Flexible Piezoelectric Sheet for Wind Energy Harvesting

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***Abstract*-Energy harvesting techniques using piezoelectric materials have been rapidly developed in the world. In our previous work, one kind of kinetic energy harvester using a piezoelectric material was proposed and developed; the harvester was called Flexible Piezoelectric Device (FPED). The FPED was applied to wave and current energy, wind energy and vibration energy. In this study, improving the FPED, a new type of wind energy harvester was proposed and developed to generate electric power from broad band of wind conditions, especially low wind and breeze. The energy harvester consists of a piezoelectric material and a thin soft material, which is Flexible Piezoelectric Sheet (FPS) for wind energy harvesting. The theoretical approach was provided using a classical modal analysis technique. The electric performance of the FPS in several wind conditions was revealed and some important design parameters of the FPS were shown based on experimental results.**

Keywords- Wind Energy; Energy Harvesting; Piezoelectric Material; Fluid-Structural Interaction

I. INTRODUCTION

Wind energy can be produced anywhere in the world. Wind resource and wind energy potential in a focusing area can be accurately estimated by some assessment programs, e.g. NREL. Several kinds of wind power generators as a wind turbine have been developed and installed in many big commercial projects. In recent years, offshore wind energy is attracting to harvest a higher wind speed above sea and then global wind-generation markets are growing more and more. It is needed to expand the use of wind energy in the world. However, wind power has some disadvantages such as the impossible prediction for wind environment, suitable areas for wind farm near the coast, and bad influence on topography of a mountain.

In recent years, energy-harvesting techniques [1-3] using piezoelectric materials have been rapidly developed. Small- or micro-scale energy harvesters for wind have been intensively developed [4-10] to harvest low frequency and broad bandwidth of wind energy. The harvesters have several features such as small volume, effectiveness for generating electric power and wireless. One of the key purposes of developing a wind energy harvester with a piezoelectric material is to progress electric performance, power density and cost effectiveness comparing with a current wind turbine, especially in low wind or breeze environments.

Under this background, in our previous work [11-14], one kind of kinetic energy harvester was proposed and developed; the harvester is called flexible piezoelectric device, FPED. The FPED can be laminated by a piezoelectric material, e.g. Polyvinylidene Fluoride (PVDF), and an elastic material such as rubber or silicone. The FPED was applied to wave and current energy, wind energy and vibration energy and it was also demonstrated that it is possible to harvest some ambient energies and to generate electric power. However, the FPED is considerably large in comparison with air density of wind filed. The FPED should be improved in terms of weight, material and structure to decrease the critical wind (cut-in speed) in low wind environments for practical use as a wind energy harvester.

In this study, improving the FPED, a new type of wind energy harvester was proposed and developed to generate electric power from broad band of wind conditions, especially low wind. The energy harvester consists of a piezoelectric material and a thin soft material as substrate structure, which is Flexible Piezoelectric Sheet (FPS), for wind energy harvesting. To optimize basic structure and size of the FPS, theoretical approach was provided using a classical modal analysis technique. The electric performance of the FPS in several wind conditions was revealed and some important design parameters of the FPS were shown based on experimental results.

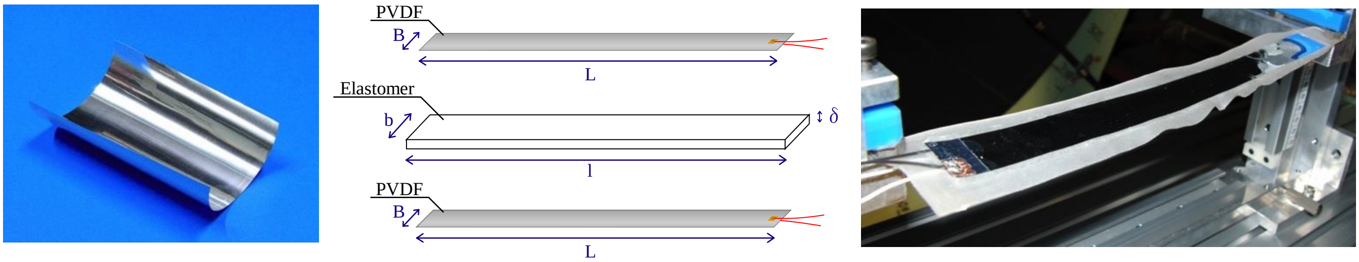
II. FLEXIBLE PIEZOELECTRIC SHEET

In our previous work, we have developed one kind of kinetic energy harvesters, Flexible Piezoelectric Device (FPED). In this section, the basic structure, electric power principle and several features of the FPED are firstly mentioned and then the Flexible Piezoelectric Sheet (FPS) is introduced.

