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Flexible Piezoelectric Vibration Energy Harvester using a Trunk-Shaped Beam Structure Inspired by an Electric Fish Fin

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This paper presents a bio-inspired structure that can enhance the efficiency of piezoelectric power generation in vibration-type energy harvester. Inspired by an electric fish, Gnathonemus petersii, a trunk structure for high-performance vibration energy harvester is explored. The proposed vibration energy harvester consists of a flexible PVDF film and thin glass fiber plate shaped with auxiliary delta wings to mimic the trunk structure of the electric fish. An experimental study of the prototype energy harvester shows that the proposed piezoelectric vibration energy harvester featuring the new bio-inspired structure produces 45% more power output than the conventional vibration energy harvester due to its electret-like material behavior.

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NOMENCLATURE

a = directional orientation of the system
h = strip thickness with strip thickness and strip thickness

1. Introduction

Vibration-based energy harvesting using piezoelectric materials is one of the most promising alternatives to generating electricity that can replace the primary battery (or cell) source for long-term, low-power autonomous sensory systems such as automotive tire pressure monitoring systems.[1] However, the performance of piezoelectric vibration energy harvesters is not sufficient to operate the electric devices.[2] In addition, conventional vibration energy harvesters are inefficient when exposed to off-resonance or at infra-low frequencies. Recent attempts to enhance the performance of the piezoelectric vibration energy harvesters have included resonance frequency tuning,[3] and the use of a nonlinear vibration oscillator (e.g., Duffing oscillator) for broadband energy harvesting[4] including *bi*-stable systems.[5-7] Some studies have examined bio-inspired compliant structures to resolve the aforementioned limitations of conventional beam structures.[7] Many researchers have recently examined alternative beam geometries to improve the efficiency of piezoelectric vibration energy harvester, while a conventional cantilever beam has several advantages. Some researchers have investigated the triangular or tapered beam geometry to make the strain distribution over the length uniform,[8,9] which provides larger average strain. The trapezoidal-shaped beam produces twice the amount of strain energy per unit volume of piezoelectric material. A right-angle (*L*-shaped) piezoelectric cantilever beam structure has been also designed to smooth the strain distribution significantly.[10] Zheng et al. have developed a new asymmetric air-spaced piezoelectric cantilever beam structure to make pure bending mode dominant to increase strain energy conversion efficiency.[11]

2. Biomimetic Approach

Inspired by the biological features observed in an electric fish, this study evaluated a new approach to enhance the performance of piezoelectric vibration energy harvesters to convert the mechanical vibration energy into electric power. All electric fish, particularly

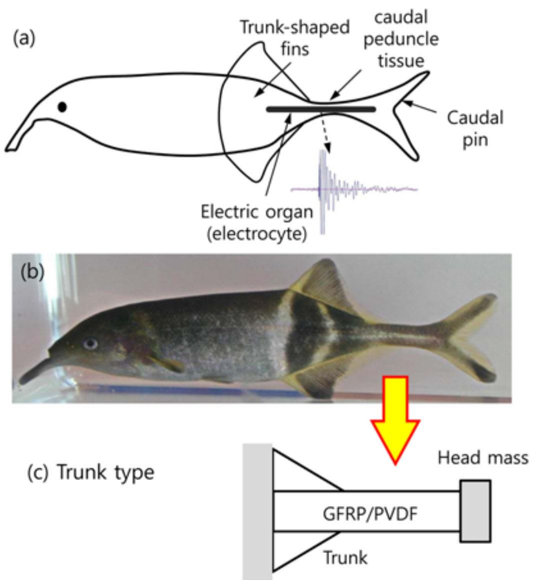

Fig. 1 (a) Schematic of an electric fish (Gnathonemus petersii), (b) its photo (courtesy of sci-toys.com) and (c) trunk-shaped model

