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Analysis and Design of Roof Turbine Ventilator for Wind Energy Harvest

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***Abstract*— Harvesting energy using roof turbine ventilator and electroactive material has been investigated to verify its performance. Since electric power gained from a single piece of regular size is usually small, auxiliary device to vibrate multiple pieces of electroactive materials in order to harvest more power is required. In this paper, an attempt of using the developed nozzle wind collector associated with the popular roof turbine ventilator employed with gear mechanism to impact and vibrate a group of electroactive material to generate electricity is proposed. Number of blade and blade angle of the roof turbine ventilator are influential to the effectiveness of wind collection. Also, number of electroactive material employed on the turbine ventilator under the wind speed in environment eventually determines the efficiency of wind harvest. A simple model is derived to estimate the minimum driving force from the wind power that needs to overcome the inertia of the turbine ventilator mechanism and the electromechanical energy conversion of electroactive materials. Wind drag force is calculated by using CFD is assumed to provide such driving force. Various combinations of the blade angle, number of blade and electroactive material actuators are investigated in simulations. Optimum design concerning the environment wind resource and configuration of turbine ventilator is discussed. According to several case studies, a few of design trends is addressed for better efficiency of energy harvest. Since multiple electroactive materials are employed, circuitry design with parallel input sources is implemented to sum up the current and integrate the power.**

Key words: roof turbine ventilator, energy harvest, electroactive material

I. INTRODUCTION

Wind energy harvesting become significant in renewable resource technology. It can be categorized with Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT) [1]. In comparison with HAWT, the VAWT is unable to extract much more wind flow, but it has a sturdy construction and can capture wind flow from any direction, also generally designed for pursuing higher torque [2]. Blade shape design is influential to the performance of both VAWT and HAWT. Four blade types including the flat blade without modified blade surface, wing shape, both edges tapered to a thin line, and both edges rounded are investigated and evaluated their performance [3]. The blades construction of VAWT are usually designed with straight (untwisted) and uniform configuration; it also doesn't need yaw mechanism for a single moving part. Hence, with these merits, the VAWT is suitable for the application purpose in this study. Different from the general power generators, how to design simple and economic apparatus to harvest and produce small amount of electricity by electroactive material through wind resource are the primary goal. Roof turbine ventilator can be recognized as a type of VAWT, because it has the same shaft position, blade form and operates in the same basic manner as VAWT. Shun et. al. investigated the correlation between wind speed and revolution speed [4]. They examined the straight type and several curved types of blade of roof ventilation. The results showed that the straight type gain higher speed than the curved type. Khan et al. also investigated wind speed against to rotation speed. At diameter 400mm, the straight blade significantly outperformed the curved blade at all wind speed conditions, and especially it is more efficient at low wind speed [5]. The straight blades construction can also hold greater forces because it is sturdier.

According to the previous studies, electroactive material had already been verified its capacity for energy harvest [6,7]. Through an appropriate RC circuitry and converter design, the generated electricity could be directly used for sensor devices or save into a battery. As known that the energy generated by a single piece of electroactive material (e.g., unimorph) is very small, integrating multiple electroactive material is necessary in practice. Roof turbine ventilator with gear mechanism that attached on the bottom side is considered to achieve that purpose. The electroactive materials employed around the ventilator will be impacted and vibrated by the rotation of gear teeth. To gain electricity, a fundamental circuitry design and performance evaluation of the roof turbine ventilator structure including wind speed, blade angle, and number of blade will be investigated.

II. VERTICAL AXIS WIND TURBINE

A. Wind Force

Roof turbine as VAWT absorbs the wind energy with their individual blade will move slower than the wind velocity. The differential speed generates a drag force to drive the blades. The drag force F_w acting on one blade is calculated as [4]

$$F_w = [C_D A \rho (U_w - U_b)^2]/2 \qquad (1)$$

where A is swept area of blade; ρ is air density (about 1.225 kg/m^3 at sea level and at temperature of 15°C); U_w is wind speed; C_D is the drag coefficient (1.9 for rectangular form)

[8]; and U_b is the speed on the blade surface. It is seen that the wind velocity U_w dominates the wind force as compared to other parameters A, C_D and ρ. As expected, more driving force F_w is easily and effectively to rotate the turbine and to gain more electricity eventually. The maximum power is obtained while $U_b = U_w/3$ [3].

