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Piezoelectric Wind Energy Harvesting by Vortex Induced Vibration of a Flexible Cylindrical Cantilever Shell

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ABSTRACT

This paper proposed a piezoelectric wind energy harvesting method by vortex induced vibration (VIV) of axial bending vibrations of a flexible cylindrical cantilever shell. In the past decade, wind energy harvesting method by piezoelectric devices had been widely studied for alternative approach to the conventional wind turbines toward supplying power sources for ultra-low power electric devices which will be used for remote monitoring of large-scale structures. However, most of them were based on the combination of a rigid bluff body (BB) cylinder and a cantilever beam which contains piezoelectric element, and had problems of low power generation and durability against repeated loading. In the authors' previous reports, a new Piezoelectric Cylindrical Shell Wind Energy Harvesting Flag (PCSWEHF) had been proposed as a flexible and durable power generation structure that utilizes VIV and power generation performance by circumferential bending motion of side-supported shell harvester was experimentally verified [5,6]. In this study, we experimentally investigated the cantilever-type flexible structure based on the PCSWEHF by using prototypes with different parameters: the cross-sectional area of the cylindrical shell is constant, and the outer and inner radii of the shell are varied.

Keywords: wind energy, energy harvesting, piezoelectric film, cylindrical shell

1. INTRODUCTION

Piezoelectric wind energy harvester (PWEH), a wind power micro-generation device that uses piezoelectric elements to generate small amounts of power on the order of microwatts, has been widely studied over the past decade as an alternative to conventional wind turbines for powering ultra-low-power electrical devices used for remote monitoring of large-scale structures [1,2,3,4].

Deivasigamani et al. added a blunt object, or bluff body (BB), to the cantilever to disrupt the airflow in order to obtain a high power output. However, fatigue fracture occurred due to stress concentration at the joint of the cantilever and BB, and durability remained an issue [1]. Vatansever et al. reported an 18 mm wide, 156 mm long strip of PWEH in the direction of the flow, but the amount of power generated was low even in a high wind speed range of 10 m/s [2]. Yuennan et al. reported high power generation with a cantilever structure with a Y-shaped fin added to the back end of a 12 mm wide and 30 mm long cantilever. However, the power generation speed was 14 m/s, and there was a problem with the power generation speed range [3]. Thus, in the structures reported in the previous studies, having high durability and adapting to power generation at low wind speeds are these important issues for PWEH.

In the previous paper, the authors proposed a Piezoelectric Cylindrical Shell Wind Energy Harvesting Flag (PCSWEHF), which consists of a flexible and thin cylinder with piezoelectric elements attached to it [5,6]. In this a flag structure, the cylindrical shell plays the roles of both the vibrating structure and the BB for vortex excitation, thus proposed PCSWEHF is a compact, flexible

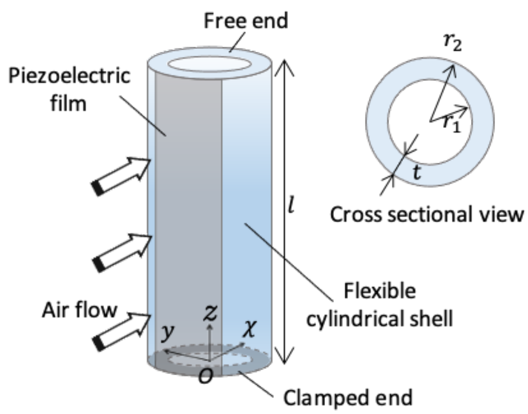

Fig. 1. Models of piezoelectric cantilever cylindrical shell wind energy harvesting flag

and durable flag structure without any joints. The power generation method using the circumferential (ring mode) bending vibration of the cylindrical shell of the PCSWEHF was investigated. However, it was necessary to increase the radius of the cylindrical shell to generate power at low wind speeds using the circumferential bending vibration of the cylindrical shell, and the larger the radius, the larger the space required for installing this cylindrical shell energy harvester in the host structure.