A. Basic Structure and Key Parameters for Electric Power

The FPED is one kind of energy harvesters for natural ambient energy such as wind, wave, current and vibration. In our previous work, the Single-Core Type having one Polyvinylidene Fluoride (PVDF) and the Quad-Core Type having four PVDFs were fabricated. The Multi-Core Type was also developed to increase electric power. However, the multi-core type should be necessary for keeping elasticity of an elastic material in the FPED even when hardness of the FPED could be increased by laminate numbers.

In this study, improving the FPED, a wind energy harvester, Flexible Piezoelectric Sheet (FPS) was proposed and developed. The FPS (l: length, b: width, δ: thickness) consists of a piezoelectric-film and a thin elastic material and it has a laminated structure with strong bonding as shown in Fig. 1. This illustration is a typical structure having three layers with two piezoelectric-films, which means a bimorph type. The substrate of the FPS located between piezoelectric-films should be light and thin to reduce weight and to cause large deformation and vibration caused by strongly fluid structure interaction due to broad band of wind conditions including low wind. Therefore, elastomers such as thin rubber, thin silicone and fibre can be employed as the substrate. The PVDF (L: length, B : width, D: thickness, 40～110 μ m) is also used as a piezoelectric film and they are pasted and covered by OPP tape. The previous work clarified that the key parameters for electric power can be influenced by distance between PVDFs, stiffness of FPED, aspect ratio of FPED and a bluff body attached on FPED. The electric power generated by the FPS would be also dependent on these key parameters.

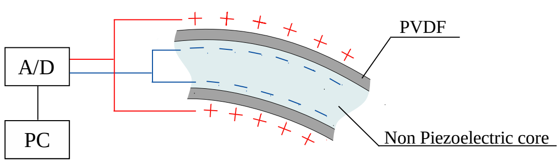


(a) PVDF (b) Basic structure (c) FPS supported by a rectangular aluminium frame

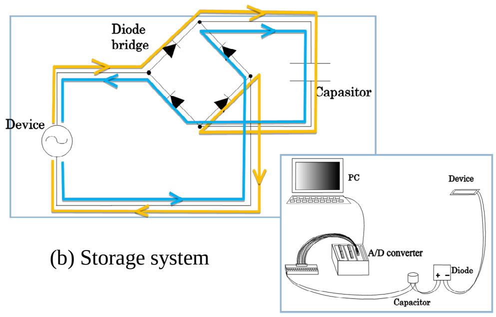
Fig.1 Flexible Piezoelectric Sheet, FPS

B. Electric Principle and Features

Fig. 2 shows the electric principle of the FPS. When the FPS is forced by wind energy, electric field is polarized and then electric current is generated from deformation of the FPS such as bending, shear stress, compression and tension. The electric power is proportional to strain rate of the FPS. Therefore the electrical efficiency is highly dependent on not static load but dynamic one. Namely, the FPS could be suitable for energy harvesting from not only an unsteady wind force but also wave and vibration force. The FPS also has main features of light, easy jointing and adaptive customizing for geometry. The previous work has proposed and developed not only oblong card type but also panel type, roll type, compressed/Tension type. These types have been already applied to harvest ocean renewable energy, wind energy and vibration energy and it was cleared that they could be useful devices for harvesting ambient energy. Using the FPS, this paper focus on electric performance under broad band of wind speed.



(a) Electric field in FPS excited by external force



(b) Storage system

Fig. 2 Electric principle and storage system

III. THEORETICAL MODELLING OF ELECTRIC POWER OF FPS

A. Theory

To predict electric performance of FPS, a theoretical model was used in this study. The model is based on the linear energy harvester model proposed by Erturk and Inman [15-16], who developed the model for a bimorph energy harvester. The extended model [17] was employed in this study.

Considering the damped equation of motion for a simple beam with a piezoelectric material as shown in Fig.3, the modal damping equation can be derived using classical modal analysis techniques [18] as below:

$$\ddot{\eta}_q(t) + 2\gamma_q\omega_q\dot{\eta}_q(t) + \omega_q^2\eta_q(t) + \varepsilon V(t)\left[W_q'(x_1 - x_2) - W_q'(x_1)\right] = \ddot{\omega}_b(t)\int_0^L m(x)W_q(x)dx \tag{1}$$

where q is the mode number, $\ddot{\eta}$ is the second derivative of the deflection with respect to time t, γ is the damping ratio, ω_q is the undamped natural frequency of the qth mode, ε is the electromechanical coupling term, $m(x_i)$ is the mass at location x on the FPS, L is the length of the FPS, W_q', representing the derivative of the Heaviside function, is the normalized eigenvector of the qth mode, and $\ddot{\omega}_b$ is the second derivative of the displacement of the base. The modal damping equation can predict modal behavior of the energy harvester and also indicate the modal response of a simple beam with a piezoelectric material relative to the base excitation.

