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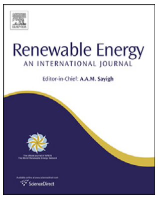

Energy harvesting from a piezoelectric biomimetic fish tail

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ABSTRACT

Understanding fish migratory patterns and movements often relies on tags that are externally or internally implanted. Energy harvesting from fish swimming may benefit the state of the art of fish-tags, by increasing their battery lifetime and expanding their sensory capabilities. Here, we investigate the feasibility of underwater energy harvesting from the vibrations of a biomimetic fish tail though piezoelectric materials. We propose and experimentally validate a modeling framework to predict the underwater vibration of the tail and the associated piezoelectric response. The tail is modeled as a geometrically tapered beam with heterogeneous physical properties, undergoing large amplitude vibration in a viscous fluid. Fluid-structure interactions are described through a hydrodynamic function, which accounts for added mass and nonlinear hydrodynamic damping. To demonstrate the practical benefit of energy harvesting, we assess the possibility of powering a wireless communication module using the underwater vibration of the tail hosting the piezoelectrics. The electrical energy generated by the piezoelectrics during the undulations of the tail is stored and used to power the wireless communication device. This preliminary test offers compelling evidence for future technological developments toward self-powered fish-tags.

1. Introduction

The design of miniature self-sustained devices powered by renewable energy sources have received considerable attention in the last few years [1–3]. Energy harvesting from the environment can especially benefit field applications, where the deployment of sensors is often hampered by limited lifetime, high maintenance, and large battery weight [4–6]. For example, the study of wildlife through externally or internally implanted sensing systems can greatly benefit from energy harvesting technologies, which could afford long observations and expand the sensory output [7–9].

Smart materials have been recently proposed to be a promising technology toward self-powered animal monitoring [7,9]. Energy harvesting of mechanical energy through piezoelectrics [10–13], ionic polymer metal composites (IPMCs) [14–18], magnetostrictive materials [19,20], and shape memory alloys [21] has been extensively studied [4–6]. Based on the current state of technology, piezoelectric materials are generally preferred for their efficiency and reliability [22–25]. For example, energy harvesting from the human body through the use of piezoelectric materials has been demonstrated in the context of walking [26], limb motions [27], jaw movements [28], and heartbeats [29]. Beyond the human body, energy harvesting from avian flight using piezoelectrics has been considered in Ref. [7].

While most of these studies have focused on in-air applications, a few recent efforts have considered the possibility of underwater energy harvesting through piezoelectric materials [30–35]. For example, the so-called energy harvesting eel converting energy from a fluid flow has been demonstrated in Refs. [30,31]. Energy harvesting from underwater base excitation of piezoelectric beams has been investigated in Refs. [32,35]. Finally, hydraulic pressure fluctuations as a source of usable energy for piezoelectric harvesting have been studied in Refs. [33,34]. Here, we seek to investigate the possibility of harvesting mechanical energy from the undulations of a fish tail toward the design of self-powered fish-tags.

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Specifically, we consider the biomimetic fish tail developed by our group in Ref. [9] to simulate the swimming of a thresher shark. The tail is fabricated through injection molding of Silicone, and a slender stainless steel beam is inserted in the mold to increase its stiffness. The active tail hosts two piezoelectric composites that are assembled following [32,35] and are attached to both sides of the tail in a bimorph configuration. As the tail vibrates under base excitation, the piezoelectric composites generates a relatively large voltage output, which can be rectified to power external batteries or other devices [22,23]. Such voltage output depends on the amplitude and frequency of base excitation, which ultimately control the underwater vibration of the biomimetic tail. We propose a tractable modeling framework to describe the underwater vibration of the tail and, ultimately, predict the voltage output for energy harvesting. The tail is modeled as a geometrically tapered beam with heterogeneous physical properties due to both the presence of the piezoelectric composites and the stainless steel beam. The effect of the surrounding water is modeled through a complex hydrodynamic function [36], which accounts for added mass and nonlinear hydrodynamic damping associated with vortex shedding and advection under large amplitude vibration. From the model of underwater vibrations, we compute the average curvature in the region covered by the piezoelectric composites, which is, in turn, used to predict the output voltage [32,35].

The model is validated through a series of experiments, in which the amplitude and frequency of base excitation are systematically varied to assess the robustness of our predictions with respect to the open-circuit voltage and the vibration at the tip. To demonstrate the possibility of converting some of the vibration energy into usable electrical energy, we design a laboratory setup to simulate a plausible instance of a self-powered fish-tag. In such a setup, we connect the piezoelectric composites to an energy storage module, which powers a wireless unit with a temperature sensor. As the biomimetic tail vibrates underwater, charge builds up in the storage module until temperature can be measured and transmitted wirelessly to an external receiver.

