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Simultaneous finite element analysis of circuit-integrated piezoelectric energy harvesting from fluid-structure interaction

Srivathsan Ravi, Andreas Zilian *

Institute of Computational Engineering, University of Luxembourg, 6 Avenue de la Fonte, 4362 Esch-sur-Alzette, Luxembourg

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ABSTRACT

Flow-driven piezoelectric energy harvesting is a strongly coupled multiphysics phenomenon that involves complex three-way interaction between the fluid flow, the electromechanical effect of the piezoelectric material mounted on a deformable substrate structure and the controlling electrical circuit. High fidelity computational solution approaches are essential for the analysis of flow-driven energy harvesters in order to capture the main physical aspects of the coupled problem and to accurately predict the power output of a harvester. While there are some phenomenological and numerical models for flow-driven harvesters reported in the literature, a fully three-dimensional strongly coupled model has not yet been developed, especially in the context of flow-driven energy harvesting. The weighted residuals method is applied to establish a mixed integral equation describing the incompressible Newtonian flow, elastic substrate structure, piezoelectric patch, equipotential electrode and attached electric circuit that form the multiphysics fluid-structure interaction problem. A monolithic numerical solution method is derived that provides consistent and simultaneous solution to all physical fields as well as to fluid mesh deformation. The approximate solution is based on a mixed space-time finite element discretization with static condensation of the auxiliary fields. The discontinuous Galerkin method is utilized for integrating the monolithic model in time. The proposed solution scheme is illustrated in the example of a lid driven cavity with a flexible piezoelectric bottom wall, demonstrating quantification of the amount of electrical energy extractable from fluid flow by means of a piezoelectric harvester device. The results indicate that in order to make reliable predictions on the power output under varying operational states, the realization of strong multiphysics coupling is required for the mathematical model as well as the numerical solution scheme to capture the characteristics of flow-driven energy harvesters.

1. Introduction

Flow in and around engineering structures may elicit various responses from the structures, such as vortex-induced vibrations, flutter, and galloping. These responses may become dangerous and destructive. In many civil engineering applications, methods are often sought to avoid these dangerous interactions of a structure with the surrounding fluid. The per-

* Corresponding author.
E-mail address: andreas.zilian@uni.lu (A. Zilian).

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spective in flow-driven energy harvesting is to use the available flow energy through controlled hydro- or aeroelasticity phenomena and harness potentially harmful fluctuations to provide power supply to low power electronic devices. In flow-driven piezoelectric energy harvesting, the dynamic strain induced in the piezoelectric material by the kinetic energy of the fluid is transformed into electrical energy through the direct piezoelectric effect.

Recent surveys [1–4] on energy harvesting from piezoelectric material show that studies have predominantly focused on harvesting energy from vibrations of the structure to which the piezoelectric harvester is attached. Experimental and theoretical studies on piezoelectric energy harvesting from the kinetic energy of fluid is limited. Allen and Smits [5] experimentally studied the behavior of slender piezoelectric eel-like strips placed behind a bluff body. Their study was continued by Techet et al. [6], where multiple eels made of PVDF were stacked vertically behind a single bluff body to study the energy harvesting capabilities of the piezoelectric strips. A similar study on energy harvesting eels placed in the wake of a bluff body was carried out by Taylor et al. [7]. Kármán vortex sheets generated by bluff bodies placed in wind flows have also been utilized to study energy harvesting capabilities of piezoelectric energy harvesters. Wind energy can be used to create flapping of flag-like membranes with piezoelectric materials in a unimorph or bimorph configuration. Robbins et al. [8] performed experiments for generating electrical energy from piezoelectric materials placed in wind flow. Erturk et al. [9] conducted experiments on energy harvesting from flow-excited morphing airfoils. In a similar study, Anton and Inman [10] investigated the possibility of harvesting vibration energy and solar energy from a mini unmanned air vehicle (UAV). They reported that the piezoelectric patches were able to harvest enough power to fully charge a small battery when the volume of the piezoelectric material was increased. The above mentioned references are some of the frequently cited experimental studies on flow-induced energy harvesting.

On the mathematical modeling front, a variety of modeling approaches have been proposed to analyze piezoelectric energy harvesters placed in wind flow. Erturk et al. [11] presented a mathematical model for analyzing the energy harvesting potential of piezoaeroelastic systems. They presented a frequency domain analysis of a wing-based piezoaeroelastic harvester. De Marqui et al. [12] presented a time domain piezoaeroelastic model for airflow excitation of cantilever plates representing wing-like structures with embedded piezoelectric material for continuous and segmented electrode configurations. Their piezoaeroelastic model was a combination of electromechanically coupled finite element model [13] and an unsteady vortex-lattice aerodynamic model. These modeling approaches are application specific. For example, the model proposed in [11] is a lumped parameter wing-section model and can be used to analyze power output of a harvester placed on the wing section of an unmanned air vehicle. Akaydin et al. [14] explored energy harvesting from unsteady turbulent flow using piezoelectric materials, where the action of turbulent boundary layers and wakes of circular cylinders at high Reynolds number on piezoelectric cantilever beams was investigated. They used FLUENT software to analyze the three-way interaction accounting for the aerodynamics, structural vibration, and the electrical response of the piezoelectric material. Navier-Stokes equation was used to model the incompressible flow field, and the piezoelectric beam was modeled as a single degree of freedom oscillator (SDOF). SDOF models are limited to a single vibration mode and cannot accurately predict the power output of a harvester [15]. Mehmood et al. [16] presented a numerical model, where the governing equations were solved simultaneously and the coupling was based on Hamming fourth-order predictor-corrector technique. More recently Amini et al. [17] presented a more comprehensive numerical model for analyzing piezoelectric energy harvesting from fluid-structure interactions. Their numerical model was a combination of openFOAM solver for fluid domain and finite element method for the piezoelectric material. The finite element model was based on Euler–Bernoulli approximations with linear through-the-thickness approximation of the electric potential. The model was validated against the results from the model proposed by [14]. The model proposed in [17] is more comprehensive than the model proposed in [14].

Numerical modeling of piezoelectric energy harvesting from fluid flow is still a very challenging task due to the strongly coupled three-way information exchange between the different domains; in order to identify the deformation of the structure and the power generated for a given load resistance, the loading from the fluid flow must first be determined. However, the fluid loads cannot be determined without the information of the structural deformation and the influence of the electric load on this deformation. The models proposed by both Akaydin et al. [14] and Amini et al. [17] follow a partitioned approach with different discretization schemes for the fluid domain and the piezoelectric structure. In partitioned approaches, strong coupling can be achieved by iterated solution of the subsystems with additional computational effort. In [14], the authors themselves suggested strongly coupled three-dimensional approach as an improvement to their proposed model.

This research work proposes a simultaneous solution to the coupled system, where the deformation of the structure, fluid flow, and the electrical outputs are solved simultaneously in time. Simultaneous solution methods are preferable for strongly coupled problems to ensure stability and accelerated convergence [18]. In this approach, the nonlinear weak form of the governing equations of the fluid, the piezoelectric structure with electrode and the electrical circuit is formulated as a single equation and solved simultaneously, along with the fluid mesh deformation within each time step. The coupled system is uniformly discretized by time-discontinuous stabilized (spatially three-dimensional) space-time finite elements, leading to a monolithic solution framework. The 3D continuum approach enables application of piezoelectric constitutive laws, simplifies the description of anisotropic material behavior and enables modeling of coupled bending-torsion harvesters. The ability of the proposed formulation to model flow-driven piezoelectric harvesters is illustrated through the example of a driven cavity with flexible piezoelectric bottom wall.