In order to utilize the PCSWEHF in a limited installing space, taking advantages of the cylindrical shell having a length in the axial direction the size of which will be able to be designed freely, a method of power generation using axial (beam mode) bending vibration must be considered.

Furthermore, the wind speed range in which cantilever bending mode can generate high power is expected to be in a lower range than that of the conventional method using the circumferential bending mode, making it possible to design the wind speed range in which VIV resonance is expected to be more low wind speed. Therefore, developing cylindrical cantilever shell wind energy harvester for low wind speed range must become a novel method to solve the issue of realizing compact and low wind speed oriented high performance energy harvester.

To design suitable flexible cylindrical cantilever shell for bending vibration energy harvester, it is significant that the virtual spring constant of the shell against shear force applied near the tip become small value. Here, a flexible structure means that the structure has low rigidity against flow induced outer force.

In this study, the flexible and durable PCSWEHF is installed perpendicular to the wind direction and the bottom of the shell is clamped as a cantilever-type flexible structure. The relationship between the wind speed that excites VIV of the cylindrical cantilever shell and shell size is theoretically investigated, and the power generation characteristics of a thin and light weight cylindrical cantilever shell made of low rigidity material were experimentally investigated. We theoretically and experimentally investigate by using prototypes with different parameters: the cross-sectional area of the cylindrical shell is constant, and the outer and inner radii as well as the length of the shell are varied.

2. DERIVATION OF THE VORTEX INDUCED RESONANCE FREQUENCY OF A CYLINDRICAL CANTILEVER SHELL

2.1 Models and coordinate system of piezoelectric cylindrical shell wind energy harvester

Piezoelectric cylindrical cantilever shell wind energy harvesting model and the coordinate system is defined as shown in Fig. 1. A cylindrical cantilever shell of length l, inner radius r_1, outer radius r_2 and thickness t was set vertically which was perpendicular to the wind direction, and the bottom of the shell was clamped.

A Cartesian coordinate system $O-xyz$ was defined with the origin O located at the center of the clamped end cross section and with the z axis coincide with the axis of symmetry of the cylindrical shell. The piezoelectric film (PVDF) was bonded on the surface of the shell, here 1/4 of the outer surface area of the cylindrical shell in the circumferential direction is covered with the piezoelectric film. It was assumed that the deformation of the ring model is uniform in the xy plane. The air flow i.e. opposite direction of the wind direction, was set to the x coordinate, and the y coordinate was perpendicular to the wind direction. When air flows from $-x$ direction, vortex induced vibration occurs with vibrational modes of cylindrical shells.

2.2 Derivation of the natural frequency of a cantilevered cylindrical shell

From the theory of the bending vibration of the beam with arbitrary cross section, natural frequency f_n Hz of the cylindrical cantilever shell was expressed as follows:

$$f_n = \frac{1}{2\pi}\left(\frac{\lambda_i}{l}\right)^2 \sqrt{\frac{EI}{\rho A}} \quad (1)$$

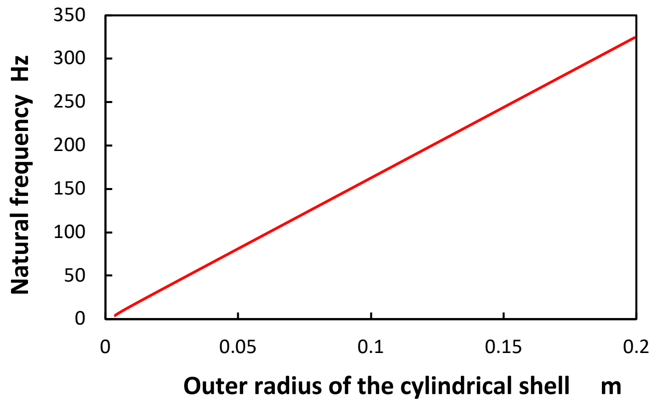

Fig. 2. Relationship between outer radius of the cylindrical shell and natural frequency ($S = 37.6$ mm^2, $E = 2.3$ GPa, $\rho = 1.2 \times 10^3$ kg/m^3)

