Bio-inspired Bistable Piezoelectric Energy Harvester for Powering Animal Telemetry Tags: Concept Design and Preliminary Experimental Validation

Feng Qian[a], Mingyi Liu[a], Jianuo Huang[a], Jiajun Zhang[a], Hyunjun Jung[b], Zhiqun Daniel Deng[a,b], Muhammad R. Hajj[c], and Lei Zuo[a,b*]

[a]Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA, USA 24061
[b]Energy and Environment Directorate, Pacific Northwest National Laboratory, Richland, WA, USA
[c]Department of Civil, Environmental and Ocean Engineering, Stevens Institute of Technology, 1 Castle Point Terrace, Hoboken, NJ 07030, USA

ABSTRACT

This paper presents the concept design, preliminary experimental validation, and performance evaluation of a novel bio-inspired bi-stable piezoelectric energy harvester for self-powered fish telemetry tags. The self-powered fish tag is designed to externally deploy on fish (dorsal fin) to track and monitor fish habitats, population, and underwater environment, meanwhile, harvests energy from fish motion and surrounding fluid flow for a sustainable power supply. Inspired by the rapid shape transition of the Venus flytrap, a bi-stable piezoelectric energy harvester is developed to generate electricity from broadband excitation of fish maneuvering and fluid. A bluff body is integrated to the free end of the bistable piezoelectric energy harvester to enhance the structure-fluid interaction for the large-amplitude snap-through vibrations and higher voltage output. Controlled laboratory experiments are conducted in a water tank on the bio-inspired bi-stable piezoelectric energy harvester using a servo motor system to simulate fish swing motion at various conditions to evaluate the power generation performance. The preliminary underwater experimental results demonstrated that the proposed bio-inspired bi-stable piezoelectric effectively converters fish swing motions into electricity. The average power output of 1.5 mW was achieved at the swing angle of 30^{o} and frequency of 1.6 Hz.

Keywords: Piezoelectric, energy harvesting, bio-inspired, bistable, underwater, telemetry tag

1. INTRODUCTION

The site selection and operation of marine hydrokinetic energy, off-shore wind energy farms, and hydroelectric power stations needs to consider the impacts on fish passage and mitigation.[1] The assessment of the impacts requires the capability of tracking and monitoring fish behavior, habitat, and motions remotely. Acoustic telemetry is a primary tool for remotely tracking fish. The telemetry tags transmit a unique acoustic signal to multiple local receivers (hydrophones) that extract the arrival time and identification code from the acoustic waveform.[2] The tagged fish could be then located from the processed data based on the time-difference-of-arrival (TDOA) algorithm in three dimensions.[3] Fish tags can be categorized into surgically implanted ones and externally deployed ones depending on the targeted animals.[4] External attachment was the most commonly used method in the initial applications (1956– 1975), later, was overtaken by surgical implantation due to the tag miniaturization and extended battery life.[4] The smallest active fish tag commercially available is 0.2 gram (Model SS400 by ATS Inc[5]). Recently,external deployment method has increased with the development of archival tags (data storage tags, DSTs), pop-up satellite archival tags (PSATs), and other environment-sensing tags. These fish tags are mostly powered by batteries which require periodic replacement due to the limited energy capacity and could cause chemical contamination to marine ecosystem. For example, the Vemco V16 tag is powered by a lithium ion battery, which will corrode over time and the plastic tag casing might rupture leading to lithium leaching[6] .

Correspondence author: Lei Zuo (leizuo@vt.edu)

The limited power supply constrains the tracking and communication distances and has been a major bottleneck that hinders the widespread applications of acoustic animal telemetry tags. Periodic battery replacements are expensive, reduce animal growth and survival, and even impossible in practice due to the far distance migration of marine animals.