Considering electrical circuit of energy harvester connected to a resistor, the output voltage $V(t)$ generated by FPS can be calculated by the following electrical equation:

$$C_p\frac{\partial V(t)}{\partial t} + \frac{V(t)}{R_{load}} = \sum_{r=1}^{\infty} - E_p d_{31} t_{pc} b_p \left[\frac{\partial W_r(x)}{\partial x}\right]_{x_1}^{x_1+x_2} \dot{\eta}_r(t), \tag{2}$$

where t_{pc} is the distance between the neutral axis and the piezoelectric material center, d_{31} is the piezoelectric material constant, E_p is the Young's modulus of the piezoelectric material, b_p is the width of the piezoelectric material, C_p is the piezoelectric internal capacitance, r is the mode number, x_1 is the offset distance of piezoelectric material from the supported end, x_2 is the piezoelectric material length, and R_{load} is the external resistance. The electrical equation consists of the modal response, mode shape, internal capacitance, load resistance, mechanical properties of materials and electric properties of piezoelectric material. A transfer matrix technique is adopted to allow for predicting natural frequency and mode shape of a structure.

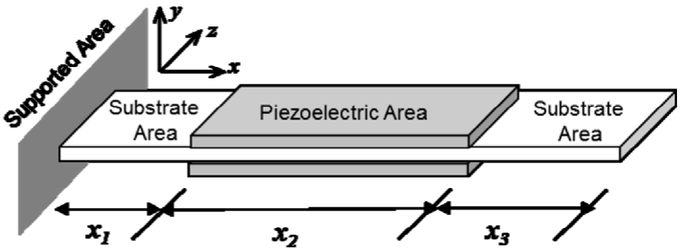


Fig. 3 Illustration of FPS (Bimorph type) in theoretical modelling

B. Deflection and Electric Power

In this section, a bimorph energy harvester is modelled and its electric power is estimated. The bimorph energy harvester consists of a substrate layer, e.g. lubber and silicone, laminated between two piezoelectric materials as shown in Fig. 4. It was assumed that the bonding between the substrate and the piezoelectric materials was perfectly connected. Both sizes of the FPS were supported by the aluminum flame with tension and were also fixed during energy force. Silicone (density: 1400kg/m^3, Young's modulus: 0.5GPa) was used as the substrate. The PVDF (density: 1780kg/m^3, Young's modulus: 3.5GPa) was also used as the piezoelectric material. The thickness of the PVDF was 80 μ m. The damping ratio was set to 0.03. The nonlinear aerodynamic interaction can be negligible during wind forcing.

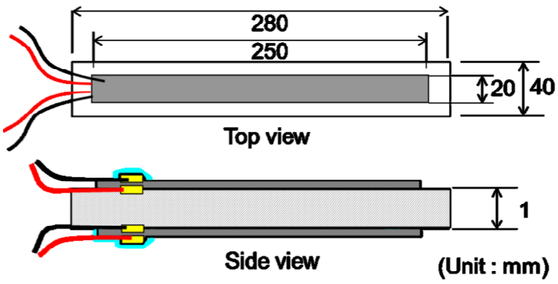
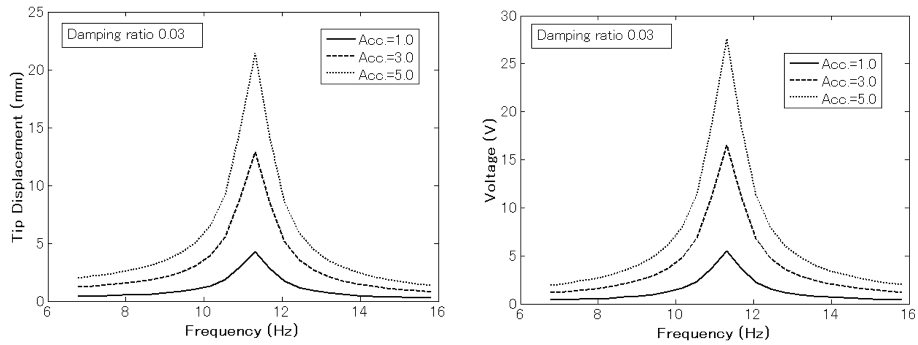


Fig. 4 Illustration of the Bimorph type of energy harvester

Figure 5 shows the central displacement of FPS and output voltage generated by the FPS at several vibration frequencies. Figure 6 shows the electric power calculated from the output voltage. It can be seen that the maximum voltage occurred at 11.3Hz, which means resonance frequency in the experiment. The electric power was increasing when the external force related to the acceleration of vibration was larger. Figure 7 shows the internal strain field along the length of FPED. The maximum strain occurred at the central location of the FPS and its value was larger as the external force was accelerated.

