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Piezoelectric eels for powering pollution monitoring wireless sensor networks in watercourses

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Abstract
Continuous monitoring of pollutants in watercourses requires an uninterrupted sensors' power supply. In the case of large networks, when sensor nodes can be placed in hardly accessible locations, energy harvesting can provide a feasible solution to assure power autonomy. The possibility to use a harvesting concept known as the piezoelectric eel is studied in this work. A custom code that implements the penalty immersed boundary method is developed and used to simulate eel's motion. Based on the results of the calculations, eel's design, consisting of a structural support covered with active piezoelectric polymer layers, is finalised. The respective power conditioning electronics is also been designed and prototyped. The obtained experimental results are finally given.

Keywords: Pollution monitoring, wireless autonomous sensor networks, energy harvesting, piezoelectric eel, PVDF

1. Introduction

The need of developing energy solutions, which can convert surrounding energy into electricity and supply low-consumption electronic devices with the necessary power, has recently arisen. The respective technologies used to convert renewable energy sources are termed energy harvesting. Wireless monitoring via wide wireless sensor networks is one of the applications that benefits mostly from these concepts. Wireless communication networks generally comprise sensor nodes, which collect and transmit data to network gateways. Depending on the required topography, there can be a large number of sensor nodes that can be placed even in hard-to-access locations. The majority of wireless sensors available today are battery-powered, thus having a limited lifetime and requiring periodical battery changes. If a large number of sensors, combined with inaccessible locations, is considered, energy harvesting can provide an elegant and environmentally friendly solution [1]. The application considered in this work is that of active wireless pollutant monitoring in river streams via a sensor network with nodes deployed directly in watercourses and communication gateways placed on the riverbanks. To achieve autonomous power supply, a piezoelectric device, called the piezoelectric eel, is investigated.

2. Piezoelectric eel concept

A piezoelectric eel is a thin flag-like composite device based on piezoelectric polymers, previously investigated in literature [2, 3] but never coupled to real electric loads (i.e. wireless sensor nodes). When placed in a watercourse behind a bluff body that, depending on fluid velocity and the size and shape of the body itself, induces Karman vortices, the eel starts fluttering (Fig. 1). Alternating electric charges build thus up on the piezoelectric polymers layers. The charges are collected by electrodes covering the piezoelectric material and conditioned by an energy harvesting electronics. Based on a thorough literature review [2-5], in this case a polyvinylidene fluoride (PVDF) eel is considered. In fact, PVDF has a piezoelectric coefficient d as much as 10 times larger than that of other polymers, an electromechanical coupling factor $\kappa = 12$ %, while being highly conductive, flexible (with elongations $\varepsilon \leq 50$ %), low weight and mechanically stable (with a yield strength $\sigma_{0.2} = 55$ MPa and an elastic modulus $E = 2\text{-}4$ GPa) [6]. Moreover, electrodes can be readily deposited onto it by using sputtering or screen-printing.

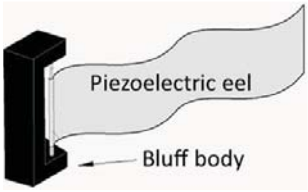

Figure 1. Piezoelectric eel concept

2.1. Eel design and prototyping

The piezoelectric eel configuration considered in this paper is based on previous work [3-4], with some modifications regarding the substrate material and watertight protection. As depicted in Fig. 2, the device consists of: a central structural $t_s = 125$ μm Mylar layer, two active $t_{PVDF} = 110$ μm PVDF layers annealed at 60 °C and plasma etched to ensure better adhesion of the electrodes, sixteen silver ink ultra-thin electrode segments deposited via screen printing, external protective watertight $t_p = 25$ μm Mylar layers and pressure sensitive $t_{ep} = 10$ μm epoxy layers between the PET and the PVDF layers. The resulting structure thus has nine layers with a total thickness $t_T \approx 450$ μm (disregarding electrodes). The length of the device is $L = 621$ mm, while its width is $w = 194$ mm. Each of the electrode segments comes with a collector that is connected at eels' clamped end with a solder tab crimped contact. To enable experimental measurements, a suitable piezoelectric eel test bed is also designed (Fig. 3).