One possible solution to the above mentioned issue is to harvest energy from the surrounding ambient and animal motions to provide continuous, reliable, and sufficient power for fish tags. In practice, the externally deployed fish tags are usually subjected to multiple excitation including fish maneuvers, fluid flows, and random disturbation over a broadband frequency range. Integrating proper transducers to fish tags to convert this kinetic energy into usable electricity enables self-powered fish tags, which could operate without solely relying on traditional battery and thus elongates the service life and the life of the tagged fish. Shafer and Morgan made a comprehensive study on the lifetime and power consumption of marine tag technologies, as well as the potential energy source in the marine environment, and concluded that harnessing either the fluid flow associated with the swimming animal or the pressure energy could meet the power requirements of currently available bio-logging systems.[7] The piezoelectric fish-like bimorph cantilevers with and without a passive caudal fin (tail) was experimentally studied for both underwater power generation and thrust under harmonic base excitation and wideband power output was observed from the one with the additional caudal fin.[8] The feasibility of energy harvesting from fish swimming was studied using ionic polymer-metal composites (IPMCs)[9] and piezoelectric macro fiber composite (MFC) transducers and experimentally demonstrated based on a biomimetic fish tail for underwater temperature sensing and wireless data transmission.[10] A self-powered fish tag was developed uses a flexible piezoelectric beam to harvest the mechanical energy from the deformation of the fish body during swimming.[11] This is the first known implantable energy-harvesting fish tag demonstrated in vivo, which could send a unique identification code for a detection range of up to 100 m. However, the linear piezoelectric beam harvester worked at a very low frequency (off-resonance) during fish moving, leading to a very small power output due to the frequency mismatch.[12]

As for the linear piezoelectric energy harvesters widely studied in literature, high power can only be attained at the resonant vibration and therefore slight frequency mismatch could lead to significant inefficiency.[12,13] While fish motion, fluid flow, and random excitation in the marine environment have a wide range of frequency components along with various uncertainties, which induces broadband frequency excitation to the harvester. These facts require that the harvester be able to scavenge enough energy effectively over a wide frequency range. Nonlinearities have been widely recognized as an effective mechanism to extend the frequency bandwidth of vibration energy harvesters.[14–16] Bi-stable nonlinear harvesters can achieve a better performance than their linear counterparts because the snap through dynamics, also referred to as global vibration, results in large-amplitude vibrations and thus high voltage output.[17–19] Bistable piezoelectric energy harvesters could be more favorable for self-powered fish tag applications since the multiple excitation from fish swimming and fluid flow under marine could increase the probability of the large-amplitude snap-through vibrations and therefore higher power output.

This paper presents the concept design and preliminary experimental demonstration of a bio-inspired bistable piezoelectric energy harvester to achieve autonomous power supply for continuous fish tracking by harvesting energy from fish maneuvering and surrounding fluid. The overall concept design of the self-powered fish tag is firstly introduced and the bio-inspired design of the bistable piezoelectric energy harvester is briefly described. Underwater experiments were performed in a water tank to demonstrate the feasibility of energy harvesting from fish swing and to evaluate the power generation performance of the bio-inspired bistable piezoelectric energy harvester. A servo motor driving system was designed to simulate the fish swing during swimming as the base excitation to the harvester. The average power output of the harvester were evaluated at different swing angles and frequencies, as well as the external electrical resistance.

2. BIO-INSPIRED DESIGN

2.1 The Overall Concept Design of the Self-powered Fish Telemetry

The overall design of the self-powered fish telemetry tag should consider the functions, reliability, and environment, among which the functions include energy harvesting from ambient excitation, sensing, and wireless data transmission. The concept design of the proposed self-powered fish tag is illustrated in Fig.1, which consists of a sucking disc for attachment and a bistable piezoelectric energy harvester with a bluff body. The acoustic transmitter, circuit board, and integrated sensors were not included in Fig.1 since they are out of the scope of this study. The bluff body is to enhance the interaction of the harvester with the surrounding fluid to facilitate the large-amplitude snap through vibration of the bistable energy harvester. As the fish tag vibrates under the base excitation from fish swing and fluid flow, the piezoelectric element mounted close the fixed end of the harvester will convert the induced strain into electric charges based on the direct piezoelectric effect.[20] The charges are managed by an energy harvesting circuit and the harvested electricity can be stored in a super capacitor which powers the sensing and data transmission units of the fish tag. Two innovations are proposed in this design, one is the sucking disc attachment method and the other one is the bistable energy harvester with the bluff body for energy harvesting. This study focuses on the latter one but a brief introduction is given to the concept design of the attachment of the harvester in the following.