B. Roof Turbine Ventilator

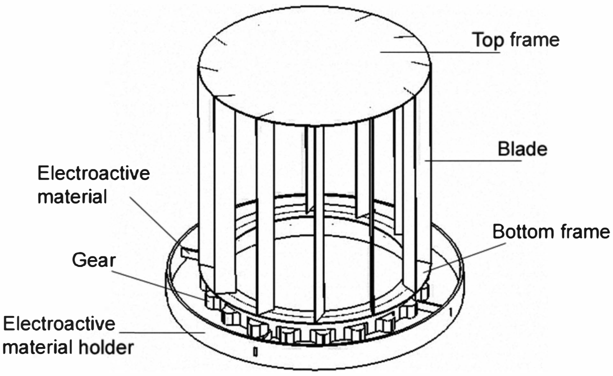


Fig. 1. Roof turbine ventilator

The roof turbine ventilator is popularly seen and used in everywhere to ventilate or circulate the air inside of the buildings. The hot air inside the room will be replaced with fresh air from outdoor. No needs of electricity for rotation and ventilation are the main advantages of using roof turbine. An attempt in this study is to develop a suitable roof turbine ventilator that can provide enough power to vibrate the electroactive material and generate electricity. In Figure 1, a roof turbine ventilator associated with gear mechanism is illustrated. The roof turbine ventilator is constructed with numbers of vertical straight blades. When the wind blows on the blades and generates enough drag forces, the roof turbine ventilator will rotate [4]. As shown in Figure 1, a gear mechanism is designed and mounted on the bottom side of the roof turbine to rotate synchronously. A series of electroactive materials are employed with equivalent distance around the circumference can be impacted by the gear teeth.

C. Minimum Requirement Force for Rotation

Regular deflection of the electroactive material resultant from impact will generate electricity. Wind power should provide enough force to overcome the inertial of roof turbine ventilator and the deflection of electroactive material. Assume friction effect is neglecting, so the inertia moment of the turbine ventilator is the only factor concerned. Torque due to the inertia in terms of force F_I can be simply expressed by

$$T = I \times \alpha = r \times F_I \tag{2}$$

where I is the moment of inertia of the turbine ventilator; α is angular acceleration; r is the radius of turbine.

Since the electroactive material employed on the structure as a cantilever beam, the force F_U required to deform an electroactive material to generate electricity can be calculated by [11]

$$F_U = \left[\frac{G_p b t_p^3}{4 l^3} \right] \delta \tag{3}$$

where G_p is young's modulus of electroactive material; b is width of electroactive material; t_p, l, δ is thickness, length, and deflection of electroactive materials respectively.

Without concerning other complicated force elements, the sum of two force items F_I and F_U are the minimum force F_{min} that required from the wind power to rotate the turbine and generate electricity. To preserve optimal efficiency of energy harvest, all electroactive materials should be impact by the gear teeth simultaneously so that the generated electricity with voltage and current would be at the same phase then can be sum up ideally [12].

Table 1 Dimension and Parameter of Turbine & Unimorph

Symbol	Description	Value	Units
Roof Turbine			
D_o	Outer diameter	250	mm
D_i	Inner diameter	200	mm
I_t	Inertia moment turbine	4.74	Kg.m^2
ρ_a	Aluminum density	2700	Kg/m^3
β	Blade angle	30-90	degree
N_b	Number of blade	12 & 18	pieces
U_W	Wind speed	3-5	m/s
ρ	air density	1.225	Kg/m^3
C_D	Drag coefficient	1.9	--
A	Swept area of blade	630.9	mm^2
A_1	Input nozzle area	78200	mm^2
A_2	Output nozzle area	15450	mm^2
t_b	Thickness of blade	0.8-1.2	mm
Electroactive Material PZT 5A			
L	Length of PZT	30	mm
B	Width of PZT	8	mm
t_p	Thickness of PZT	0.3	mm
G_p	Young's modulus	63	GPa
Δ	Deflection of electroactive material	5	mm
g_{31}	Electroactive material voltage coeff.	-13.7e-3	Vm/N
g_{33}	Electroactive material voltage coeff.	16.6e-3	Vm/N
C_{11}	Elastic stiffness constant	121	GN/m^2
C_{12}	Elastic stiffness constant	75.4	GN/m^2
C_{13}	Elastic stiffness constant	75.2	GN/m^2
Cp	Electroactive material capacitance	15.8	nF

