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Modeling and experimental study of a piezoelectric energy harvester from vortex shedding-induced vibration

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ABSTRACT

Piezoelectric energy harvesters (PEHs) from fluid energy sources, particularly vortex shedding–induced vibrations, have received considerable attention in recent years. However, there still exists a common problem with these harvesters: the current optimum position of a vortex shedding–induced PEH located in the wake of a bluff body is commonly obtained through a series of experiments. This study proposes a theoretical model to determine the best position and demonstrate this mechanism. This theoretical model, which consists of fluid–-structure and electromechanical couplings, is derived from the proposed PEH with a flapping sheet structure. The equivalent harmonic force in the fluid–structure coupling part caused by the vortexes on the flapping sheet is expressed by Bernoulli's law and Lamb–Oseen vortex model. The system equations in the electro–mechanical coupling part are then obtained utilizing Euler–Bernoulli beam theory and an equivalent circuit model. This model was validated initially through the published data in the reference and then through the experimental results from a proposed PEH prototype. The optimum position of the PEH in the flow field is revealed by the analytical solution in numerical results and examined in experimental results. Moreover, the balanced match of fluid velocity and bluff body diameter can also contribute to the high–level system performance under the optimal load resistance.

1. Introduction

With the rapid development of precision manufacturing and measurement technology over the past decade, low-power electronics become much lighter and smaller [1]. This phenomenon puts forward higher demands for the power supplement of these devices in a variety of technical fields [2,3]. The traditional battery technology has not kept pace with the rapid advancements of these devices [4]. Using novel energy harvesting technology to gain energy available from ambient environment is an effective solution to solve the current issues. According to operating principles, energy harvesters can mainly classified into electromagnetic [5], electrostatic [6], triboelectric [7] and piezoelectric [8] types.

Piezoelectric energy harvesters (PEHs) have been proposed for low–power electronics to transform vibration energy [9], fluid energy [10], and deformation energy [11] from the ambient environment into electrical energy. These advanced energy harvesting technologies can gradually replace traditional battery technologies with limited lifetime and low energy density [4]. PEHs have been widely employed in wireless sensor network nodes, biomedical medical equipment, and health monitoring devices [12] due to its advantages of high energy density, simple architecture, and scalability.

Fluid energy widely exists in natural and industrial environments from the microscale to the macroscale. PEHs scavenging fluid energy have received much attention recently [13–16]. Two common approaches for them are used, namely, rotation-induced type [17,18] and direct flow-induced type [19,20]. The former type usually utilizes the traditional turbine technology which has a rotary structure of fan blades paired with piezoelectric materials. Although these harvesters can use multiple blades and piezoelectric elements excited simultaneously to capture power in a low-speed flow condition, the complex mechanical structures result in low reliability for long-term applications. The latter type is usually based on aerodynamic or hydrodynamic instability phenomena [10]. Different techniques have been employed, such as high-performance piezoelectric materials [21], bi–stable configurations [22], and hybrid excitations [23], to improve the performance of this type PEH.

Vortex shedding–induced vibration (VSIV) [24] is commonly

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utilized as an excitation source for direct flow-induced PEHs. One issue with designing the VSIV–type PEH system is that the specific position of a harvester can significantly affect the system performance. The optimum position for the maximum output power was first determined by tuning the location of the flow-induced PEHs in experiments [15,19,25]. Although the best location for a specific PEH can be determined by several experimental tests, the internal mechanism is unclear. A dimensional analysis proposed by Akaydin et al. [25] describes the PEH power distribution, which is set at several positions along the wake centerline of a cylinder. The complete power-distance curve which represents the power distribution in their paper could be divided into the growth and decline regions according to the peak output power. After reaching the point of the largest output power, this analytical method can properly describe the nonlinear decay relationship between the power and separation distance from the piezoelectric beam to the cylinder. However, the first part of the curve (as shown in Fig. 6(a) with a green[1] dotted line frame) which shows the increasing relationship between the power and separation distance was not fitted and analyzed in their work. Moreover, this method still cannot predict the optimum PEH position. No theoretical solution currently exists to solve this issue. Thus, developing a theoretical model is necessary to determine the optimum position in the flow for VSIV–type PEHs in practical applications. The current study establishes a three-field coupling model for VSIV–type PEHs by assuming an equivalent harmonic force to determine the optimum position and its affecting factors.