One challenge of fish tracking technologies is how to attach telemetry tags to fish with minimum or without influence on their normal life. Instead of clamping them to the fin or surgically implanting them inside bodies, a novel attachment inspired by the symbiotic phenomenon between remoras and shark is proposed to attach the harvester on fish. As shown in Fig.1 (a), remoras are able to attach to a shark by special sucking discs in their mouths. This action is referred to as symbiotic relationship. It was observed that regardless of the size of remora fish, it is unlikely that the shark will dislodge a remora by increasing its swimming speed.[21] The remoras' low drag profile and suction-based attachment strategy are the keys for the shark to travel everywhere without paying for any steamer ticket. This symbiotic relationship does not influence the movement of the shark, but benefits both the remoras and the shark. This interesting phenomenon inspired a novel attachment design for fish tagging in a more efficient manner, leading to the concept of replacing the remoras by a smaller and lighter self-powered bio-inspired fish tag. Understanding the mechanism of this process provides new sights in the design of attachable devices. The adhesive disc on the remora's head has a complex mechanism that includes a modified fin structure with teeny spikes (called lamellar spinules) that generate friction to adhere to the host. By learning and mimicking this fin structure with teeny spikes, a bio-inspired attachment sucking pad can be designed for the proposed self-powered fish tag.

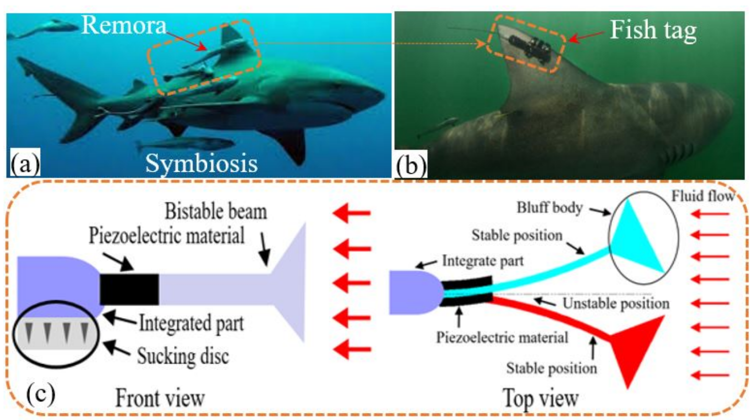

Figure 1. Bio-inspired design of the self-powered fish telemetry tags: (a)symbiotic relationship between remora and shark (b) electronic tagging externally deployed on a shark fin (c) concept design of the attachment and the proposed bi-stable piezoelectric energy harvester with a bluff body for the enhancement of fluid-structure interaction.

2.2 Bio-inspired Bistable Piezoelectric Energy Harvester

The self-powered fish tag needs to provide sufficient power from multiple excitation including fish swing motion, fluid flow, perturbations, and random excitation, under which traditional linear resonant energy harvesters are inefficient due to the frequency mismatch. However, the bistable energy harvester design is quite challenging for the specified application conditions of the underwater marine environment. Existing mechanisms in literature to realize bistabilities mainly include mechanical pre-loading,[12,22] magnetic interaction,[23,24] or residual thermal stress in laminate composite.[25,26] Both the axially preloaded and magnet-based bistable beam energy harvesters will make the system awkward because redundant constraints are essential for these methods, while laminate composites are not reliable and stable in an aquatic environment. This study aims to investigate a novel bi-stable piezoelectric energy harvester inspired by the biology phenomenon of Venus flytrap (Dionaea muscipula) to provide continuous, reliable and sufficient power source for externally deployable fish tags. The Venus flytrap is a good example of bi-stable non-linearity in nature which could trap agile insects by quickly closing its two curvature leaves within a very short time (100 ms),[27] as shown in Fig.2 (a) and (b). A rapid shape transition occurs from the open state (Fig.2 (a)) to the close state (Fig.2(b)) when the leaves are triggered to snap shut. This rapid shape transition is referred to as the snap-through of bi-stable structures, which is usually accompanied by large energy release.

By studying the structures of the Venus flytrap leaves which substantially contribute to the bistability of the plant, it is found that the leaves curve and stretch in two directions at the open state and store potential energy in the stretched deformation. The snap-shut motion from the open state to the close state is accompanied by a large energy release from the leaves. Inspired by the bi-curved shape of the Venus flytrap leaves, a bi-stable piezoelectric energy is designed in this section by pre-stressing two sub-beams tailored from a cantilever, as shown in (Fig.2(c)). The strip at the middle of the cantilever along the length direction is cut off and then a piezoelectric MFC is attached to the fixed end of one of the resultant two sub-cantilever beams. In-plane displacement constraint is then applied to the free ends of the two sub-beams so that the two beams move toward each other at the free ends, as illustrated in (Fig.2(d)). The in-plane displacement constraint bends and twists the two sub-beams so that the two sub-beams are curved in two directions similar to the Venus flytrap leaves and therefore induces mechanical potential energy. The displacement constraint is held by the rigid blocks and two screws at the free end which also connect the cantilever with the bluff body. Since the bending and twisting deformations are bi-directional, as shown in (Fig.2(e) and (f)), the harvester is bistable. The detailed design and working principle of the bistable structure is referred to the Ref.[28] .The bluff body is added to the free end of the harvester to increase the fluid-structure interaction for energy harvesting from fluid flow, such as galloping vibration. The combination of the galloping energy harvesting strategy with bi-stable characteristics creates a new harvester which is expected to have a much better performance in terms of the power generation. When the harvester is integrated into fish tags and deployed on the dorsal fin of fish, it will be subjected to the base excitation from fish swing and ambient fluid flow. The multiple excitation could benefit the large amplitude inter-well oscillations of the bi-stable harvester, which are desirable for large power output.

