEH provides maximum output power with a peak value of $43\ \mu\text{W}$ at 2 Hz and 20 m/s^2 rotational speed and acceleration level, respectively. Even though there are lots of research on it, the rotational speed is much higher than the wind turbine application. The rotational speed of wind turbine is around 5 rpm to 20 rpm corresponding to 0.08 Hz to 0.3 Hz. Besides, the average power is positively related to the rotational speed. Thus, the design of frequency up-conversion mechanism and the PEH device are the main challenges in this paper.

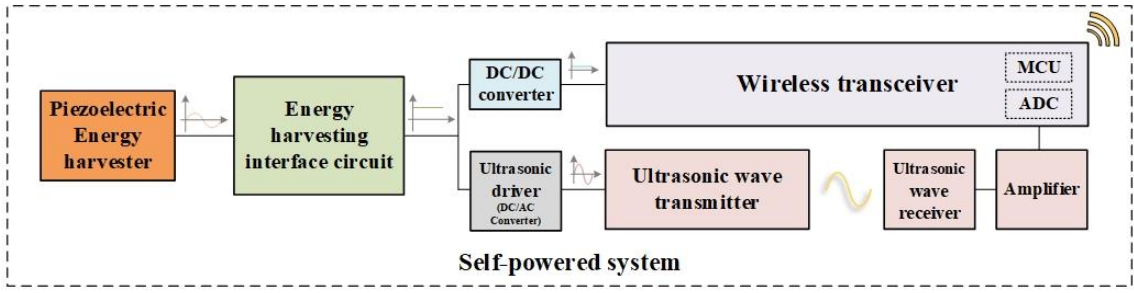


Figure 1 The proposed self-powered surface condition monitoring system

This paper is divided into three parts. The first part is the equivalent nonlinear model for rotational PEH. First part is the nonlinear model for energy harvesting system including the PEH and the nonlinear magnetic force. Then, it goes to the fabrication process of PEH and the brief power consumption of the self-powered SCMS system. The experimental setup and experimental results of PEH in different shape, with different magnet spacing and at different rotational speed will be shown in the last part.

2. MODEL AND FABRICATION PROCESS

2.1 Model

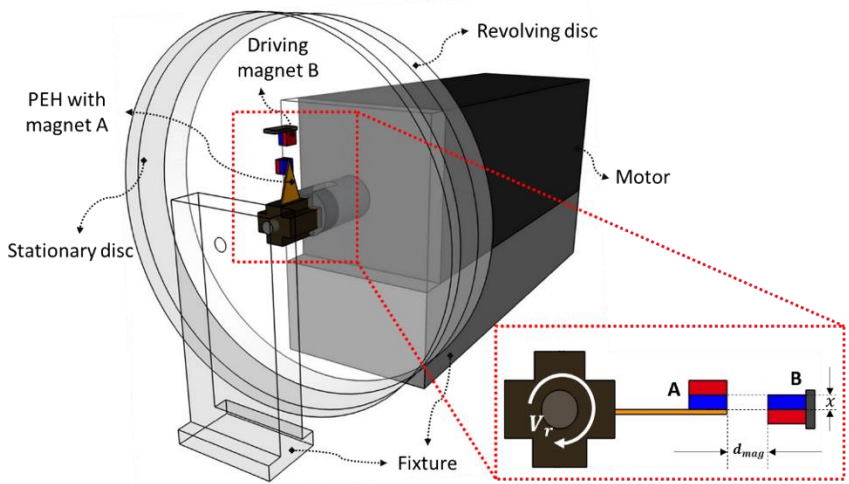


Figure 2. Schematics diagram of rotational energy harvesting system

The nonlinear model of PEH excited by magnetic plucking can be divided into two parts. One is the nonlinear mechanism of piezoelectric energy harvester and the other is the nonlinear magnetic force. Consider a unimorph PEH with a magnet A at its free end clamped on a revolving disc with varying rotational speed V_r . There is another driving magnet B is fixed

on a stationary disc as shown in Figure 2. The driving magnet B is periodically applying a repelling force on magnet A with the closest distance d_{mag} between magnet A and B. The governing equations of the nonlinear PEH can be described as following equations [5] and its equivalent model is shown as Figure :

$$m\ddot{x} + F_D + F_S = F_{mag} - F_P \quad (1)$$

$$-\theta\dot{x} + C_p\dot{V} + \frac{V}{R_L} = 0 \quad (2)$$

$$F_D = c_1\dot{x} + c_2x^2\dot{x}, F_S = k_1x + k_2x^3, F_P = \theta V \quad (3)$$