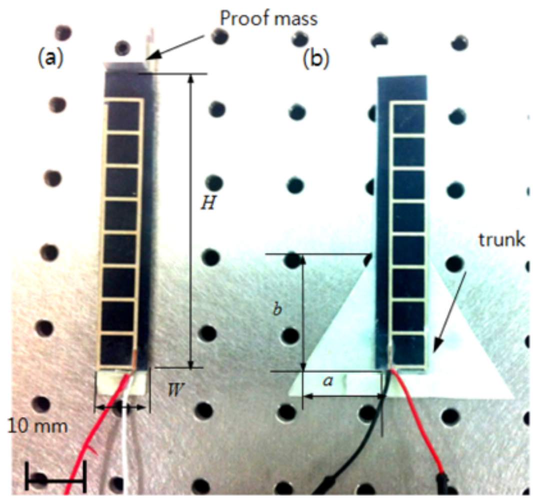

Fig. 2 Piezoelectric vibration energy harvesters based on (a) cantilever beam and (b) with trunk-shaped beam

Table 1 Summary of the piezoelectric energy harvesters

Items	cantilever beam	Trunk-shaped beam
Substrate	rectangular beam	rectangular + trunk-shaped beam
Piezoelectric	PVDF film	PVDF film
Width *(W)*	0.0153 m	0.0153 m
Height *(H)*	0.098 m	0.098 m
a	N/A	0.022 m
b	N/A	0.037 m
PVDF area	0.0015 m^2	0.0015 m^2

Gnathonemus petersii, a member of the mormyrid family, which is also called an elephant nose fish, produce electricity from an organ in the tail called an electric organ, which contains electrically excitable cells called electrocytes, as shown in Fig. 1. In mormyrids, this electric organ is embedded inside the only caudal peduncle, which is a flexible beam structure called caudal peduncle tissue between the trunk structure that forms a delta-shaped skirt in the middle of the body and the caudal pin.[11] In addition to the obvious visual interest (i.e. elephant nose), this creature has attracted the interest of many evolutionary biologists because of the evolution of electrosensory system and unique structural appearance observed in the electric fish family. For example, this electric fish generates electric pulse signals for navigation and communication. Although it is well-known that the electric organ has evolved repeatedly during the diversification of electric fish and the key function of excitable cells (electrocytes) is to open and close the sodium ion channel in response to muscle movement, the detailed evolutionary mechanism through which mechanical energy is converted to electricity and the evolutionary implications are unclear.[12] The primary objective of this study is to show the evolutionary solution inspired by the trunk structure of the electric fish for vibration-based mechanical energy harvesting.

3. Experimental and Numerical Approaches

3.1 Fabrication

Inspired by the trunk structure of the electric fish, particularly elephant nose fish, a new piezoelectric vibration energy harvester was designed, and fabricated using a flexible piezoelectric polymer, polyvinylidene fluoride (PVDF). The conventional piezoelectric vibration energy harvester was typically designed by using a cantilever beam structure, where the piezoelectric beam is clamped at one end and is freely vibrating at the other end in response to the base excitation normal to the surface of the beam, resulting in mechanical vibrations to the out-of-plane motion. Therefore, polymer-based piezoelectric materials, such as macro fiber composites (MFC) and PVDF can provide some advantages over ceramic-based piezoelectric materials (e.g., bimorph PZT), because the piezoelectric voltage constant in the d_{31}-mode of polymer-based piezoelectric materials have is typically higher than other modes due to their better bending ability.[13] Moreover, the PDVF film used as the piezoelectric energy harvesting material in this study can be processed easily by cutting due to their thin grid-type electrode on both sides coated by the conducting polymer (PEDOT, t = 20 mm), which can provide an inexpensive way to examine the impact of the beam shape.

The proposed piezoelectric vibration energy harvester consists of the PVDF film (t = 80 umm), adhesives, and a glass-fiber reinforced plastic (GFRP) substrate shaped with a trunk-shaped beam structure, which can be represented by a modified cantilever beam connected rigidly with auxiliary delta wings to mimic the trunk structure of electric fish, as shown in Fig. 2(b). A thin GFRP plate (t = 0.5 mm) manufactured by Composite Structure Technology was also used to imitate the flexible caudal peduncle tissue. An additional advantage of the trunk-shaped beam harvester is that the piezoelectric material is a conventional rectangular shape because delta wings do not require be covering by the PVDF film, which suggests that the manufacturing cost will be low, comparing to the non-rectangular shape (e.g., triangular). The conventional cantilever and triangular beam structure are also fabricated to evaluate the performance of the proposed beam structure.