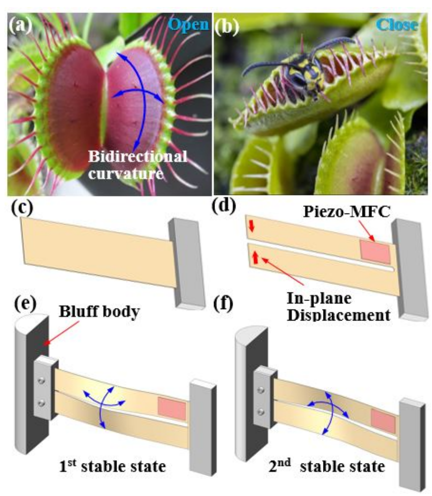

Figure 2. Bio-inspired design of the bistable piezoelectric energy harvester: (a) open state of the Venus flytrap with the leaves curved in two directions (b) close state of the Venus flytrap (c) cantilever beam (d) tailored cantilever beam with the attached piezoelectric MFC transducer and the applied in-plane displacement constraint at the free ends of the sub-beams (e) first stable state and (f) second stable state of the bio-inspired bistable piezoelectric energy harvester.

3. EXPERIMENTAL SETUP

Experiments are conducted in a water tank to characterize the energy harvesting performance of the proposed bio-inspired bistable piezoelectric energy harvester based on the simulated underwater fish swing motion. A controlled servo motor system was designed to mimic the fish swing motion to provide the base excitation for the harvester. The goal of the experimental studies is to investigate how the swing angle, swing frequency, and electric resistance affect the dynamics and power generation performance of the harvester. The resistance sweep experiments are firstly conducted for two swing angles of 15° and 30° at constant swing frequencies to identify the optimal resistance and maximum power output. Then frequency sweep experiments are also performed at the two swing angles and constant resistance to see the onset frequency of the large-amplitude snap-through vibration and the corresponding average power output of the harvester. The power generation performance of the harvester is investigated at local vibration and global snap-through vibration under different excitation amplitudes and frequencies.

In the experiments, a servo motor (57HSE2.2N+HBS57 Closed-loop step motor) is employed to simulate the fish swing motion that drives the harvester to vibrate. The overall experimental setup is shown in Fig. 3, where the left part shows the water tank test layout. A wood shaft was used to transfer the motor rotation to the harvester fixed at the low end of the tank. A hollow shaft precision potentiometer (NP32HS) is installed on the output shaft of the motor to measure the rotational angle, which is also the base excitation angle of the harvester. The servo motor is connected to the wood shaft with a 3D printed U shape adapter to transfer the rotation stably. A bearing at the bottom of the tank is used to hold the shaft so that it can keep stable and rotate along with the motor shaft. The swing angle defined in this paper is the peak-to-peak rotation angle of the shaft. The FLEX SEAL (B00L3MDI0I, Swift Response, LLC), a rubberized sealant spray coating, is sparged over the piezoelectric FMC and wires for water proof in the experiment. The right part shows the DC power source, energy harvesting circuit, and the circuits for the entire experiment system control. The servo motor was controlled by the stepping motor drive (HBS57). The excitation angle amplitude and frequency was programmed and fed to the micro controller (MSP432, Texas Instruments) which controls the servo motor drive. The MASTECH DC power supply (HY3005F-3) is used to power the servo drive, motor, potentiometer, and the control circuit. The oscilloscope (Tektronix TDS2014C) is used to display and record the generated voltage of the harvester and the sensor signal.