Where F_{mag} is the magnetic force from driving magnet B, m is the mass of magnet A, x is the tip displacement of the beam, \dot{x} is the velocity, \ddot{x} is the acceleration, c_1 and c_2 are linear and nonlinear damping ratio, k_1 and k_2 are the terms of linear and nonlinear stiffness, θ is the piezoelectric coupling factor, V is the voltage across the load resistance R_L , C_p is the clamped capacitance of piezoelectric.

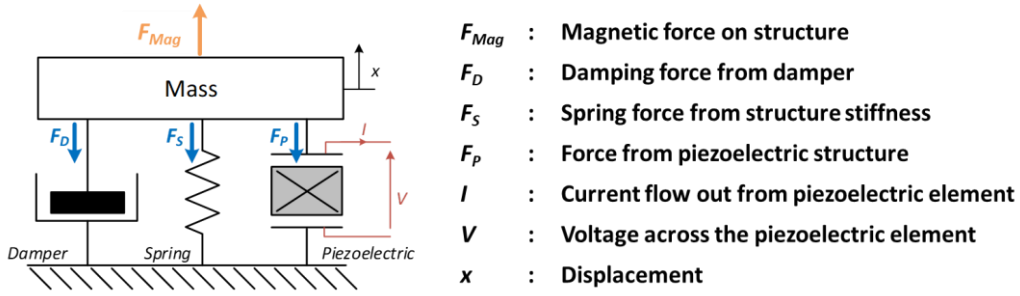


Figure 3 Equivalent model of nonlinear PEH excited by magnetic plucking

In order to calculate the magnetic force when the driving magnet B crossing to magnet A, we evaluate the magnetic force distribution while the closest distance d_{mag} is 1 mm, 2 mm and 3 mm. The magnetization of two magnets is 0.73 T. The hollow data points in Figure show the normalized magnetic force distribution from simulation. We can describe it by a two Gaussian functions of x as shown in equation (4).

$$F_{mag} = \frac{A}{B\sqrt{2\pi}} \left\{ \exp\left(-\frac{(x-w)^2}{2B^2}\right) - \exp\left(-\frac{(x+w)^2}{2B^2}\right) \right\} \quad (4)$$

where A , B and w are fitting parameters, x is the magnet spacing in out-of-plane direction as shown in Figure .

The solid lines in Figure are the curve fitting results and the values of fitting parameters A , B and w are shown in Table 1. The results indicate the peak value of magnetic force is decreasing when the d_{mag} is increasing. The value of the fitting parameter w is corresponding to the absolute x-axis value of the two peaks. With the shortening of the d_{mag} , the w value is slightly increasing. Besides, because the magnetic force in this application is periodic, x can be represented as eq. (5).

$$x = x_0 + \frac{2\pi r \cdot V_r}{60} \cdot \delta(t - T_r) \quad (5)$$

$$T_r = 60/V_r \quad (6)$$

Where x_0 is the initial position relative to the driving magnet B, V_r is the rotational speed and T_r is the rotational period.

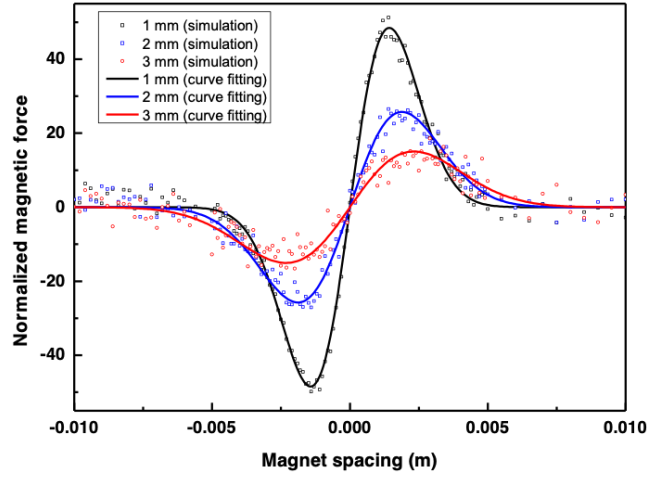


Figure 4 The normalized magnetic force with different magnet spacing

Table 1 The fitting parameters of magnetic force distribution

Magnet spacing (mm)	Fitting parameters		
	A	B	w
1	0.7453	1.3396e-4	0.00143
2	0.083	0.0012	0.00174
3	0.082	9.25565e-4	0.00224