It is found that the electric power and the deformation of the FPS were affected by the size of piezoelectric material, fundamental structural layer, vibration frequency and amplitude related to external force. Some preliminary results for designing FPS were utilized on the basis of characteristic results such as electric performance, deflection and strain, calculated by the theoretical model. Using the designed FPS, experiments were performed as detailed in the next section.



(a)Displacemen (b)Output

Fig. 5 Displacement at central location and output voltage generated by FPS

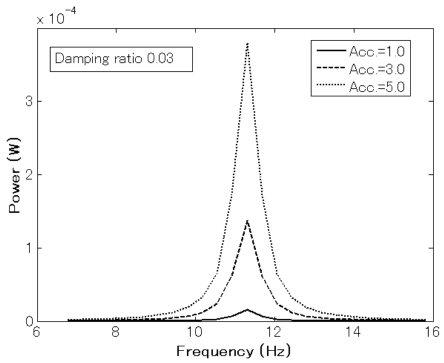


Fig. 6 Electric power generated by

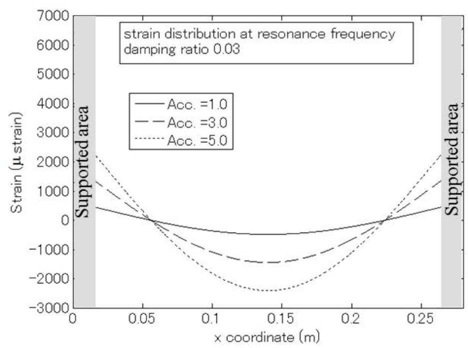


Fig. 7 Strain distribution on

IV. ELECTRICAL PERFORMANCE OF FPS DUE TO WIND ENERGY

A. Experimental Setup

Table 1 shows the dimensions of FPS and PVDF as shown in Fig. 1. The length *L* of PVDF is 250mm and the width *B* of PVDF is 10 to 30 mm. The length *l* of the FPS is 280 mm and the width *b* is 20 to 50 mm and then the resultant aspect ratio AR (*L/B*) = 8.3 to 25.0. The thickness of the PVDF is 40, 80 or 110 μ m. Figure 8 shows one example of the produced FPS. The distance between PVDFs, which is one of the most important parameters for electrical effectiveness and efficiency, is 1 mm in all cases to work well based on previous researches. The density of the elastic material is 1.25 g/cm^3 as a central core elastomer. The hardness is 0, 15, 40 or 60.

TABLE 1 DIMENSIONS OF FPS AND PVDF

Case	L (mm)	B(mm)	l (mm)	b (mm)	δ (mm)
AR25.0	250	10	280	20	1
AR12.5	250	20	280	40	1
AR8.3	250	30	280	50	1
AR25.0 (PVDF)	250	10	280	40	1
AR8.3 (PVDF)	250	30	280	40	1

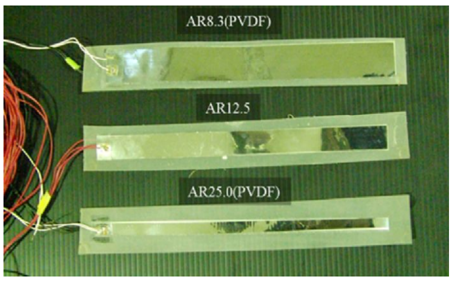
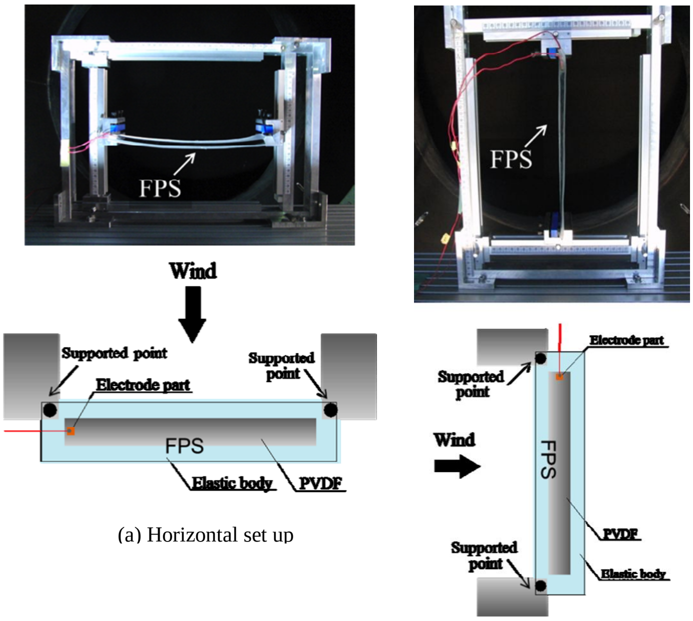


Fig. 8 Examples of produced FPS

Both edges of the FPS can be horizontally and vertically supported by the rectangular aluminum frame as shown in Fig. 9. The frame can also allow to support the FPS by both local pinching and linear holding. The width of the frame can be changed to control distance between both edges of the FPS and the resultant tension at initial conditions. The supported tension of the FPS can be measured by a digital force meter. The tension at initial conditions was set as zero to 5N. The experimental work was conducted in the 1.65 m-diameter wind tunnel of Hiroshima University as shown in Fig. 10. The rectangular frame was located at 0.9 m downstream from the wind tunnel mouth where the wind speed can be stable. To track deformation of the FPS during wind forcing, high-speed camera was also employed.