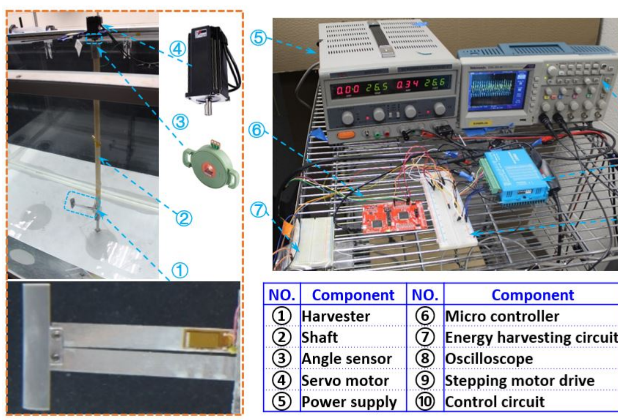

Figure 3. Underwater experimental setup

4. RESULTS AND DISCUSSION

To evaluate the energy harvesting performance of the bio-inspired bistable piezoelectric energy harvester, different excitation angels and frequencies are considered in the experiments. Electrical resistance sweep was also conducted by switching the resistors in the energy harvesting circuit to find the optimal resistance for maximum power output at different load conditions. As an example, Fig. 4 plots the voltage output and the potentiometer sensor output voltage for the swing angle of 30° and frequencies of 1.1 Hz and 1.5 Hz. It is observed during the experiments that the harvester oscillated around one of the local stable state at the excitation frequency of 1.1 Hz and snapped through from one stable state to the other at the excitation frequency of 1.5 Hz. The peak-to-peak voltage output of the harvester at the two excitation frequencies are 80 V and 181 V, respectively, which implies that much large voltage was obtained from the large-amplitude snap-through dynamics of the bistable energy harvester. The sensor output shows almost the same peak-to-peak values with a slight off set from the equilibrium position which is resulted from the accumulated errors in each step of the step motor.

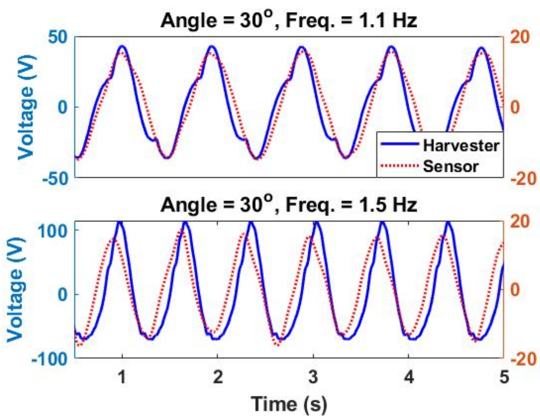

Figure 4. Open circuit voltage output and sensor output at the swing angle of 30° and frequencies of 1.1 Hz and 1.5 Hz.

Fig. 5 presents the average power output of the harvester over various external resistance for the swing angle of 15° at the swing frequencies of 1.0 Hz and 1.1 Hz. No snap-through dynamics was observed during these experiments because of the small swing angle and lower frequencies. The harvester followed the shaft rotation and oscillated around one of the stable states. The maximum average power output is small, which is 0.027 mW and 0.020 mW at the two excitation frequencies, as shown in Fig. 5. The corresponding optimal resistance is 1.5 MΩ. The average power output of the harvester at the swing angle of 30° and frequencies of 1.0 Hz, 1.1 Hz, and 1.2 Hz is plotted in Fig. 6 (a) versus the varying resistance. The maximum average power at these frequencies is around 0.143 mW, 0.088 mW, and 0.058 mW and the corresponding optimal resistance is the same, i.e. 1.5 MΩ. Although the large-amplitude snap-through vibrations were still not observed at these excitation frequencies, the average power output is much larger than the one at the swing angle of 15° in Fig. 5 because of the increase in the swing angle.

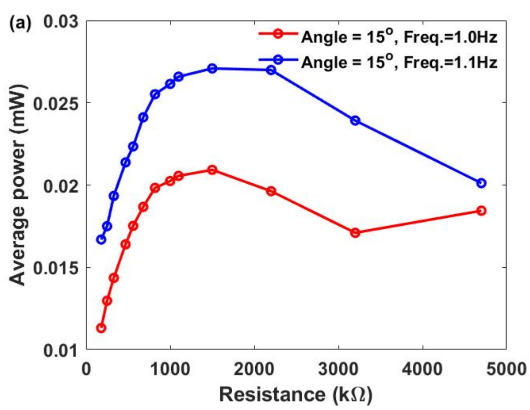

Figure 5. Average power output at the swing angle of 15° and frequencies of 1.0 Hz and 1.1 Hz