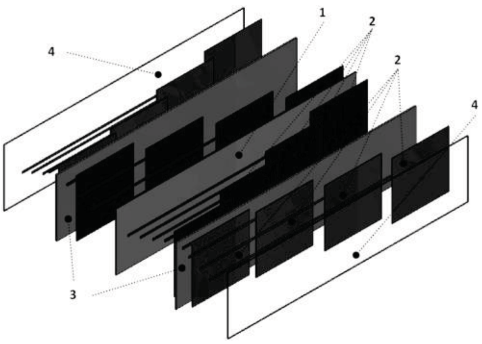

Figure 2. Piezoelectric eel structure: central Mylar layer (1), silver ink electrodes (2), PVDF layers (3), outer Mylar layers (4)

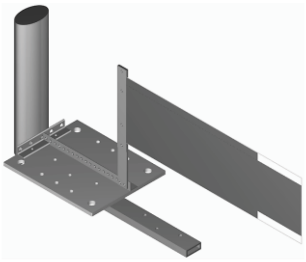

Figure 3. Piezoelectric eel test bed with exchangeable bluff bodies and variable eel positions

2.2. *Numerical model*

To model the behaviour of the eel, a custom C++ code is developed. The penalty immersed boundary method, where the fluid flow is modelled using Navier-Stokes equations for an incompressible viscous fluid, is implemented. The eel is modelled as two beams: one massless, which interacts with the fluid, and a second massive, which is connected to the first one with stiff springs [7]. The two-dimensional model (Fig. 4), allowing vorticities and their interaction with the eel to be clearly visible, constitutes the basis for the optimisation of eel's structure and fluid flow conditions by employing the GoSUMD software by AIMdyn, Inc. [8]. Via the resulting optimisation process and sensitivity analyses of the design parameters aimed at maximising the output voltages, the domain of bluff body dimensions and distances between the bluff body and the eel, to be investigated experimentally, is determined.

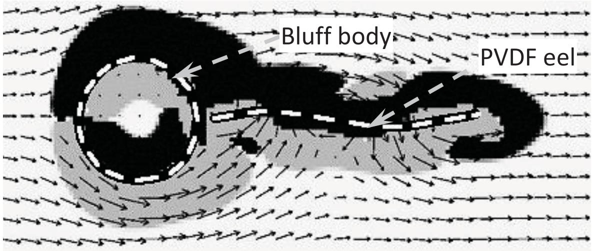

Figure 4. Numerical simulation of piezoelectric eel's behaviour

2.3. *Energy harvesting circuitry*

The output voltage of the proposed energy harvesting solution has an AC character and its amplitude depends on the river flow velocity, bluff body geometry etc. On the other hand, constant DC voltage levels are required by the load. For this purpose, an energy harvesting circuitry, based on a Fujitsu harvesting chip with an embedded full wave rectifier, is designed and manufactured. It also enables charging a supercapacitor where excessive energy is stored. When the sensor nodes are activated, the supercapacitor supplies the required energy bursts enabling thus the repetitive measurement and transmission cycles.

2.3. *Experimental results*

Using the described eel prototype and test bed of Figures 2 and 3, experiments are performed in controllable flow conditions with flow velocities in the $v = 0.5$-2 m/s range in the flow tunnel at the Naval Research Institute in Zagreb, Croatia (Fig 5). Flows with $v < 2$ m/s induce the twisting of the eel resulting in its partial delamination and eventually even breakdown.

The experiments allowed establishing that the largest rms voltages are obtained by using a $\phi = 200$ mm tubular bluff body at a $l \approx 100$ mm distance from eel's fixation, at a flow velocity $v \approx 1$ m/s. The oscillatory shape of the eel in this condition, as shown in Fig. 5, is sinusoidal, with the highest voltages produced, longitudinally, in the 2nd and 3rd piezoelectric section (electrodes' position) along the eel (cf. Fig. 2). The resulting maximal output voltages reach $U_{\max} \approx 30$ V. Based on the respective supercapacitor's charging periods, the corresponding output power can be estimated to be in the $P \approx 10$ mW range. The overall power could ultimately be enhanced by using several eels.

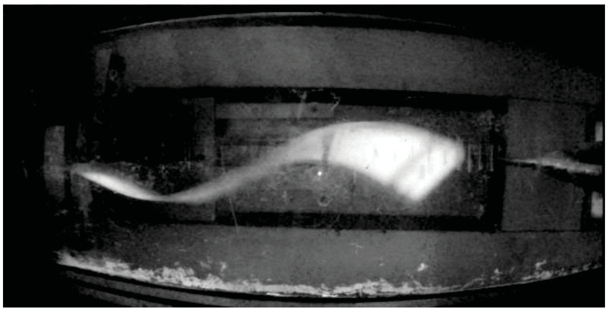

Figure 5. Piezoelectric eel during experiments in the flow tunnel

3. Conclusions and outlook

This paper presents a novel energy harvesting concept for powering wireless sensor network nodes in watercourses. A piezoelectric eel is hence prototyped and a corresponding numerical model is developed. The optimization of eel's design is performed by using a suitable software package based on computational algorithms for nonlinear model representation and sampling, enabling simultaneous examination of all the design degrees-of-freedom. Experiments performed in a flow tunnel allowed assessing that output voltages up to 30 V and powers of up to 10 mW can be obtained for a single eel at an optimal distance from a $\phi = 200$ mm tubular bluff body.

In future work the device will be tested also in real river conditions, paired with a real sensor cluster.

Acknowledgements

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