Here, λ_i is the root of the characteristic equation of the vibration of the beam, E and ρ are the Young's modulus and density of the shell, respectively. A and I are cross section and the area moment of inertia of the cross-section of the cantilever cylindrical shell and expressed as follows, respectively:

$$A = \pi({r_2}^2 - {r_1}^2) \tag{2}$$

$$I = \frac{\pi({r_2}^4 - {r_1}^4)}{4} \tag{3}$$

Substituting Equations (2) and (3) into Equation (1) yields:

$$f_n = \frac{1}{2\pi}\left(\frac{\lambda_i}{l}\right)^2 \sqrt{\frac{E({r_2}^2 + {r_1}^2)}{4\rho}} \tag{4}$$

In this paper, to investigate the effect of the shape of the cross section on the generation characteristics of the PCSWEHF, the cross section of cylindrical cantilever shell, A, was set to constant, say S m^2. Then, the relationship between outer and inner radius of the cylindrical shell is:

$$S = \pi({r_2}^2 - {r_1}^2) \tag{5}$$

From Equation (5), we can eliminate r_1 in Equation (4) and,

$$f_n = \frac{1}{2\pi}\left(\frac{\lambda_i}{l}\right)^2 \sqrt{\frac{E\left(2{r_2}^2 - \frac{S}{\pi}\right)}{4\rho}} \tag{6}$$

When the outer radius is large enough as $r_2 \gg \sqrt{S/(2\pi)}$, Equation (6) can be approximately as:

$$f_n \simeq \frac{1}{2\pi}\left(\frac{\lambda_i}{l}\right)^2 \sqrt{\frac{E}{2\rho}} r_2 \tag{7}$$

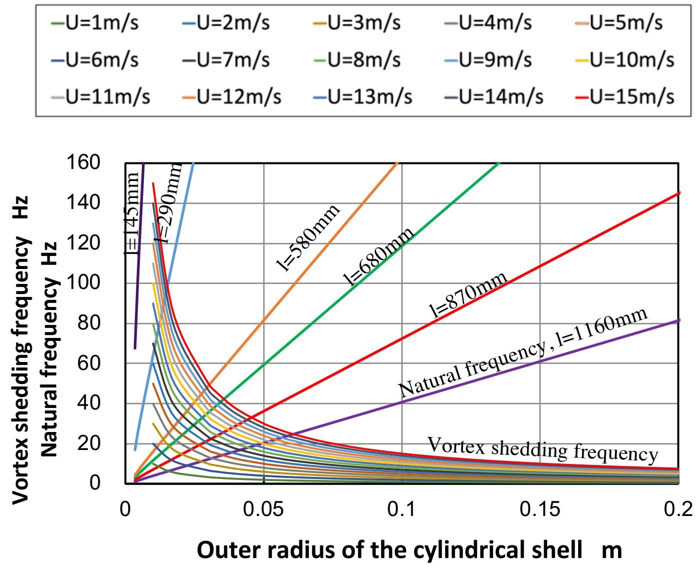

Fig. 3. Relationship between outer radius of the cylindrical shell and natural frequency or vortex shedding frequency

Comparing Equations (6) and (7), it is shown that the natural frequency of the cylindrical cantilever beam approach asymptotically to be the relationship which is proportional to the outer radius of the shell as this radius of the shell is increased.

A typical example of the relationship between radius of the cylindrical shell and natural frequency using Equation (6) was plotted in Fig.2. Here, the constant cross section area $S = 37.6$ mm^2, and using the values of $E = 2.3$ GPa and $\rho = 1.2 \times 10^3$ kg/m^3. The characteristic root is $\lambda_1 = 1.875$ because first bending mode is considered here.