As the swing frequency further increased to 1.3 Hz and 1.5 Hz, the large-amplitude snap-through dynamics was observed and higher voltage output was achieved. The average power output at the excitation frequencies of 1.3 Hz and 1.5 H is plotted in Fig. 6 (b) over different resistance. Compared with the results in Fig. 6 (a), it can be seen that much larger power output is attained as the swing frequency exceeded 1.3 Hz because of the harvester oscillated from one stable state to the other one. The maximum average power output at the frequencies of 1.3 Hz and 1.5 H is 0.70 mW and 1.18 m W, respectively. Another observation is that the optimal resistance corresponding the maximum power is 1.0 MΩ, which has been reduced compared to the one at lower excitation frequencies. This is because that the voltage responses of the proposed bistable piezoelectric energy harvester contain higher frequency components during the snap through vibrations.[28] The optimal resistance for a piezoelectric energy harvester is related to the capacitance C_p of the transducer and the vibration frequency ω by $\frac{1}{\omega C_p}$.[29] This indicates that the optimal resistance reduces as the vibration frequency of the harvester increases for the given capacitance.

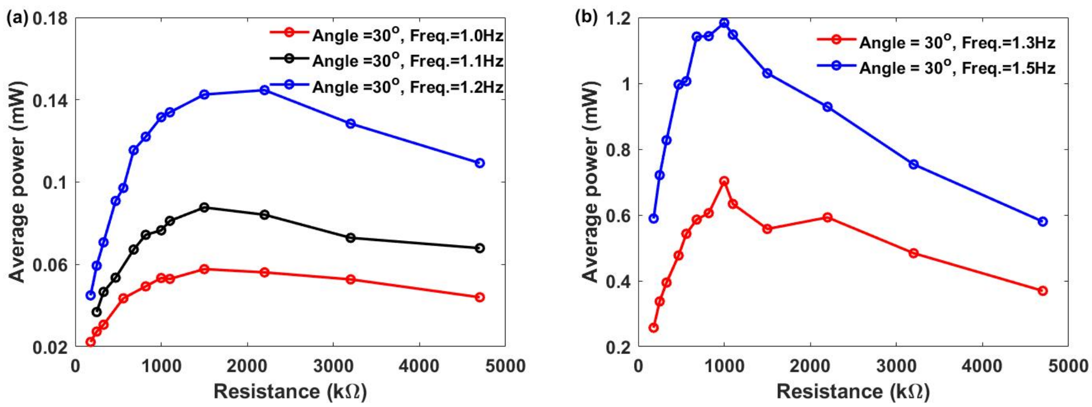

Figure 6. Average power output of (a) local vibration at the swing angle of 30° and frequencies of 1.0 Hz, 1.1 Hz, and 1.2 Hz (b) global vibration at the swing angle of 30° and frequencies of 1.3 Hz and 1.5 Hz.

To further explore the influence of the swing frequency on the power generation performance, experiments were conducted to the harvester at the varying frequency for the two swing angles of 15° and 30° at the constant external resistance of 1 MΩ. This resistance was chosen in the experiments because it's optimal for the case of the large-amplitude global vibration. The average power output of the harvester is presented in Fig. 7 for the two swing angels versus the varying excitation frequency. The results show that for both swing angles the average power output is very small when the swing frequency is less than 1.2 Hz because the harvester oscillated around one of the local stable states. The onset frequency of the large-amplitude snap-through vibration is 1.4 Hz for the swing angle of 15° and 1.3 Hz for the swing angle of 30°. The average power output of the harvester increases quickly along with the swing frequency after the snap-through vibration was activated. The maximum average power output is around 1.5 mW at the swing angle of 30° and frequency of 1.6 Hz. It's worth mentioning that this study aims to validate the concept design and feasibility to harvest energy from fish swing and surrounding fluid for self-powered fish tags. There are still a large space to improve and fine the design, materials, and system integration in future study for practical applications. In addition, the energy harvesting circuit, energy storage and management, sensing circuit , wireless data transmission, and proper attachment are needed to develop and integrate to enable the self-powered fish tags.