(a) Horizontal set up

(b) Vertical set

Fig. 9 Experimental setup of the FPS supported by the

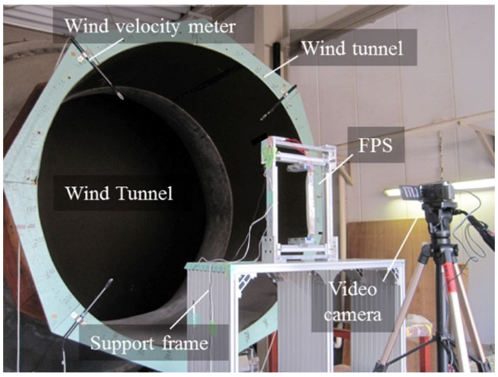
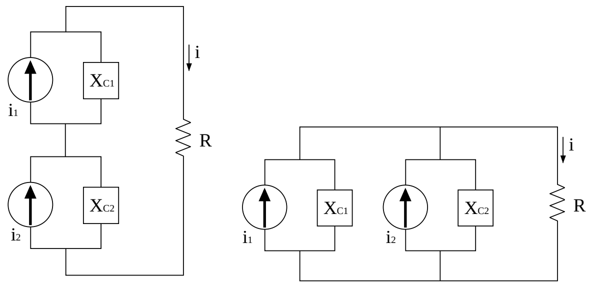


Fig. 10 Wind tunnel and experimental setup

The uniform wind speed was 2.0 to 11.0 m/s and the wind speed was averaged from four wind velocity meters located at the wind tunnel mouth. Output voltage generated by the FPS was measured through A/D converter (KEYENCE Co. Ltd.) with internal resistance of 1MΩ. The sampling frequency was 1,000Hz and the measuring time was 30s. The average power P_{avg} was calculated by Ohm law, $P_{avg} = (V_{\mathrm{rms}})^2/R$, where R is internal resistance of the A/D converter and V_{rms} is root mean square of the measured output voltage. The maximum power P_{max} is also defined by $P_{max} = (V_{\max})^2/R$. The electric performance due to the FPS is strongly influenced by the electric circuit design with impedance matching of PVDF. Therefore, the impedance matching using external resistance was also considered in this research. Figure 11 shows examples of serial and parallel circuit using two PVDFs laminated in the FPS. In the previous work, it was revealed that output voltage in series circuit is quite different from that in parallel circuit. It was clarified that electric performance depends on the ratio α of impedance of PVDF to internal resistance of measurement device. The high output voltage in parallel circuit is generated when $\alpha > 1$ as shown in Fig. 12. On the other hand, when $\alpha < 1$, series circuit is preferable for high electric performance. In this research, the ratio α was optimized to $0.6 < \alpha < 1.5$ under focused wind conditions and dimension of the FPS. Two circuits were examined in this paper. It is noted that electrical circuit design must be optimized for high electric performance of FPS after kinetic performance because fluid structure interaction is demonstrated under a design force even though vibration frequency would be changed in different ratios α.



(a) (b)Parallel

Fig. 11 Examples of electric circuit using FPS

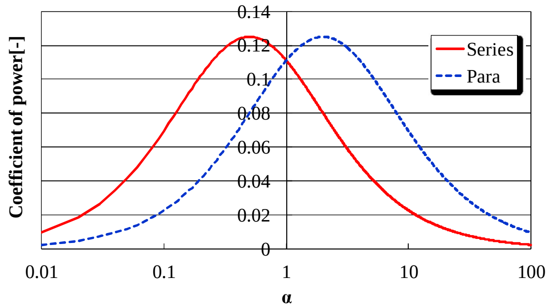
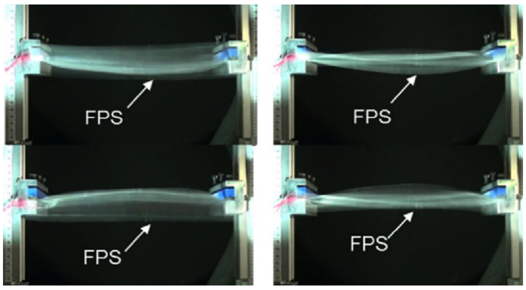