2.2 Fabrication process

From our previous results of the PEHs under base excitation, the tapered shape of PEHs show outstanding output performance and better durability comparing to the widely used rectangular shape of PEHs [6]. In this paper, the magnetic force acts as a body load on the tip magnet which is similar to the behavior of external force under base excitation. Therefore, the tapered shape of PEHs are expected to have better output performance and durability. Figure shows the schematics diagram of the PEHs in this paper.

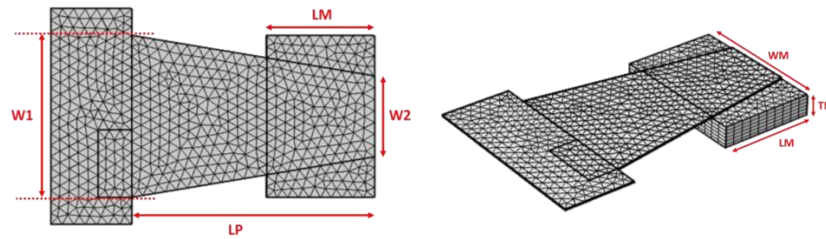


Figure 5 Schematics diagram of cantilever device

Table 2 The geometrical parameters of the devices

Symbol	Description	Value	Units
W1	Width of fixed end	6	mm
W2	Width of free end	0, 6	mm

LP	Length of beam	9	mm
LM	Length of magnet	3.8	mm
TM	Thickness of magnet	2	mm
WM	Width of magnet	3.8	mm

In this study, Lead zirconate titanate (PZT) thick film was used as the active material due to its great piezoelectric properties. The geometrical parameters of each device are shown in Table 2. The width of the free end of PEH is designed as 0 mm (tapered shape) and 6 mm (rectangular shape), respectively. All the dimensions of devices except the width of the free end are kept constant. A neodymium magnet with dimension 3.8 mm × 3.8 mm × 2 mm (length × width × thickness) is bonded on the tip of each PEH.

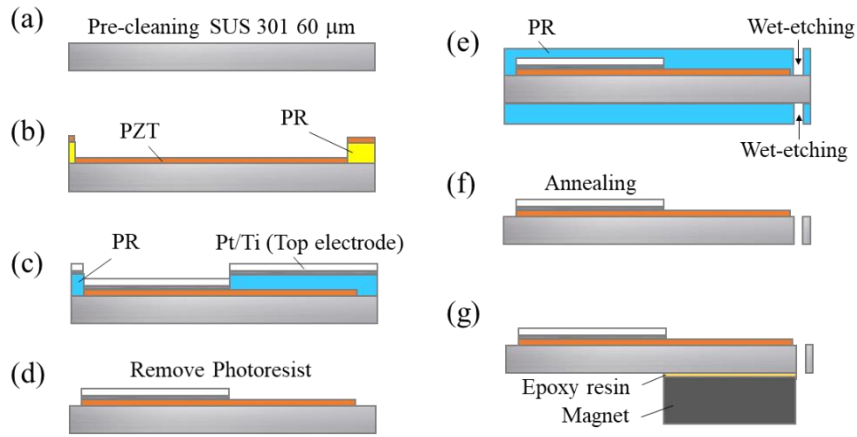


Figure 6: The fabrication process of rotational PEH

The flow chart of fabrication process is shown in Figure . First of all, the pre-cleaning process of 301 stainless steel should be done to remove the metallic oxide and organic residues on the surface. After the pre-cleaning process, the 9 μm thick PZT layer is deposited on the steel by aerosol deposition method. Around 220 nm Pt/Ti layers is then deposited on the top of PZT film as the top electrode of PEH devices. The beam shape was defined with photolithography and released with wet etching by using aqua regia solution. Finally, all the devices are annealed and the magnet is attached on the tip of each beams.