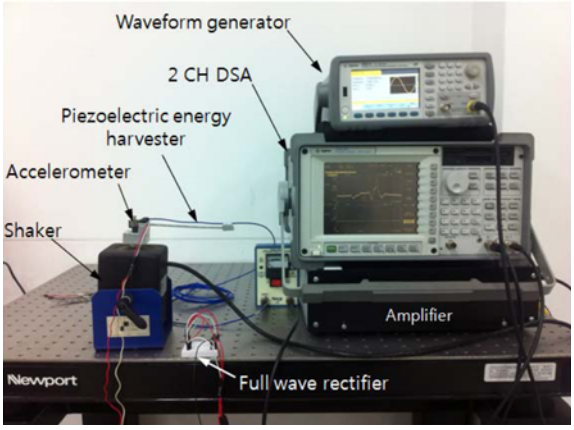

Fig. 3 overall schematic of experimental setup

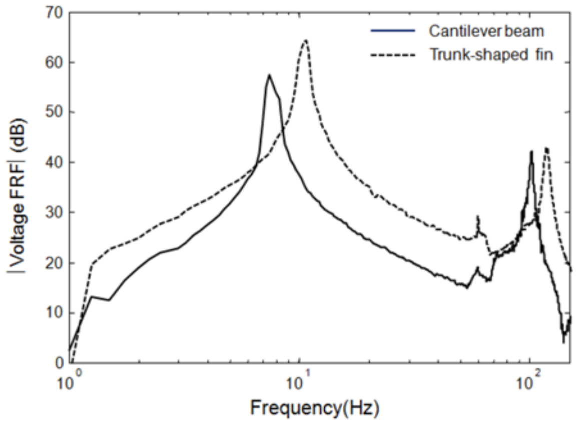

Fig. 4 Multi-mode voltage FRFs with AC voltages (before rectifying)

The two rectangular PVDF films were first bonded to the cantilever and trunk structure, respectively, using 3M Epoxy (model: DP460). The dimensions of the truncated triangular (more properly trapezoidal) PVDF film were adjusted so the film area of the three structures could be the same (0.0015 m^2). A proof mass of 0.005 kg was attached at the end tip of the three piezoelectric vibration energy harvesters. Table 1 lists the dimension of three piezoelectric vibration energy harvesters.

3.2 Experimental test

The bio-inspired piezoelectric vibration energy harvesters designed in Section 2 were validated experimentally through laboratory tests, as shown in Fig. 3. The piezoelectric harvester was harmonically excited by an electromagnetic shaker (model: Modal Shop 2007E). To calculate the frequency response functions (FRFs), the base acceleration was also measured using an accelerometer (model: 355B02, PCB Piezotronics Inc) mounted on top of the shaker. To excite the base of the vibration energy harvester, the sinusoidal signal was first generated using a waveform generator (model: Agilent 33521A), and applied through a linear amplifier to the shaker. The voltages from the accelerometer and piezoelectric harvester were sampled, and analyzed using a dynamic signal analyzer (model: HP35670A). The raw voltage output should be rectified into DC voltage because the output of the piezoelectric vibration energy harvester is a sinusoidal waveform. This process can be carried out using a simple rectifying circuitry. Using a commercial bridge diode (model: DF06S), a simple full-wave rectifier was built easily on a breadboard. A capacitive storage element (capacitor C of 1 mF) was connected in parallel to smooth the transient response, and measure the average power output. Although an optimum resistive element (resistor R) is typically connected in series for the electrical load resistance, only the open-circuit voltage (i.e., without a resistive load) was analyzed.

To identify the structural modal characteristics, the multi-mode voltage frequency response functions (FRFs) for two different beam structures were first estimated using the AC output voltage before rectifying and the applied acceleration (approximated root mean square (RMS) value of 1 m/s^2. The structures were first excited using the random source signal. A sampling frequency of 400 Hz was chosen to be sufficient to capture all of the natural frequencies of interest ranging from 5 Hz to 200 Hz.