Table 2 F_{min} for different N_U

N_U (piece)	F_{min} (N)	
	N_b= 12	N_b= 18
1	0.44	0.46
2	0.84	0.86
3	1.24	1.26
6	2.44	2.46

With the material properties and dimension listed in Table 1, the force F_I is about 0.04N and 0.06N for N_b=12 and 18 calculated by eq.(2) respectively, and F_U is about 0.4N calculated by eq.(3) for employed unimorph N_u=1, 2, 3 and 6 in this case study with 5mm vibration displacement generated in each of them. Therefore, the minimum force F_{min} is calculated for N_b=12 and 18 respectively and listed in Table 2.

III. DESIGN OF ROOF TURBINE

A. Roof Turbine Ventilator

The top view of roof turbine is illustrated in Figure 2. The straight blades are used for its better efficiency [5]. Blade angle is defined as the straight blade located with an angle with respect to the radial direction of the turbine. Since blade angle of the roof turbine influence to the swept area, it deserves comprehensive study in order to efficiently collect wind and produce enough driving force to rotate the roof turbine.

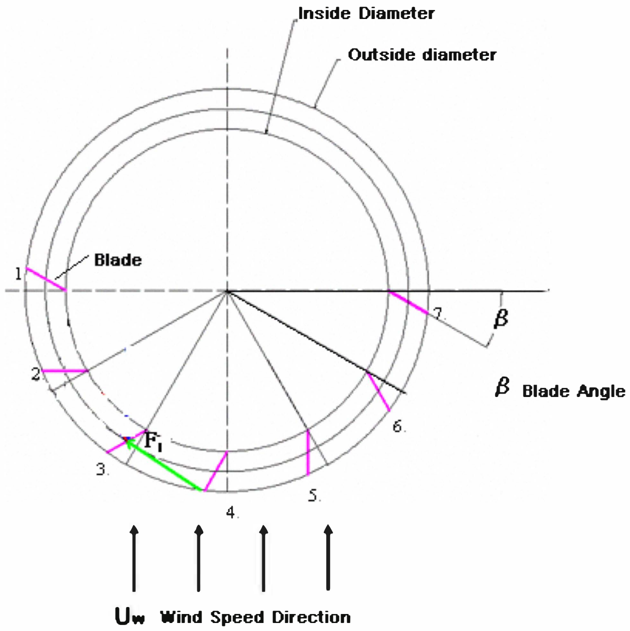


Fig. 2 Top view of roof turbine and wind flow

Besides the blade angle, number of blades employed on the roof turbine is another key parameter of how much wind can be collected. Also, number of unimorphs is another significant factor of electricity generation. Hence, the goal of this research is to find the optimum design of blade angle and number of blades as well as unimorph under various conditions of the wind speed that is enough to rotate the roof turbine and vibrate the electroactive materials so the roof turbine can produce more electricity. Diameter of the roof turbine used in this study is 250mm. Various combinations of blade angle (β =30°, 45°, 60°, and 90°) and number of blades (N_b=12,18) are chosen to examine the performance. Different number of pieces of electroactive materials (N_u=1,2,3,6) are also assigned. In this case is assumed wind flow from one direction. The wind speeds are assumed to be 3, 4 and 5m/sec to closely emulate the real environment. The drag coefficient (C_D) is assigned with 1.9 for rectangular shape of blade [8]. From the results in calculation, almost all conditions at wind speed less than 3m/s can not produce electricity, only for few conditions with large blade angle and low revolution speed can gain small electricty.