5. CONCLUSION

Inspired by the symbiotic relationship between the remora fish and shakers, a self-powered fish telemetry tag is proposed in this study which includes a novel attachment and a bistable piezoelectric energy harvester. The design of the bistable piezoelectric energy harvester was originated from the bistability of the Venus flytrap leaves and is to harvest energy from fish swing and surrounding fluid. The harvester was tailored from a cantilever beam and curved in two directions by applying a displacement constraint at the free ends of the resultant two sub-beams. A semicircular bluff body was added to the free end of the bistable piezoelectric energy harvester

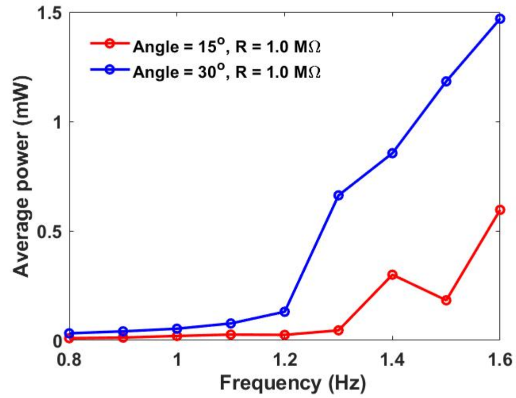

Figure 7. Average power output over the varying swing frequency at the excitation angles of 15° and 30°.

to enhance the fluid-structure interaction for promoting the power output. An experimental setup consisting of a water tank and a servo-drive system was designed to simulate the fish swing and underwater environment for the test of the bio-inspired bistable piezoelectric energy harvester. Different swing angles and frequencies, as well as various external resistance, were considered in the experiments. The results demonstrate that the proposed bio-inspired bistable piezoelectric energy harvester could effectively scavenge energy from fish swing and the surrounding fluid as a sustainable power source for electronic fish tags. The harvester could have much large power output at properly selected swing angle and frequency because of the snap-through phenomenon of the bistable harvester. An average power of 1.5 mW was achieved at the swing angle of 30° and the frequency of 1.6 Hz.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the National Science Foundation (Award Number: 1935951)

REFERENCES

[1] Skerritt, D. J., Fitzsimmons, C., and Polunin, N., "Fine scale acoustic telemetry as an offshore monitoring and research tool recommended practice," *Marine Biology, Ecosystems and Governance Research Group, NERC* (2015).

[2] Lu, J., Deng, Z., Li, H., Myjak, M., Martinez, J., Xiao, J., Brown, R., and Cartmell, S., "A small long-life acoustic transmitter for studying the behavior of aquatic animals," *Review of Scientific Instruments* **87**(11), 114902 (2016).

[3] Voegeli, F. A., Smale, M. J., Webber, D. M., Andrade, Y., and O'dor, R. K., "Ultrasonic telemetry, tracking and automated monitoring technology for sharks," *Environmental Biology of Fishes* **60**(1), 267–282 (2001).

[4] Jepsen, N., Thorstad, E. B., Havn, T., and Lucas, M. C., "The use of external electronic tags on fish: an evaluation of tag retention and tagging effects," *Animal Biotelemetry* **3**(1), 1–23 (2015).

[5] Brunnschweiler, J. M., "Sharksucker–shark interaction in two carcharhinid species," *Marine Ecology* **27**(1), 89–94 (2006).

[6] Allen, K., "Shark mitigation and deterrent measures Submission 47, Appendix 2 – Overview of key concerns regarding acoustic tagging." Parliament of Australia `https://www.aph.gov.au/DocumentStore.ashx?id=93ddfac1-42ea-4509-9e3f-26feceaf13c9&subId=508725`.

[7] Shafer, M. W. and Morgan, E., "Energy harvesting for marine-wildlife monitoring," in [*ASME 2014 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*], American Society of Mechanical Engineers Digital Collection (2014).

[8] Erturk, A. and Delporte, G., "Underwater thrust and power generation using flexible piezoelectric composites: an experimental investigation toward self-powered swimmer-sensor platforms," *Smart materials and Structures* **20**(12), 125013 (2011).

[9] Cha, Y., Verotti, M., Walcott, H., Peterson, S. D., and Porfiri, M., "Energy harvesting from the tail beating of a carangiform swimmer using ionic polymer–metal composites," *Bioinspiration & biomimetics* **8**(3), 036003 (2013).

[10] Cha, Y., Chae, W., Kim, H., Walcott, H., Peterson, S. D., and Porfiri, M., "Energy harvesting from a piezoelectric biomimetic fish tail," *Renewable Energy* **86**, 449–458 (2016).

[11] Li, H., Tian, C., Lu, J., Myjak, M. J., Martinez, J. J., Brown, R. S., and Deng, Z. D., "An energy harvesting underwater acoustic transmitter for aquatic animals," *Scientific reports* **6**(1), 1–9 (2016).