2. Structure design, working principle and motion process

2.1. Structure design

The schematic of the proposed VSIV–type PEH is shown in Fig. 1. The bimorph piezoelectric vibrator consists of one non-piezoelectric layer and two piezoelectric layers (lead zirconate titanate (PZT)), which are placed in the flow wake behind a bluff body (i.e., a smooth cylinder). The fixed end of the beam in the downstream is near the outlet of the tube, whereas the free end is near the cylinder in the upstream. The PZT materials are selected in this work because they have relatively higher piezoelectric constants that compared to the ones of PVDF which are usually used for the PEHs in the fluid environment. In order to solve the high stiffness problem of PZT materials while taking advantage of high piezoelectric constants of them, a thin flapping sheet connected to the free end of the beam is designed in this paper (Fig. 1). The magnets assembled on both sides of the sheet top and bottom surfaces can adjust the natural frequency of the vibrator by changing sizes and shapes. This configuration can offer sufficient space for the vortexes shed from the cylinder to excite the sheet and match the natural frequency of the vibrator with the shedding frequency of the coherent vortexes.

The coordinate systems and dimensions are depicted in Fig. 2. For being convenient to analyze this system, a pure resistance of R is connected as the load circuit. PZT layers with the same poling direction are wired in parallel to this resistance.

On the other hand, considering that high fluid density and high excitation frequency are both effective ways to improve the system output performance, the liquid (water) is chosen as the fluid media in the turbulent environment with high Reynolds numbers in this work.

2.2. Working principle and motion process

The piezoelectric vibrator attached a mass adapter sheet at the free end serves as an energy conversion component in this system. The PEH operation principle is detailed in Fig. 3, where t_0 and t_2 are two instants when the beam vibrates to the upside, whereas t_1 is the instant when it vibrates to the downside. T ($T = t_2–t_0$) is evidently one cycle of the vortexes from one side. The working process is presented as follows:

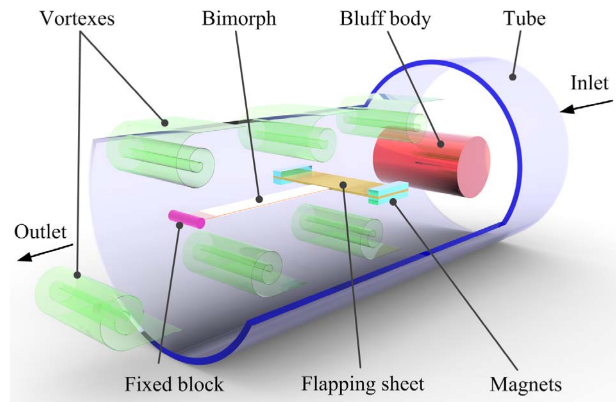

Fig. 1. Schematic of the proposed VSIV type piezoelectric energy harvester.

(a) Firstly, at the moment of t_0, the induced flow ahead of the clockwise vortex A_1 at the upside of the center line impacts on the mass adapter sheet which enables the vibrator deformed upward to bend away from this vortex. Meanwhile, the low pressure region of the counterclockwise vortex B_1 at the opposite of the center line pulls the vibrator down.
(b) Then, when the vibrator deflects to the lowest position at the moment of t_1, the induced flow ahead of the vortex B_2 impacts on the sheet which makes the vibrator deformed downward to bend back. At this time, the low pressure region where the vortex A_1 stagnates produces a suction effect on the sheet which pulls the vibrator up again. The induced flow behind of the vortex B_1, which has little influence on the vibrator due to the large energy dissipation in the process of fluid-structure interaction, takes part of the water away from the sheet surface.
(c) Finally, at the moment of t_2, the next vortex A_2 behind A_1 generates a recirculating pattern of the vibrator motion while the vortex B_2 takes the place of B_1 at the moment of t_0. Theoretically, the time interval between t_0 and t_2 is one cycle of the equivalent harmonic force applied on the sheet by the vortex pair of A_1 and B_1. In other words, the excitation frequency of the equivalent harmonic force is equivalent to the vortex shedding frequency from one side of the cylinder though the locations of A_1 and B_1 are out of phase by π.

Consequently, the periodic process from t_0 to t_2 make the vibrator undergo continual oscillation in the coming flow. Under the excitation of continuous vortexes, the fluid energy derived from a series of vortexes is first transformed into the PEH vibrating energy. Then, the PHE utilizes the direct piezoelectric effects of PZT materials to convert this mechanical energy into electrical energy, which is finally consumed in the optimized resistance.

3. System modeling

A lumped parameter theoretical model, which should truly reflect the multi-filed coupling effects in the hydrodynamic, structural, and electrical aspects of this system, is established to attain the maximum power and clarify the inherent influence factors. This model is mainly divided into two parts: fluid–structure and electro–mechanical couplings.

3.1. Equations of fluid-structure coupling

The first part of the theoretical model focuses on the expression of the equivalent harmonic force caused by the vortexes on the flapping sheet. Given that the PEH vibration is periodic, this force can be

[1] For interpretation of color in Figs. 6 and 12, the reader is referred to the web version of this article.

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