3. DAILY ENERGY CONSUMPTION OF SCMS

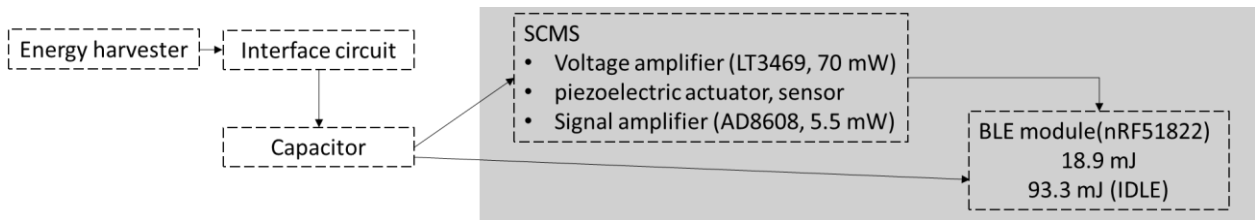


Figure 7 The self-power surface condition monitoring system

The self-powered SCMS building blocks are shown as Figure . Typically, the self-powered system is very low-duty working and therefore the energy harvesting interfacing circuit has to turn on all the time and to harvest as much power as possible into capacitor. To have a brief estimation of daily energy consumption of this system, we suppose that there is only one measurement in a day and each measurement takes one second. For the SCMS, a commercial voltage amplifier LT3469 is selected to amplify the output voltage from the capacitor to drive the ultrasonic actuator in SCMS. In order to

have an obvious sensing signal into signal processing, a low noise signal amplifier AD8608 is selected. A Bluetooth low energy module of nRF51822 is used to send the data back to the information center. The daily energy consumption is around 0.2 J.

4. EXPERIMENTAL SETUP AND RESULTS

4.1 Experimental setup

Figure 8 shows the experimental setup of rotational PEH excited by magnetic plucking. The revolving disc is fixed on the motor controlled by a laptop and a motor controller. The range of rotational speed is set from 5 rpm to 30 rpm which generally covers the typical rotational speed of wind turbines. The PEH is clamped and fixed on the revolving disc and the driving magnet B is attached on another stationary base. The output voltage and output power are measured by connecting PEH to its optimal impedance of 100 k Ω . Since the input voltage range of the data acquisition (DAQ) is from -10V to +10V, the output voltage is connected to a voltage divider before getting into DAQ.

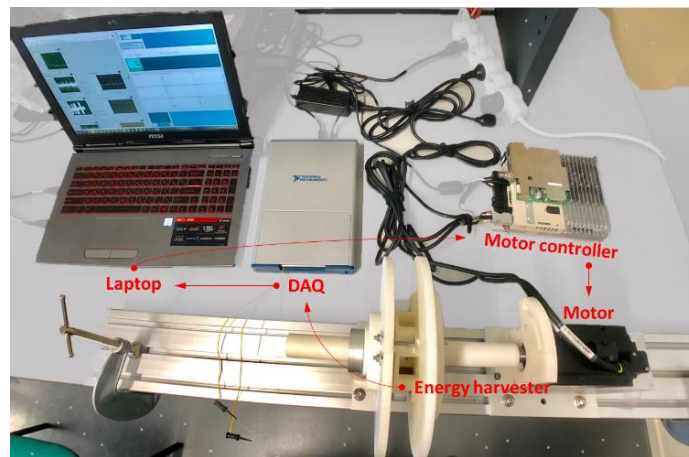


Figure 8 Experimental setup for rotational PEH

From the magnetic force distribution profile shown in Figure , the magnetic force is increasing (i.e. increasing the output performance of PEH) with decreasing magnet spacing. However, the durability of PEH becomes a very important issue especially for the wind turbine application. While considering the durability of PEHs, the magnetic force cannot be increased endlessly to destroy the piezoelectric layer. Thus, the following discussion will focus on the output performance and durability of PEH excited by different magnitude of magnetic force.