2.3 Derivation of the vortex shedding frequency

The well-known vortex shedding frequency f_v Hz of the Karman vortex generated in the wake of a cylinder placed in a uniform flow is obtained by the following equation [7].

$$f_v = St\frac{U}{2r_s} \tag{8}$$

Here, U represent the flow velocity, and St represents the Strouhal number. Considering the air flow around a cylinder, the Reynolds number Re can be obtained by the following equation when the radius of the cylinder is denoted by r_s, and the kinematic viscosity is expressed in terms of υ.

$$Re = \frac{2Ur_s}{\upsilon} \quad (9)$$

In this study, the diameter of the cylindrical shell type wind turbine flag using piezoelectric material is in the order of d =0.1m, and if the kinematic viscosity coefficient of air is υ =1.5 × 10^{-6}m^2/s, the Reynolds number is around Re = 4 × 10^4 when U =6 m/s. This puts it within the range of 300 $\leq$ Re $\leq$ 3 × 10^5. So, the Strouhal number here can be put as St =0.2.

2.4 *Designing VIV resonance of the beam bending mode of the cantilever shells*

Fig.3. shows the relationship between outer radius of the cylindrical shell and natural frequency or vortex shedding frequency. Using equation (8), the vortex shedding frequency versus the outer radius of the shell was plotted in the range of wind speed from 1 m/s to 15 m/s by 1 m/s step. In addition, using equation (6), the natural frequency versus the outer radius of the shell was plotted for the cases in which the length of the cantilever was l=145mm, 290mm, 580mm, 680mm, 870mm and 1170mm, respectively. These intersections of natural frequency curves and vortex shedding frequency curves indicate the parameters of the cylindrical shell that excite the vortex induced resonance vibrations at the corresponding wind speeds. Considering these intersections from Fig.3, it was found that to utilize cantilever bending modes especially against low wind speed area for energy harvesting, there would be upper limits of the radius as well as lower limits of the thickness of the cylindrical cantilever shell. Based on this Fig.3, we could start to design and manufacture flexible cantilever shells for the energy harvesting experiment shown in chapter 3.

3. EXPERIMENTS

3.1 *Experimental equipment*

In this section, we present an experimental investigation based on the piezoelectric cylindrical cantilever shell wind energy harvesting model shown in the previous section. Fig. 4. shows an overview of the wind tunnel apparatus used in this study. In order to evaluate the power generation performance of the wind tunnel, experiments were conducted using a closed-circuit type wind tunnel. A sirocco fan was used as a wind source to generate a constant wind speed within the measurement space. In addition, a circular pipe with an inner diameter of approximately 200 mm was installed between the backflow measurement space and the

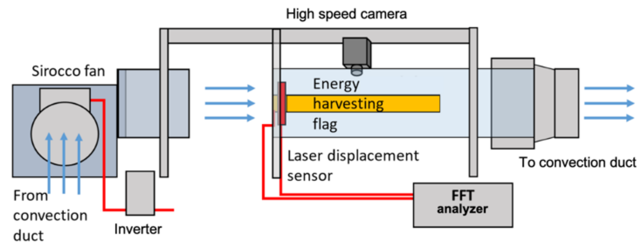

Fig. 4. Schematic diagram of experimental device

sirocco fan, and the air circulating through these pipes was made into a closed-circuit type wind tunnel to create a constant wind speed. In this way, an experimental space of about 700 mm can be obtained along the wind direction. The wind energy is applied to a generator flag located in the measurement section, and when dynamic stress is applied to the piezoelectric material, electric charge is generated by piezoelectric material due to the direct piezoelectric effect.

3.2 *Configuration of cylindrical shell type wind power generation flag using piezoelectric film*

The piezoelectric cylindrical shell wind energy harvesting flag in this experiment consists of a cylindrical plastic film and a piezoelectric material bonded on the surface of the plastic film.

First, as a preliminary experiment, a cylindrical shell made of polycarbonate with an axial length of 290 mm, an outer radius of 15 mm, and a thickness of 0.04 mm was used. The piezoelectric film (PVDF) has an axial length of 290 mm, a width of 23.5 mm and a thickness of 40 micron, and 1/4 of the circumferential outer surface area of the cylindrical shell is covered with the piezoelectric material.

The results of the power generation experiment of the cylindrical cantilever shell of this size were shown in Fig. 5. As the wind speed increases, the amount of power generation gradually increases, however, the amount of power generation obtained at any wind speed was extremely low.