Fig. 12 Relationship between the ratio α and

B. Experimental Results

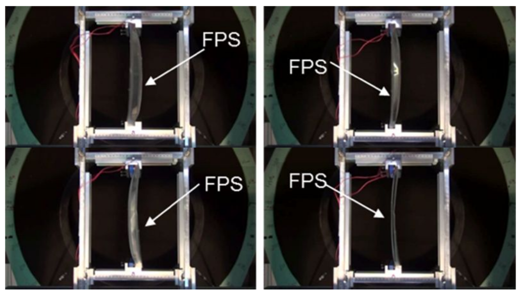
1) Thickness of FPS and Initial Supported Tension:

Snapshots of the vibrating FPS (Case: AR12.5, PVDF thickness: 110 μ m, Hardness: 15) caused by wind energy are shown in Fig. 13 and Fig. 14. It can be seen that there is a little difference in the vibration amplitudes at the center of FPS. The configuration of the vibrating FPS is only 1st mode in loosely supported case and tightly supported one. More detailed discussion is presented later.



(a) Loose (b)Tight

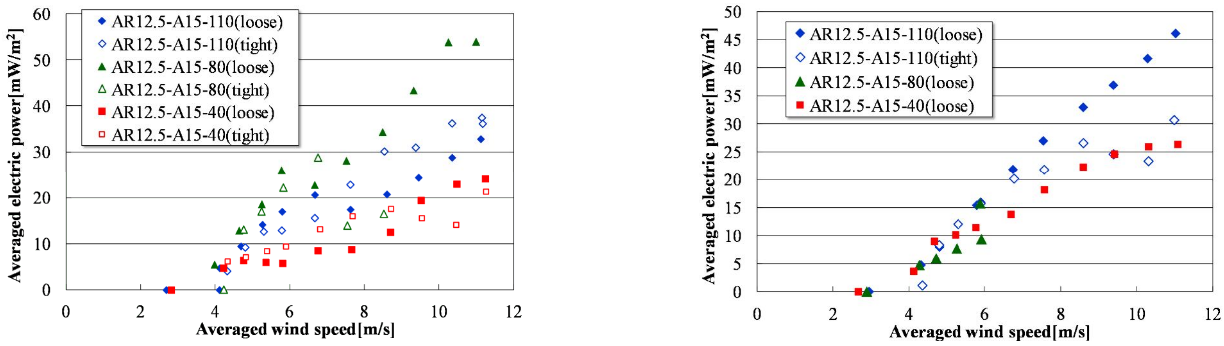
Fig. 13 Snapshots of vibrating FPS (Horizontally



(a) Loose support (b) Tight

Fig. 14 Snapshots of vibrating FPS (Vertically supported)

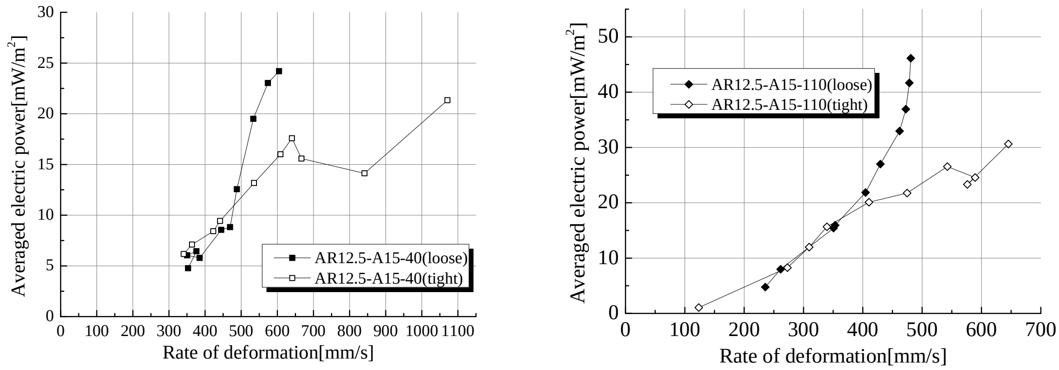
Figure 15 shows the relationship between wind velocity and average electric power in horizontally supported case and vertically supported one. The legend title is characterized by some conditions such as aspect ratio, hardness, thickness, tension of FPED, e.g. AR12.5-A15-110 (loose) means aspect ratio of 12.5, Hardness A=15, PVDF thickness of 110 μ m, and loose support. The elastomers of FPS (Aspect ratio: 12.5, Hardness: 15) are compared and focused on in this section. The output voltages generated from the PVDFs attached on both side of the elastomer are almost the same. Therefore, only the output voltage on one side was investigated. The average electric power in all cases was roughly increasing with increasing wind power. In the horizontally supported case, maximum electric power was occurred when the PVDF thickness was 80 μ m. On the other hand, in both cases, the electric power was gradually decreasing when the PVDF thickness was 40 μ m. These results mean that the FPS should be optimized by designed wind force because the stiffness of FPS and its motions in wind conditions are strongly influenced by the thickness of PVDF. However, the supported conditions such as tension and its direction are independent of electric power generated from the FPS.