4. Results and Discussion

4.1 Structural analysis

Fig. 4 shows the multi-mode voltage FRFs. As expected, the voltage FRFs appeared to be increased only for the fundamental vibration mode and attenuated for higher vibration modes due to the proof mass. The first two natural frequencies of Type 1 (= beam structure) are 7 Hz and 90 Hz, respectively. The first two natural frequencies are 10 Hz and 108 Hz for the Type 2 (i.e., trunk-shaped). As the shape of the piezoelectric energy harvester is changed from a rectangular shape to a non-rectangular shape, (i.e., trunk and triangular) the fundamental natural frequencies increased from 7 Hz to 10 Hz. Note that the ratio of the fundamental natural frequency to the second natural frequency was also increased gradually (from 0.078 to 0.093). Compared to the conventional Type 1, Type 2 shows an increased FRF. Note that the proposed Type 2 structure shows an increased FRF over the excitation frequency range.

4.2 Energy harvester test

With the rectifying circuit, the output AC voltage was rectified to a DC voltage when the vibration was applied at $t = 6.8$ seconds. For instance, the open-circuit DC voltages at the fundamental natural frequency of the three structures were compared, as shown in Fig. 5. Because of the capacitive element, the open-circuit voltages showed smooth transient responses. The time interval required to reach the steady-state open-circuit voltage is however different. The measured DC voltages reached their steady-state values of 13.4 V (trunk-shaped beam), and 4.2 V (cantilever beam), respectively. These steady-state values as a function of the excitation frequencies were collected and compared, as shown in Fig. 6. The trend of the frequency response curves is the same as the multi-mode voltage frequency response functions (i.e., FRFs in Fig. 4).

With open-circuit DC voltage responses, the average power output capability of the piezoelectric harvesters can be calculated as:

$$P_{avg} = I \cdot V = \frac{dQ}{dt} \cdot V = \omega CV \cdot V = (2\pi f)CV^2 \quad (1)$$

where, C is the capacitance of capacitor rectifying the induced AC output (1 mF in this study), V is the open-circuit voltage of the

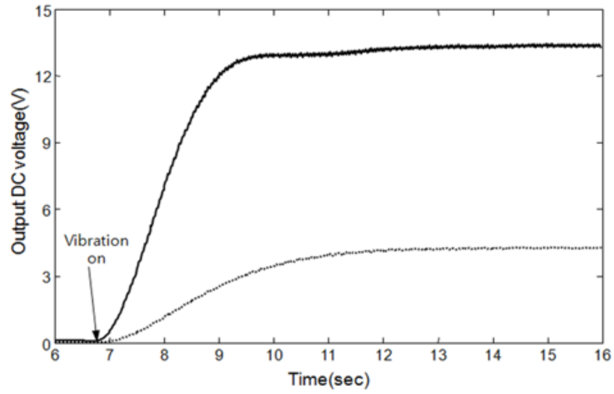

Fig. 5 Open-circuit DC voltages of cantilever beam type (f = 7 Hz, dot line) and trunk-shaped beam (f = 10 Hz) at the fundamental natural frequency

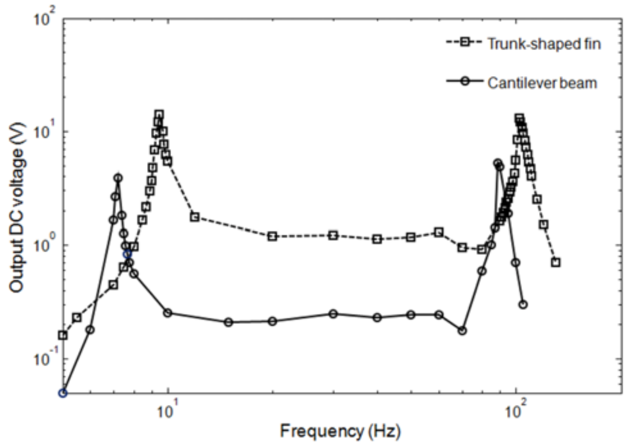

Fig. 6 Frequency response curves of two vibration energy harvesters

Table 2 Output power calculation of piezoelectric energy harvesters

Items	cantilever beam	Trunk-shaped beam
1st resonance frequency	7 Hz	10 Hz
Output voltage	4.2 V	13.4 V
Output Power	78 µW	113 µW

piezoelectric harvester. For example, the average power outputs at the fundamental natural frequency were measured, and compared. Table 2 shows the fundamental frequency, output voltage and the calculated power output of two cases. While the estimated average output power for the cantilever beam type is approximately 78 mW, the estimated average output power for the new type of structure is 113 mW, which suggests that a piezoelectric vibration energy harvester based on the trunk-shaped beam structure produces 45% more power than the conventional vibration energy harvesters - cantilever beam type. This proves that the biological electric fish evolved in its structure so as to maximize its electrical power generation. By inspiring from the electrical fish, we were able to enhance the performance of vibration energy harvester.