Therefore, it was necessary to create a cantilever cylindrical shell that can excite VIV at more realistic wind speeds of no more than 10 m/s, referring to Fig. 3. Fig. 3. shows that a cylindrical shell with an axial length of 680 mm, an outer radius of 30 mm, and a thickness of 0.2 mm can excite VIV at a wind speed of around 10 m/s.

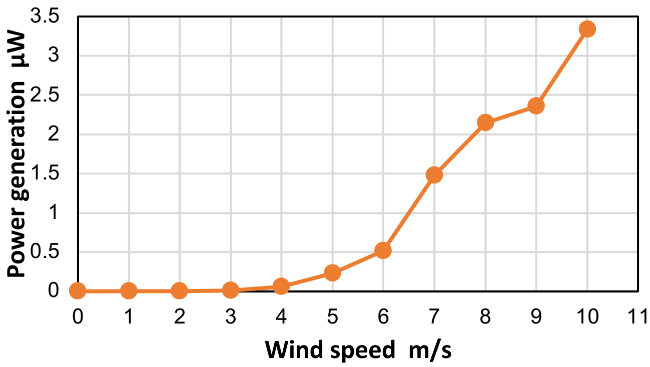

Fig. 5. Relationship between wind speed and power generation (r_2=15mm, t=0.04mm, l=290mm)

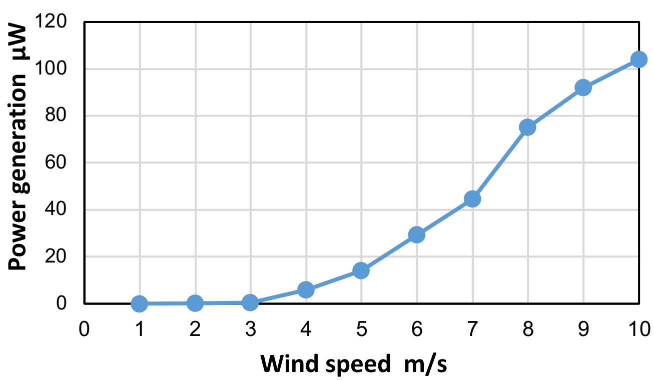

Fig. 6. Relationship between wind speed and power generation (r_2=30mm, t=0.2mm, l=680mm, circumferential bending mode free)

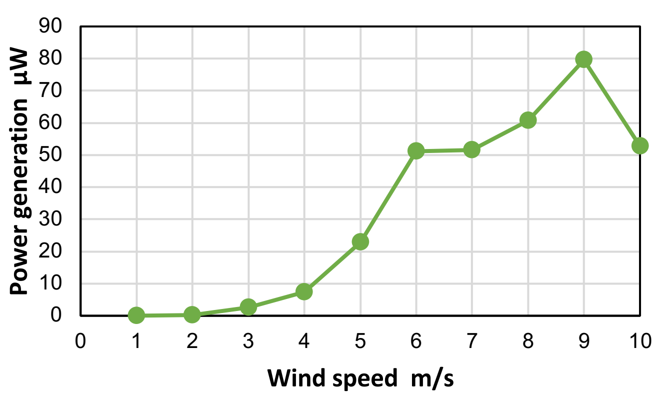

Fig. 7. Relationship between wind speed and power generation (r_2=30mm, t=0.2mm, l=680mm, circumferential bending mode restricted)

Therefore, this size of cylindrical shell was used as a second prototype for this experiment.

3.3 Experimental method and evaluation method of power generation

A cylindrical cantilever shell wind power generation flag was installed in a simple wind tunnel, and wind energy in the wind speed range of 1-10 m/s was applied. The rotation speed of the sirocco fan was controlled in high precision by an inverter controller, and the output voltages of the piezoelectric film at wind speed of 1-10 m/s were measured. Here, the output voltage of a resistor with a resistance value of R ohm connected in parallel to the piezoelectric element was measured through a recorder, and the measured data was further analyzed by waveform observation software. To evaluate the amount of power generation, the rms value of the output voltage, X_{rms} V, was calculated by taking the average of several samples.