(a) Horizontal support (b) Vertical support

Fig. 15 Average electric power versus wind speed

Figure 16 shows the relationship between wind velocity and vibration frequency of FPS captured by the high-speed video camera. The relationship between deformation rate of FPS and average electric power is also shown in Fig. 17. In the tightly supported case, the vibration frequency was higher when the wind velocity was high. The deformation rate was also increasing with increasing vibration frequency of the FPS. Even though, in the high wind velocity condition, the rate of deformation was continuously increasing and then the average electric power was drastically increasing. On the other hand, in the loosely supported case, the vibration frequency reached the maximum value in the low wind velocity condition and then it was almost constant. The electric power was not increasing with the wind velocity. The result was also supported by the deformation rate of the FPS.



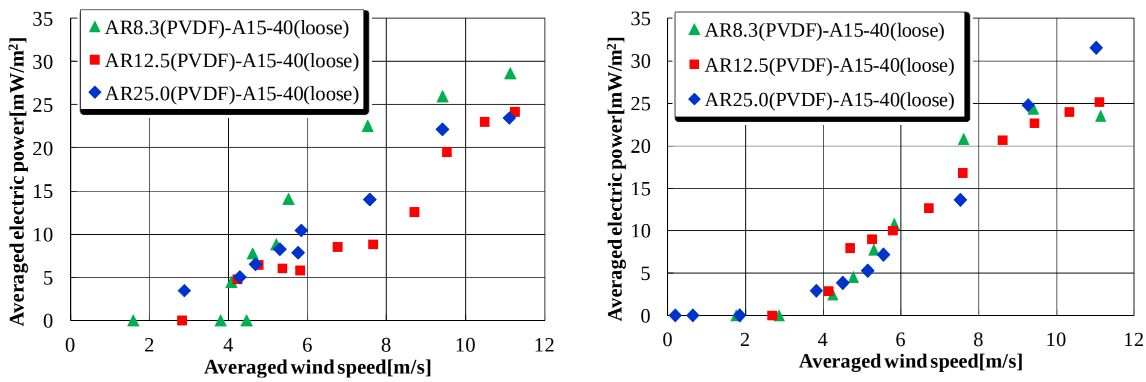
(a) Horizontal support (b)Vertical support

Fig.17 Relationship between deformation rate of FPS and electric power

This result reveals that electric performance of the FPS is proportional to its rate of deformation. Therefore, tight support allows the FPS to generate high electric power. It can be seen that the supported tension could actively control the motion of FPS and its deformation in several wind conditions. This control is one of the options for taking out effective electric power.

2) Aspect Ratio of FPS:

In this section, the influence of aspect ratio of FPS on electric power is examined. The FPS having hardness *A*=15 and PVDF thickness of 40 μ m and constant width was loosely supported. Figure 18 shows comparison of average electric power in horizontally supported case and vertically supported one. The aspect ratio AR is 8.3, 12.5 or 25.0. In the horizontally supported case, the electric power was highest in all cases of 5m/s wind speed when the aspect ratio AR was 8.3. At the aspect ratio AR=12.5, the electric power was lower than those at other ratios. The cut-in wind speed (a critical wind) at the initial condition was 3.0m/s in the case of aspect ratio of 25.0. On the other hand, in the vertically supported case, there is no tendency of the electric power. The effectiveness and stable electric performance can be shown comparing with that in the horizontally supported case. These results means that it is suitable for the FPS having low aspect ratio and with the vertical support, e.g. AR=8.3, to generate high electric power. This is because flow velocity and pressure fluctuation near surface of the FPS would be a strong turbulent flow and then the resultant vibration of the FPS is increased when the length of the FPS is longer in flow direction.



