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Harvesting flow-induced vibration using a highly flexible piezoelectric energy device

Hidemi Mutsuda [a,*], Yoshikazu Tanaka [a], Rupesh Patel [b], Yasuaki Doi [a]

[a] Division of Energy and Environmental Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Japan
[b] Faculty of Engineering, University of Nottingham, NG7 2RD Nottingham, UK

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ABSTRACT

Energy harvesting is a topic of global interest in both academic research and practical application across many fields. The main concept in energy harvesting is to convert wasted ambient energy into useful electrical energy. In particular, piezoelectric materials can be used to convert strain energy into electric power directly, and piezoelectric materials can be used to harvest external vibration forces.

This paper proposes and develops a highly flexible piezoelectric energy device (FPED) to harvest flow-induced vibration by converting ambient kinetic energy such as ocean, current and wind energy into electric power. The energy harvesting device uses piezoelectric layers (e.g. PVDF) and elastomer materials (e.g. rubber or silicone) to achieve high electric performance and efficiency. The design of the FPED was optimized by considering the aspect ratio, support system, initial tension and incorporates a bluff body to generate turbulence. A theoretical model based on the transfer matrix method was used with the initial tension force and natural frequency of the harvester. The model demonstrated the maximum electric performance and optimized the structural layers and size under the parameter studies. Numerical and experimental results proved the potential of the highly flexible piezoelectric energy device to convert ambient kinetic energy from flow-induced vibration into useful electrical energy.

1. Introduction

Concentrated electrical infrastructures with large scale such as thermal power station, hydraulic power plant and nuclear power plant, have been already constructed and utilized in social network systems in the world. However, a tremendous or unexpected damage could be occurred by natural disaster such as super typhoon, mega-class earthquake and huge-scale tsunami, e.g. 2011 Tohoku earthquake [1], and then the resultant huge tsunami could cause much damages and fatal electric crisis in wide are. Therefore, it has been strongly required to propose and develop an innovative technology with safety and reliability in small or middle-scale distributed electrical infrastructure for a smart energy grid system in next generation. In recent years, energy harvesting is a topic of global interest in both academic research and practical application in many field. One of the concept in energy harvester is to convert from wasted ambient energy into useful electrical energy. A typical ambient energy is wasted kinetic one such as mechanical vibration due to vehicle and machine in factory, ocean and wind energy, human behaviors, etc. Energy harvesting technologies could combine a national grid system with smart grid one in electrical infrastructure, and therefore it is possible to make a paradigm shift as a new electrical generation in social system.

In preliminary and advanced technologies of energy harvesting [2–4], piezoelectricity and electromagnetism are utilized to capture a wasted ambient kinetic energy and then the generated energy can be used to activate wireless sensors such as environmental monitoring in air and water, mechanical sensing and structural diagnostic. In particular, energy harvesting using piezoelectric materials could be established and utilized in periodic external force. Piezoelectric material directly converts strain energy into electric energy. Many previous works on energy harvesters with simply-supported beam have been conducted to generate electric power in micro- to milli-Watt and also they can be used as a standalone. Most of the piezoelectric devices are designed, modeled and applied to a practical use as a cantilever. Therefore, energy harvesting with piezoelectric materials has addressed to many different designs [5–7]. Some of them have been applied to wind energy harvesting [8–10] and to ocean energy harvesting [11–16]. In more advanced research works, fluid-structure interaction between flow field and piezoelectric material has been considered to extract

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* Corresponding author.
E-mail address: mutsuda@hiroshima-u.ac.jp (H. Mutsuda).
URL: http://home.hiroshima-u.ac.jp/mutsuda/ (H. Mutsuda).

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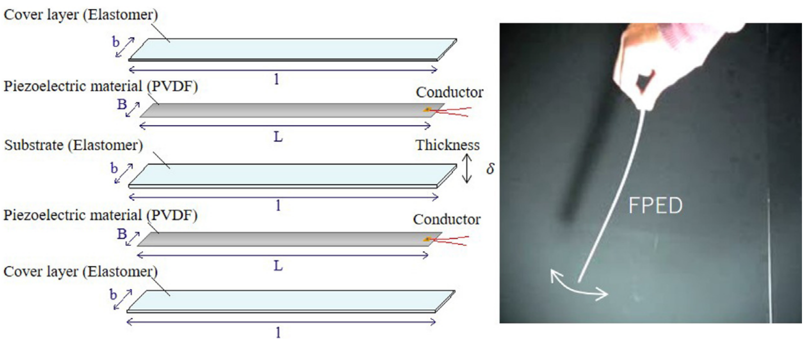

Fig. 1. Overview of flexible piezoelectric energy device, FPED.