4.2 Different magnet spacing and rotational speed

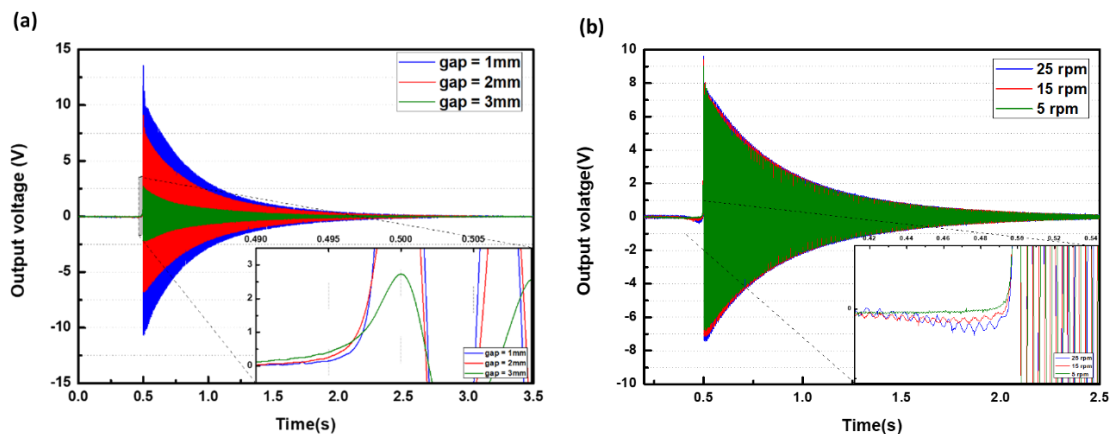


Figure 9 The output voltage of tapered shape PEH with (a) different magnet spacing and (b) different rotational speed

Figure shows the output voltage of tapered-shape PEH with different magnet spacing and rotational speed. The output voltage profile can be divided into three parts that are magnet B approaching to magnet A, magnet B crossing magnet A and the beam free-oscillating region. For the first part, the output voltage slightly decreases when the magnet B approaching and repelling magnet A. For the second part, the magnet B releases the beam in a short period and quickly crossing by magnet A. Finally, the magnet B leaves from magnet A and the PEH starts oscillating at its natural frequency without any external magnetic force. By mean of magnetic plucking, PEHs can be operated at its resonant frequency by using an off-resonant external force which is known as frequency up-conversion method.

For the rotational speed at 5 rpm, the maximum output voltage is 13.58 V, 9.10 V and 2.73 V for magnet spacing at 1 mm, 2 mm and 3 mm, respectively. The subplot in Figure also indicates the voltage profile is highly related to the magnetic force profile. Because of the narrow and sharp magnetic profile of magnet spacing at 1 mm, the output voltage not only changes dramatically in the very beginning but also achieve the highest amplitude.

Comparing to the output voltage at rotational speed from 25 rpm to 5 rpm, the maximum output is 9.60 V, 9.41 V and 9.0 V, respectively. The output voltage of PEH at higher rotational speed is slightly decreasing in the very beginning and then rapidly increasing as the driving magnet B crossing magnet A. In addition, the damping effect caused by magnetic force is more obvious in the case of low rotational speed. The damping effect will reduce the output performance during the free oscillation after the magnet B crossing to magnet A. Thus, for the comparison of the output energy from single magnetic excitation, the better performance at higher rotational speed can be expected.

4.3 Different shape of PEH beams

Secondly, we consider the output performance difference and durability by changing the shape of PEH. In order to make a fair comparison, the brand new PEHs in tapered-shape and rectangular-shape beams were used to verify the output performance. Figure shows the output voltage of PEHs with magnet spacing at 2 mm and rotational speed at 5 rpm. The maximum output voltage of PEH is -7.0 V and -5.7 V respectively in tapered shape and rectangular shape of the beam.