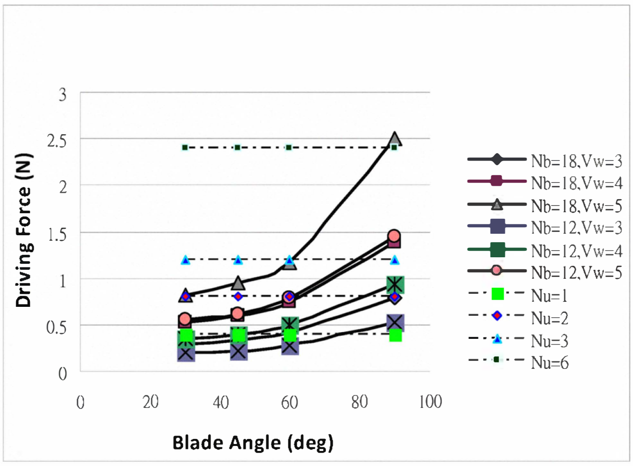


Fig. 3 Driving force F_D vs. blade angle β

As shown in Figures 3 for various number of blade (N_b=12,18), higher wind speed could generate more wind power so that larger driving force is obtained. Blade angle of 90° would generate larger driving force. For example, with N_u=3 and blade angle of 90°, number of blade N_b=12 at wind speed 5m/sec is the only condition that can rotate the turbine and N_b=18 wind speed V_W=4 and 5m/sec can rotate the turbine.

B. Roof Turbine with Wind Collector

With more pieces of electroactive materials, of course, the burden is increased and the revolution speed is reduced. But more electricity is harvested for more blades will impact the electroactive material more times in one revolution, thus more vibrated electroactive material generate electricity. To overcome higher burden result from more electroactive materials, higher wind speed is desired. As shown in Figure 4, nozzle wind collector will be attached on roof turbine ventilator to collect wind from ambient and to increase wind speed. The ratio of nozzle area is the key design parameter of a nozzle wind collector. The wind collector is designed of several equivalent sections with same shape to capture the wind from different directions. Ratio of nozzle area will be designed to increase wind velocity so it can generate higher force to propel and rotate the roof turbine ventilator faster than without wind collector. Additional nozzle in front of the roof turbine will affect F_w in eq.(1), the force then becomes

$$F_{WN} = [\frac{2}{9} C_D A \rho (U_W A_1/A_2)^2] \tag{4}$$

where A_1 is inlet nozzle area, A_2 is outlet nozzle area.

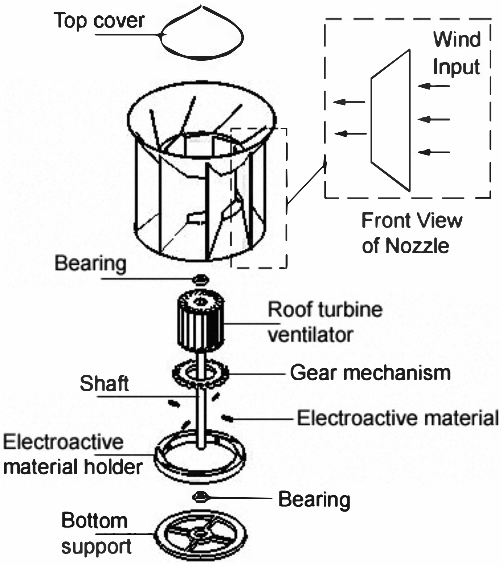


Fig. 4. Roof turbine with wind collector

IV. ELECTROACTIVE MATERIAL

A. Cantilever Structure

An electroactive material constructed with PZT 5A is used for energy harvesting. Cantilever structure is used in this study to get 3-1 mode excitation as shown in Figure 5. Force is applied to the electroactive material along z axis. Deformation of the electroactive material will generate electric charge in 3-1 mode. In Figure 5, electroactive material is under point load at the free end. The deflection of electroactive material can be calculated as [9]

$$\delta(x)=\frac{F_U\cdot x^2(3l-x)}{6G_pI} \qquad (5)$$

where δ is deflection; F_U is point load; l is length of electroactive material; x is location of the point load; G_p is elastic modulus of electroactive material, I is inertia moment ($I=bt_p^3/12$), b and t_p is the width and thickness of electroactive material respectively.

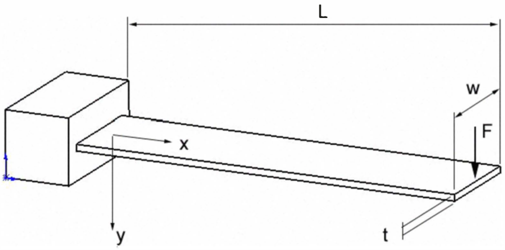


Fig. 5. Electroactive material as cantilever structure

B. Electric Response of Electroactive Material

Response of electroactive material can be calculated as [10]

$$V=\frac{3}{8}\left(\frac{t}{L}\right)^2[g_{31}(c_{11}+c_{12})+g_{33}\cdot c_{13}]\cdot\delta \qquad (6)$$

where V is electricity voltage; g_{31} and g_{33} are electroactive material voltage constant; and c_{11}, c_{12} and c_{13} are elastic stiffness constant of electroactive material.