[12] Qian, F., Abaid, N., and Zuo, L., "Multiple-scale analysis of a tunable bi-stable piezoelectric energy harvester," *ASME Letters in Dynamic Systems and Control* **1**(2) (2021).

[13] Fan, K., Tan, Q., Zhang, Y., Liu, S., Cai, M., and Zhu, Y., "A monostable piezoelectric energy harvester for broadband low-level excitations," *Applied Physics Letters* **112**(12), 123901 (2018).

[14] Li, Y., Zhou, S., Yang, Z., Guo, T., and Mei, X., "High-performance low-frequency bistable vibration energy harvesting plate with tip mass blocks," *Energy* **180**, 737–750 (2019).

[15] Fu, H. and Yeatman, E. M., "Rotational energy harvesting using bi-stability and frequency up-conversion for low-power sensing applications: Theoretical modelling and experimental validation," *Mechanical Systems and Signal Processing* **125**, 229–244 (2019).

[16] Huang, D., Zhou, S., Han, Q., and Litak, G., "Response analysis of the nonlinear vibration energy harvester with an uncertain parameter," *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics* **234**(2), 393–407 (2020).

[17] Zou, H.-X., Zhang, W.-M., Wei, K.-X., Li, W.-B., Peng, Z.-K., and Meng, G., "A compressive-mode wideband vibration energy harvester using a combination of bistable and flextensional mechanisms," *Journal of Applied Mechanics* **83**(12) (2016).

[18] Tan, T., Yan, Z., Ma, K., Liu, F., Zhao, L., and Zhang, W., "Nonlinear characterization and performance optimization for broadband bistable energy harvester," *Acta Mechanica Sinica* **36**(3), 578–591 (2020).

[19] Qian, F., Zhou, S., and Zuo, L., "Approximate solutions and their stability of a broadband piezoelectric energy harvester with a tunable potential function," *Communications in Nonlinear Science and Numerical Simulation* **80**, 104984 (2020).

[20] Priya, S., Song, H.-C., Zhou, Y., Varghese, R., Chopra, A., Kim, S.-G., Kanno, I., Wu, L., Ha, D. S., Ryu, J., et al., "A review on piezoelectric energy harvesting: materials, methods, and circuits," *Energy Harvesting and Systems* **4**(1), 3–39 (2017).

[21] Flammang, B. E. and Kenaley, C. P., "Remora cranial vein morphology and its functional implications for attachment," *Scientific reports* **7**(1), 1–5 (2017).

[22] Masana, R. and Daqaq, M. F., "Electromechanical modeling and nonlinear analysis of axially loaded energy harvesters," *Journal of vibration and acoustics* **133**(1) (2011).

[23] Stanton, S. C., McGehee, C. C., and Mann, B. P., "Nonlinear dynamics for broadband energy harvesting: Investigation of a bistable piezoelectric inertial generator," *Physica D: Nonlinear Phenomena* **239**(10), 640–653 (2010).

[24] Cao, J., Wang, W., Zhou, S., Inman, D. J., and Lin, J., "Nonlinear time-varying potential bistable energy harvesting from human motion," *Applied Physics Letters* **107**(14), 143904 (2015).

[25] Syta, A., Bowen, C., Kim, H., Rysak, A., and Litak, G., "Experimental analysis of the dynamical response of energy harvesting devices based on bistable laminated plates," *Meccanica* **50**(8), 1961–1970 (2015).

[26] Pan, D. and Dai, F., "Design and analysis of a broadband vibratory energy harvester using bi-stable piezoelectric composite laminate," *Energy conversion and management* **169**, 149–160 (2018).

[27] Kim, S.-W., Koh, J.-S., Lee, J.-G., Ryu, J., Cho, M., and Cho, K.-J., "Flytrap-inspired robot using structurally integrated actuation based on bistability and a developable surface," *Bioinspiration & biomimetics* **9**(3), 036004 (2014).

[28] Qian, F., Hajj, M. R., and Zuo, L., "Bio-inspired bi-stable piezoelectric harvester for broadband vibration energy harvesting," *Energy Conversion and Management* **222**, 113174 (2020).

[29] Liao, Y. and Sodano, H. A., "Optimal parameters and power characteristics of piezoelectric energy harvesters with an rc circuit," *Smart materials and Structures* **18**(4), 045011 (2009).