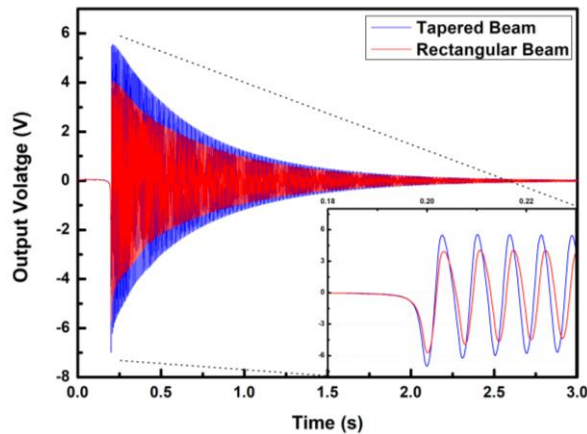


Figure 10 The output voltage of tapered-shape and rectangular-shape PEH

In order to quantify the output energy during single magnetic plucking, the output power was integrated in a single period. Besides, the durability of PEHs were tested from low speed to high speed and the magnet spacing changes from 3 mm to 1 mm as shown in Figure . Although both of PEHs show stable output energy in all parameters tests, the output energy of rectangular PEH starts decreasing as the magnet spacing of 1 mm. The cause of output energy decreasing is related to the crack of top electrode under large deformation. Additionally, the magnetic damping effect was magnified while the magnet B slowly crossing by the magnet A. The damping effect at low speed mode leads to the decreasing of energy output. For the rotational speed range from 30 rpm to 5 rpm, the output energy is decreased by around 10%.

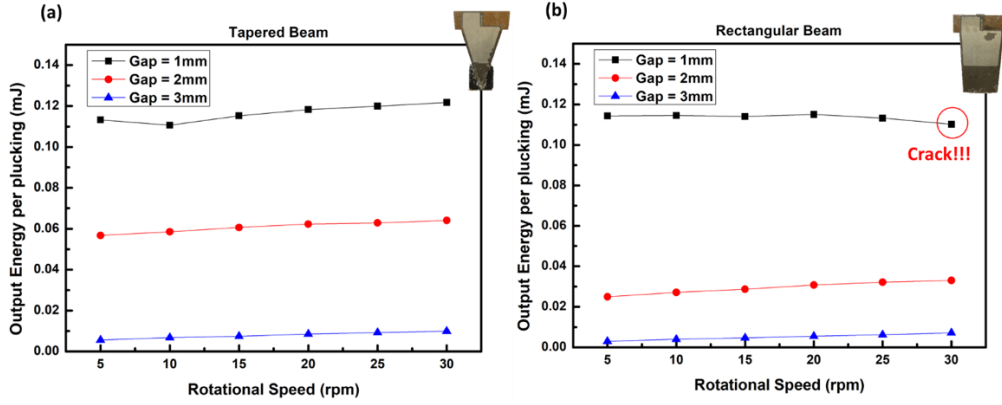


Figure 11 Output energy per magnetic plucking of (a) tapered beam and (b) rectangular beam

Due to the output voltage is substantially decreased before the next magnetic excitation even though the rotational speed is up to 30 rpm. The output energy of PEH can be calculated by equation (7).

$$E_{Daily} = E_p \cdot \int V_r(t) \cdot dt \quad (7)$$

where the E_p is the output energy per plucking shown in Figure .

Assuming that this PEH is excited at a fixed rotational speed in a day, the results are shown in Figure . For the rotational speed of 15 rpm, the daily output power of tapered PEH with magnet spacing at 3 mm to 1 mm is 160.1 mJ, 1309.0 mJ and 2489.0 mJ, respectively. Under the same condition, the output daily energy of rectangular beam is 102.2 mJ, 619.1 mJ and 2462.4 mJ respectively to the magnet spacing of 3 mm, 2 mm and 1 mm.