(a) Horizontal support (b) Vertical support

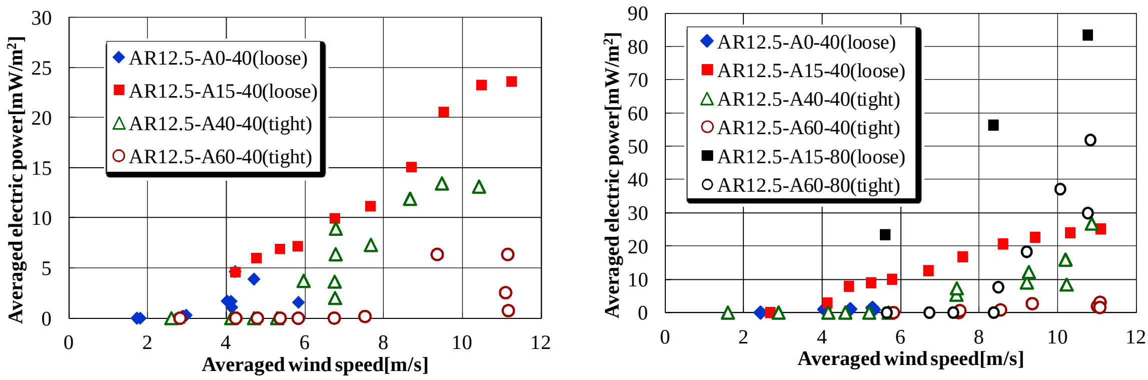
Fig.18 Relationship between electric power and wind speed

3) Hardness of Substrate in FPS:

In this section, influence of the elastomer hardness of FPS on electric power is examined. The FPS is employed with the aspect ratio AR=12.5 and the PVDF thickness of 40μm. Figure 19 shows comparison of electric power generated from the FPS supported in horizontal and vertical directions. The hardness of the FPS was set to *A*=0, 15, 40, 60 or 80. The FPS was not vibrated and could not generate electric power when the FPS was loosely supported and its hardness was 40 or 60. Therefore, in this figure, these cases were not plotted. Comparing with the electric power of all FPS, the electric power generated at the hardness *A*=15 was increasing in the broad band of wind condition and the increasing tendency was almost linear. The cut-in wind speed related to the initial trigger was very low. This means the FPS with the hardness *A*=15 could work well in practical use. On the other hand, with the strong hardness $A > 40$, the electric power generated by the FPS tightly supported is available at the wind speed $V > 7$m/s. These results mean that the electric power of the FPS is considerably influenced by not only the hardness of the elastomer in FPS but also the aspect ratio. In next section, effects on both key parameters are investigated under broad band of wind condition in more details.

4) Influence of Aspect Ratio and Hardness:

The FPS with the aspect ratio AR=12.5, 25.0 and the hardness A=15, 40, 60 was used for comparison of electric performance and the FPS was vertically supported. The thickness of the PVDF was 80 μm in all cases. Figure 20 shows comparison of average electric power of FPS having different hardness and aspect ratios. To compare remarkable electric power, only the cases of high wind speed (10m/s over) are focused on in this figure. In the case of the FPS with aspect ratio AR=25.0, the electric power is increasing in all cases comparing with the same hardness, especially, 200m W/m^2 with the hardness A=60. This result reveals that the FPS having high aspect ratio and high hardness can generate considerable electric power in high speed wind condition because the FPS vibrates coupling with fluttering and twist motions. The best mixed design conditions among aspect ratio of FPS, elastomer hardness, thickness of PVDF and support condition with tension should be optimized in wide range of broad band of wind including turbulence.



(a) Horizontal support (b) Vertical

Fig. 19 Relationship between electric power and wind speed

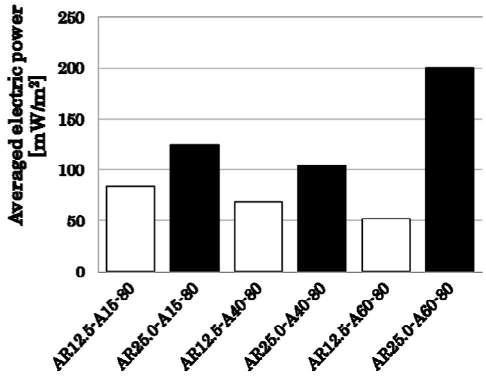


Fig. 20 Comparison of average electric power of FPS with different hardness and aspect ratios

V. CONCLUSIONS

A wind energy harvester with a piezoelectric material, FPS (Flexible Piezoelectric Sheet), was proposed and developed in experimental and theoretical study. The FPS consists of some PVDFs and a soft material thinly laminated with bonding. The main results are concluded as follows.

The FPS can be theoretically designed through coupling modelling with the modal damped equation of motion for a simple beam with a piezoelectric material and electrical equation considering modal response, mechanical properties of materials and electric properties of piezoelectric material. Solidity and motions of the FPS are influenced by thickness of the PVDF. Therefore, the thickness of PVDF should be optimized considering wind conditions. The supported tension of the FPS can allow to control motion and deformation of the FPS for generating a high electric power. The FPS should be vertically supported at both sides. Aspect ratio of the FPS has to be smaller to generate high electric power. For a high wind velocity condition, both high hardness and large aspect ratio of the FPS should be needed when a flattering and twist vibration strongly occurs.

In future work, optimized design parameters for the FPS should be found in broad band of wind conditions through theoretical modelling. Electric performance of the FPS (Max. in this research: 200mW/m^2) should be improved in low wind speed, especially breeze condition.

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