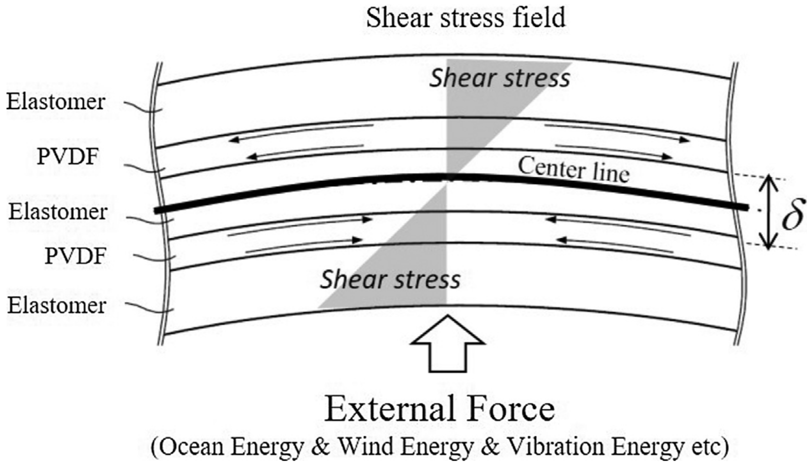

Fig. 2. Shear stress field in FPED.

high electric performance from vortex induced vibrations (VIV) and self-excited vibrations (SEV)[17–22]. Based on the previous works by many researchers, output voltage generated from piezoelectric material is proportional to strain rate of an energy harvester. One of the dominant parameters for high electric performance and efficiency is deformation and frequency of an energy harvester. On the other hand, ambient kinetic energies in ocean, current and wind flow have some scattering of the data as external forces can be widely varied in real-world scenarios. Therefore, FPEDs are highly flexible and adaptable for harvesting energy from various external forces and can also be customized and optimized to tailor to the forcing magnitude and electrical demand.

Under the above mention as the background, the previous works [23–28] have proposed and developed an energy harvester, which is called flexible piezoelectric energy device (FPED), in order to utilize ambient kinetic energy such as vibration, ocean and wind energy. FPED consists of polyvinylidene fluoride (PVDF) film and elastic material such as silicone, rubber and textile. It can be clarified that FPED can be easily deformed by several external forces. And then the internal strain can be stored in PVDF and the electromotive force can be generated on PVDF, which is proportional to strain rate of FPED, Moreover, the theoretical model based on [29] has been developed by Patel et al. [30–32] to estimate electric power and deformation of a designed FPED. The model is capable of analyzing a simple beam comprising of several layers with different material composition. Moreover, the model can estimate electric performance of FPED at several vibrated conditions and it can be applied to multi-layered device with many pairs of piezoelectric material located either side of the neutral axis of FPED.

The purpose of this study is to propose and develop a highly flexible piezoelectric energy harvester using flow-induced vibration in order to convert ambient kinetic energy such as wave, current and wind energy into electric power. The energy harvester consists of piezo-material (e.g. PVDF) and elastomer (e.g. rubber and silicone) to achieve high electric performance and efficiency in flow-induced vibration. In this study, a new type of FPED is designed and optimized in aspect ratio, support system, initial tension and a bluff body to be applied in flow-induced vibration. Moreover, a theoretical model based on transfer matrix is developed considering initial tension force and natural frequency and also it is applied to evaluate electric performance and to optimize structural layer and size in parameter studies.

2. Overview of flexible piezoelectric energy device, FPED

The concept of using a flexible piezoelectric energy device (FPED) to harvest ambient kinetic energy from flow-induced vibration applications was proposed previously by the authors.

As shown in Fig. 1, the FPED consists of a thin laminated structure constructed from an elastic substrate material (silicon, rubber and textile) with a piezoelectric material (polyvinylidene fluoride, PVDF) embedded within the substrate. The PVDF material used had a thickness 40–200 μm and the thickness of the FPED is less than 5 mm, making it highly flexible. The number of layers used in FPED can be customized and optimized with considering application fields. A bimorph FPED can be constructed by embedding a pair of PVDF layers either side of the neutral axis of the device. The illustration of shear stress distribution of FPED including PVDF is shown in Fig. 2, where δ is the distance between PVDFs. The figure indicates that the shear strain is larger as the distance between the centerline of FPED and the location of the installed PVDF is longer. The distance δ between the piezoelectric paint layer and the neu-