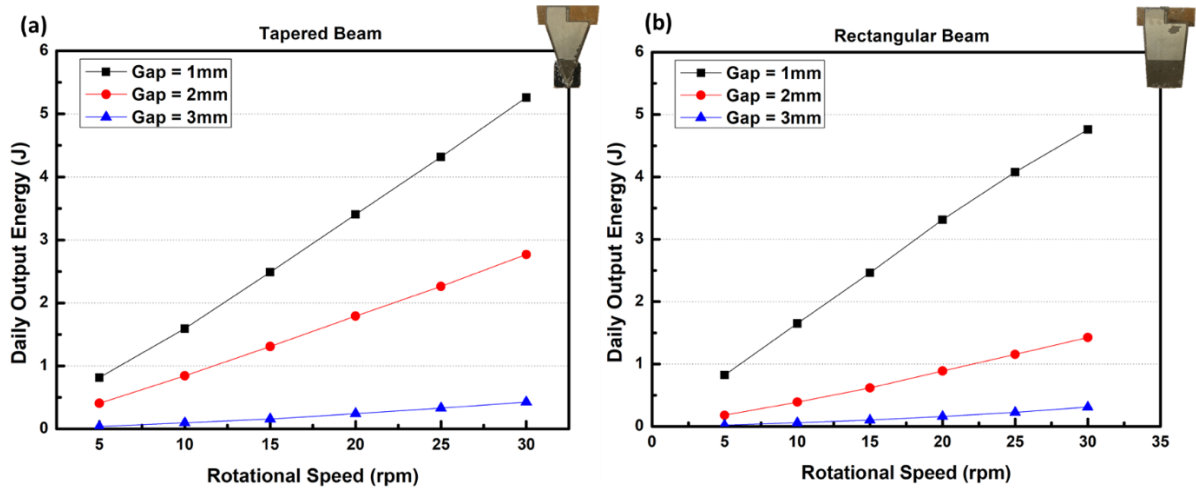


Figure 12 Daily output energy of (a) tapered beam and (b) rectangular beam

4.4 Practical rotational speed of wind turbine

In general, the wind turbine is operating at varying rotational speed of 5 rpm to 20 rpm. The practical rotational speed in 24 hours is shown in Figure . The minimum and maximum rotational speed of VESTAS V80/2000 wind turbine is controlled at 9 rpm and 17 rpm. The total output energy of PEH is calculated to be 1036.8 mJ through equation (7). The output energy is much higher than the 200 mJ of SCMS's daily energy consumption.

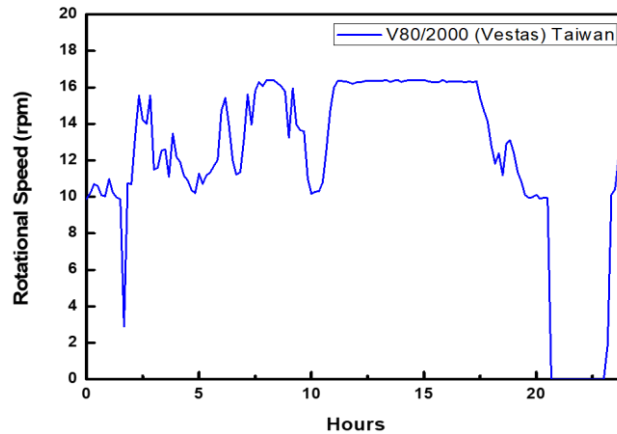


Figure 13 The rotational speed of wind turbine blade in Taiwan (Date: 2014.01.01)

5. CONCLUSIONS

In this paper, a cantilever type of PEHs with tapered beam shape are used to convert rotational energy into electrical energy to power SCMS. The PEH in meso-scale is composed of a beam with dimension of $6 \text{ mm} \times 9 \text{ mm} \times 69 \text{ }\mu\text{m}$ (width \times length \times thickness) and a tip magnet with dimension $3.8 \text{ mm} \times 3.8 \text{ mm} \times 2 \text{ mm}$ (length \times width \times thickness). The high quality PZT film in $9 \text{ }\mu\text{m}$ thickness is deposited as the active layer by aerosol deposition method. The tapered beam shape is confirmed to improve the output energy and the durability under the large deformation. A frequency up-conversion mechanism is realized by two repulsive magnets to accommodate PEH at varying rotational speed of wind turbine. For the rotational speed from 5 rpm to 30 rpm, the output voltage is increased from 9.0V to 9.6V with the magnet spacing of 2 mm. For the case of low-speed mode, the magnetic damping effect obviously reduces the output energy when the driving magnet B crossing tip magnet A. For the magnet spacing from 3 mm to 1 mm, the maximum output voltage is increased from 2.73 V to 13.58 V. In order to evaluate the daily output energy, the practical rotational speed of the wind turbine is put into consideration. The daily output energy is estimated to be 1036.8 mJ which is much higher than the 200 mJ of daily energy consumption of self-powered SCMS, leading our new device to be a very promising solution for autonomous monitoring of wind turbines.

6. ACKNOWLEDGEMENTS

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