3.4 Results and discussions

The results of a power generation experiment are shown in Fig. 6. and Fig. 7. Here, these figures are expressed in terms of wind speed on the horizontal axis and power generation on the vertical axis. From Fig.6, it can be seen that in the case of the cantilever cylindrical shell with an axial length of 680 mm, outer radius of 30 mm, and thickness of 0.2 mm a sharp increase in power generation was observed after a wind speed of 6 m/s, with a maximum power generation of about 100 μW at a wind speed of 10 m/s. Fig. 7. shows the results when the circumferential bending mode is restricted by attaching a thin light weight circular ring radius of which was equivalent to that of the cantilever shell to the tip of the cylindrical cantilever shell. The amount of power generation was lower than that without the circular ring at the tip of the cantilever shell. The reason for this lower average power generation was because the cylindrical cantilever shell utilizes only one of the axial and circumferential bending modes during power generation. However, power generation with ring was larger than that without ring at the wind speed U=6.0m/s, due to the VIV of pure first bending mode of the cantilever beam, as the axial bending motion was not affected by the circumferential bending motion.

Toward the future, we are currently discussing the relationship between more precise vibration modes of the cylindrical cantilever shell and generation characteristics of these PCSWEHFs.

4. CONCLUSION

This paper proposed a piezoelectric wind energy harvesting method by vortex induced vibration (VIV) of axial bending vibrations of a flexible cylindrical cantilever shell. Taking advantages of the cylindrical shell having a length in the axial direction the size of which will be able to be designed freely, a method of power generation using axial bending vibration was considered in which the VIV resonance is excited at lower wind speeds. By introducing vibration theory of the flexible beam and considering under the constraints that the cross-sectional area of the cantilever shell was constant, theoretical prediction showed that to utilize cantilever bending modes for energy harvesting, there would be an upper limit of the radius of the cylindrical cantilever shell. The design method to create a flexible cylindrical cantilever shell utilizes VIV at low wind speed was also shown.

We conducted power generation experiments using a cylindrical cantilever polycarbonate shell with an axial length of 680 mm, an outer radius of 30 mm and a thickness of 0.2 mm on the surface of which a piezoelectric film was bonded. The results show the validity of the theoretically obtained values. By using a cylindrical cantilever shell with an even longer axial length than this prototype, power generation using the axial bending mode at lower wind speeds will be expected.

Further discussion will be needed to clarify the relationship between the vibration modes of the current cylindrical cantilever shell and generation characteristics of the proposed energy harvester based on the PCSWEHF concept.

REFERENCE

[1] Deivasigamani A, McCarthy J, John S, Watkins S, Trivailo P, Coman F. Piezoelectric energy harvesting from wind using coupled bending-torsional vibrations. Modern Applied Science 2014;8(4):p.106-126.

[2] Vatansever D, Hadimani R, Shah T, Siores E. An investigation of energy harvesting from renewable sources with PVDF and PZT. Smart Materials and Structures 2011;20(5).

[3] Li S, Yuan J, Lipson H. Ambient wind energy harvesting cross-flow fluttering. Journal of Applied Physics 2011;109(7).

[4] Robbins P, Marusic I, Morris D, Novak O. Wind-generated electrical energy using flexible piezoelectric materials. ASME2006 2006;12:IMECE2006-14050.

[5] Chisuzu O, Tsutomu N. Study on structural design and power generation characteristics of the wind energy harvesting flag using piezoelectric films. SPIE Smart Structures + Nondestructive Evaluation 2021 2021;11588.

[6] Chisuzu O, Tsutomu N. Effect of supporting boundary conditions on the generation characteristics of the piezoelectric cylindrical shell wind energy harvesting flag. The ASME 2021 Conference on Smart Materials, Adaptive Structures and Intelligent Systems 2021;68408.

[7] Gabbai R, Benaroya H. An overview of modeling and experiments of vortex-induced vibration of circular cylinders. Journal of Sound and Vibration 2005;282:p.576-616