When the deflection of electroactive material is 5mm, AC electricity is generated 2.7V from an electroactive material using eq. (6) and parameters in Table 1. For example, with the input wind speed V_W=5m/sec and blade number N_b=18, 6 units of electroactive material can be employed. To harvest the electricity from electroactive material, simple circuitry is used as shown in Figure 6. Full bridge rectifier is used as AC-DC converter. Capacitor C_f is used for smoothing voltage from converter. R_L is load resistor. Previous research suggested an optimized matching resistance between load resistance and electroactive material resistance for output power ($R_L=1/2\pi fC_p$) [6], where C_p is electroactive material capacitance and f is operational frequency. Using single piece of electroactive material, output voltage of electroactive material is measured 2.53V as shown in Figure 7 while using load resistance R_L=91kΩ.

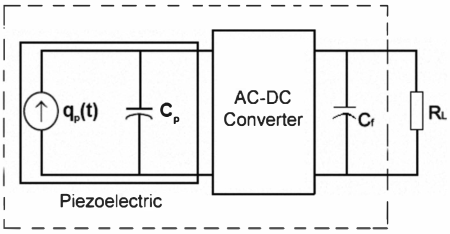
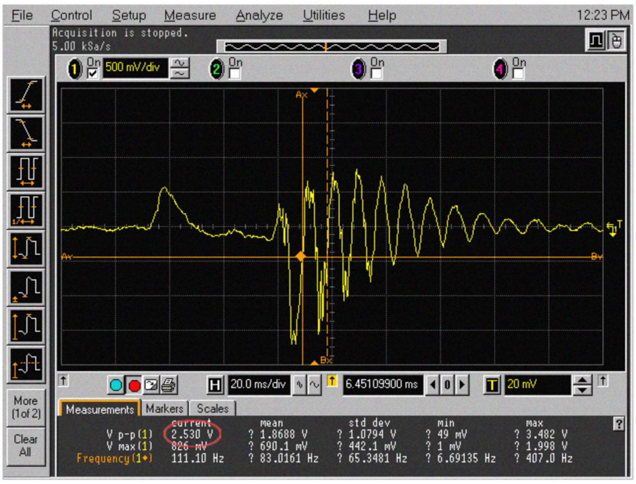


Fig. 6. Storage circuitry



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Acquisition is stopped.
5.00 kSa/s
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                current       mean          std dev       min           max
    V p-p(1)    2.530 V     ? 1.8688 V    ? 1.0794 V    ? 49 mV       ? 3.482 V
    V max(1)    826 mV      ? 690.1 mV    ? 442.1 mV    ? 1 mV        ? 1.998 V
Frequency(1•)   111.10 Hz   ? 83.0161 Hz  ? 65.3481 Hz  ? 6.69135 Hz  ? 407.0 Hz
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Fig. 7. Output voltage of electroactive material from measurement

Since output current 5.41μA and power 13.68μW of a single electroactive material is small, multiple electroactive materials are used. Assuming each electroactive material is impacted and vibrated to generate almost the same magnitude of voltage and current with the same phase, total current is the sum of each on by using a parallel circuit design structure. In case employed 6 pieces electroactive materials, the current is measured 16.41μA and power

45.23μW. Detailed design of the parallel circuit is presented in [11]. In analytical calculation using equation *P=VxI*, electrical power energy is 16.2μW and 48.6μW for a single and multiple (6 pieces) electroactive materials. In comparison the analytical and experimental results, both are quite near.

V. CONCLUSIONS

More wind speed provides more driving force to rotate the turbine. In addition, number of blades and blade angle are also important factors. According to the current modeling and analysis, large blade angle is necessary. Blade number design is dependent on the wind speed and the inertial of the turbine. Hence optimum design should concern the environmental resource and the feature of the roof turbine ventilator. With nozzle wind collector, wind speed is considerably increased so that increasing force to impact the electroactive material and to rotate the ventilator faster. Because of using roof turbine ventilator, it is likely to sum up the power gained from each electroactive material with appropriate arrangement of the gear teeth and electroactive materials. Regarding the parallel circuitry design to save the energy and its performance, it will be presented in other article. Analytical estimation and experimental measurement gives close approximation for voltage, current and power.

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