From the structural aspect, the same sized PVDF sheet was used for

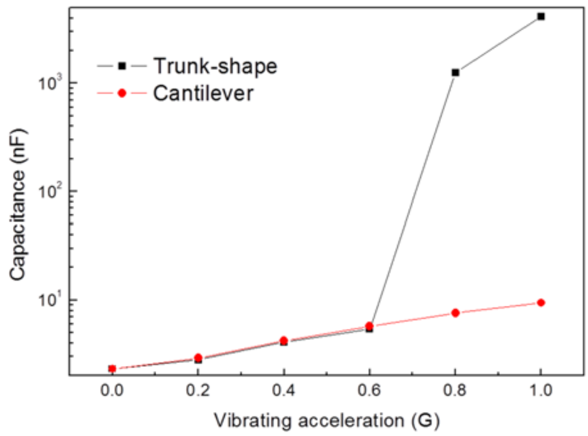

Fig. 7 Measured intrinsic capacitances of cantilever beam and trunk-shaped beam structures as a function of vibrating acceleration. The operating frequency is 7 Hz and 10 Hz for cantilever beam and truck-shape structure, respectively

two energy harvesting structures. However, the arising question is why the trunk-shape beam structure improved the power output? The only difference is the geometrical difference between the cantilever and the trunk-shaped beam structures. It is clear that more induced charge production from the PVDF sheet resulted in more power output. There could be two possible reasons on the increased charge generation from the trunk-shaped beam structure: more strain generation on the PVDF sheet or nonlinear piezoelectric behavior of PVDF associated with charge generation. To prove the first reason, a preliminary finite element analysis of two structures was performed and we found that bending mode shapes of two structures are about the same and it is hard to distinguish the difference of strain generation on the PDVF. However, more accurate modeling of the structure including bonding layer and PVDF sheet would be necessary to pinpoint the strain generation on the PVDF sheet, which is future plan on this study.

Next possible reason can stem from the nonlinear behavior of PVDF sheet. To reveal the nonlinear behavior of PVDF, we measured the capacitance of both structures using a precision LCR meter (HP 4285A) in parallel mode. Fig. 7 shows the result. There is no significant capacitance difference between both structures under the vibrating acceleration lower than 0.6 g. However, beyond the acceleration condition of 0.6 g, the capacitance of the trunk-shaped beam structure drastically increased, while that of the cantilever beam structure linear increased. This might be associated with the nonlinear behavior of PVDF. Compared to solid state piezoelectric materials (i.e., PZT, and quartz) PVDF is a polymer based piezoelectric material, which belongs to an electret that can possess quasi-permanent charge storage which associates with its chemical structure.[14] This phenomenon in other piezoelectric material, like cellulose, has been observed in elsewhere.[15] As the PVDF sheet attached on the trunk-shaped beam structure, charge accumulation on the PVDF sheet could be nonlinearly enhanced.

5. Conclusions

In this study, a PVDF film based-piezoelectric vibration energy harvester inspired by the trunk-shaped beam structure of electric fishes was presented to enhance the performance of conventional piezoelectric vibration energy harvester based on a rectangular cantilever beam. An experimental study of the prototype energy harvester showed that the proposed trunk-shaped beam structure piezoelectric vibration energy harvester produces 45% more power output than the conventional vibration energy harvester. The electret like-charge accumulation of PVDF was attributed to the trunk-shaped beam structure. Compared to the conventional cantilever beam type, the proposed trunk-shaped beam structure based piezoelectric energy harvester offers a simple but effective way of enhancing electric power output over a wide frequency ranges (*i.e.*, off-resonance range between the first two natural frequencies), as well as at the resonance frequency.

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