From practical and methodological points of view, the main contributions of this effort are: i) addressing the feasibility of energy harvesting devices for fish tags using a piezoelectric biomimetic fish tail; ii) demonstrating the entire energy harvesting and usage process, from capturing mechanical energy to sensing and powering a wireless communication module; and iii) developing a mathematical framework to model the process, including the underwater large amplitude vibrations of the biomimetic fish tail, the energy conversion through piezoelectric composites, and the storage of the harvested electrical energy.

This paper is organized as follows. In Section 2, we introduce the modeling framework to predict the undulations of the tail and the voltage output of the piezoelectrics. In Section 3, we demonstrate the accuracy of the model through a series of experiments in which the base excitation is parametrically varied. In Section 4, we discuss the practical implementation of the approach through the ad-hoc experimental setup. Conclusions are summarized in Section 5.

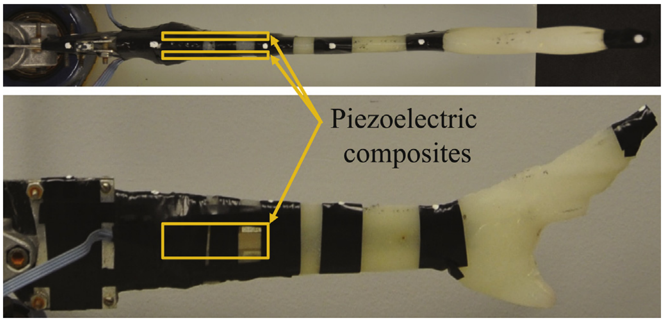

Fig. 1. Biomimetic fish tail hosting two piezoelectric composites. White markers on the black electrical tape aid in tracking the tail motion through video processing.

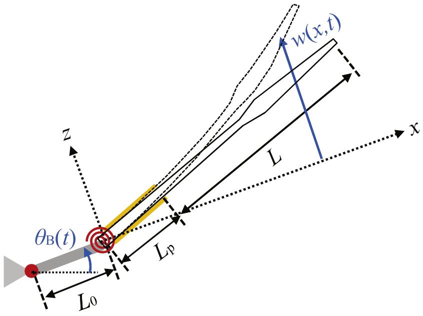

Fig. 2. Schematic of the undulation of the biomimetic fish tail.

2. Modeling

2.1. Underwater base excitation

The passive biomimetic fish tail used in this study is equivalent to that designed in Ref. [9], see Fig. 1. To simplify the analysis and compensate for imperfections in the realization of the clamp, we model the thick portion of the tail that is not covered by the piezoelectrics and is adjacent to the base as a rigid pendulum, connected to the rest of the structure through a torsional spring. As displayed in Fig. 2, we place the origin of the material abscissa x in correspondence of the torsional spring of stiffness κ and focus on the base excitation of a beam with varying geometrical and physical properties. The base excitation is controlled through the rotation $\theta_B(t)$, so that the x-axis rotates with respect to the otherwise quiescent fluid and the elastic deflection is measured along the rotating z-axis.

Next, by assuming that the portion of the tail covered by the piezoelectric composites is considerably stiffer than the rest of the tail, we neglect its dynamics. Specifically, we hypothesize that for $0 < x < L_p$, the tail elastic deflection $w_p(x,t)$ can be approximated by:

$$w_p(x,t) = A_1(t)x^3 + A_2(t)x^2 + A_3(t)x + A_4(t) \tag{1}$$

where $A_1(t)$, $A_2(t)$, $A_3(t)$, and $A_4(t)$ are unknown functions of time. Note that Eq. (1) is the solution of the elastica with a null distributed load and constant stiffness [37]. These constants are determined from the following boundary conditions:

$$w_p(0,t) = 0 \tag{2a}$$

$$\kappa \left.\frac{\partial w_p(x,t)}{\partial x}\right|_{x=0} = k_p \left.\frac{\partial^2 w_p(x,t)}{\partial x^2}\right|_{x=0} \tag{2b}$$

$$w_p(L_p,t) = w(L_p,t) \tag{2c}$$

$$k_p \left.\frac{\partial w_p(x,t)}{\partial x}\right|_{x=L_p} = k(L_p) \left.\frac{\partial w(x,t)}{\partial x}\right|_{x=L_p} \tag{2d}$$

$$k_p \left.\frac{\partial^2 w_p(x,t)}{\partial x^2}\right|_{x=L_p} = k(L_p) \left.\frac{\partial^2 w(x,t)}{\partial x^2}\right|_{x=L_p} \tag{2e}$$