Design and experimental analysis of broadband energy harvesting from vortex-induced vibrations

L.B. Zhang [a], A. Abdelkefi [b], H.L. Dai [a,*], R. Naseer [b], L. Wang [a]

[a] Department of Mechanics, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM 88003, USA

A R T I C L E   I N F O

A B S T R A C T

In this paper, an operable strategy to enhance the output power of piezoelectric energy harvesting from vortex-induced vibration (VIV) using nonlinear magnetic forces is proposed for the first time. Two introduced small magnets with a repulsive force are, respectively, attached on a lower support and the bottom of a circular cylinder which is subjected to a uniform wind speed. Experiments show that the natural frequency of the VIV-based energy harvester is significantly changed by varying the relative position of the two magnets and hence the synchronization region is shifted. It is observed that the proposed energy harvester displays a softening behavior due to the impact of nonlinear magnetic forces, which greatly increases the performance of the VIV-based energy harvesting system, showing a wider synchronization region and a higher level of the harvested power by 138% and 29%, respectively, compared to the classical configuration. This proposed design can provide the groundwork to promote the output power of conventional VIV-based piezoelectric generators, further enabling to realize self-powered systems.

1. Introduction

In recent years, harnessing kinetic energy from ambient vibrations to generate electricity has attracted considerable attention due to its potential applications in operating portable, wearable, and implantable microelectronic devices [1–3]. For example, based on flow-induced vibrations or base excitations, significant effort has been devoted to create realization about a renewable and sustainable energy harvester using one of the transduction mechanisms, such as piezoelectric [4–8], electromagnetic [9,10], and electrostatic [11]. Among all, the piezoelectricity is one of the most attractive transfer mechanisms in mechanical energy conversion [12–14].

There are several aeroelastic phenomena that give rise to dynamic responses of the piezoelectric material structures subjected to wind loading, including galloping [15–18], vortex-induced vibration (VIV) [19–23], and flutter [24]. Among them, VIV-based energy harvesting has received increasing concerns due to its unique features of self-excited and self-restricted oscillations in the lock-in (synchronization) region as the vortex shedding frequency is close to one of the natural frequencies of the structure [25]. The concept of VIV-based energy converter was earlier proposed by Bernitsas et al. [26], who designed the device of vortex-induced vibration aquatic clean energy (VIVACE) which consists of a cylinder submerged

---

perpendicularly to water flows. By virtue of wind flows, Akaydin et al. [27] investigated the performance of a piezoelectric energy harvester undergone VIV oscillations. Afterwards, Dai et al. [28] developed a distributed-parameter model and explored the effects of the parameters of structure dimensions and electrical load resistance on the output efficiency and performance of the VIV-based energy harvester. However, one of the main drawbacks in VIV energy harvesting is the narrow synchronization (lock-in) region and hence any fluctuation in wind speed results in a drastic decrease of the harvested power [29]. This to some extent restricts high efficient of energy harvesting from VIV.

Consequently, some researchers devoted to designing and proposing various techniques such as multimodal configurations [30], optimizing structural geometry [31] and adding small rods [32] to enhance the output performance and widen the synchronization region of energy harvesting systems. Yet there has been much interest in exploiting nonlinear restoring forces to increase vibration responses for high efficient energy harvesting [33–40]. One of the representative to utilize nonlinear restoring forces for energy harvesting was performed by Cottone et al. [41] who used two magnets and observed the bandwidth effect. Subsequently, the extensive and intensive investigations on nonlinear energy harvesters with monostable [42–44], bistable [45–51] and even tristable [52–54] characteristics have been studied to improve the efficiency of energy conversion over a wide operating excitation frequencies. Nevertheless, it should be mentioned that the above significant work almost focuses on energy harvesting from base excitations with introduction of nonlinear restoring or magnetic forces. Quite few studies employed such an approach for energy harvesting from flow-induced vibrations. Bibo et al. [55] designed a galloping energy harvester with nonlinear restoring forces and studied the effects of magnetic force coefficients on the cut-in speed and output performance. Recently, Huynh and Tjahjowidodo [56] simulated the VIV energy harvesting in bistable configurations by using spring components and found the chaotic responses of the harvester.

In this work, for the first time, we experimentally report an original effort to design high-efficient VIV-based piezoelectric energy harvesters using two magnets to provide a nonlinear restoring force, thus enabling to capture power across a broadband synchronization range of wind speed, which is not addressed before. For the sake of demonstrating broadband energy harvesting from VIV, a piezoelectric beam with a circular cylinder attached to its free end is fabricated and placed like a pendulum, with a small circular magnet (upper magnet) added on bottom of the cylinder. Another small circular magnet (lower magnet) is placed on the support which produces a repulsive force and can be adjusted in vertical and horizontal directions resulting in nonlinear magnetic forces, as shown in Fig. 1.

2. Experimental setup

The prototype of the energy harvesting system is shown in Fig. 1(b), which is subjected to cross flows (U) in the wind tunnel with a 35 cm × 35 cm test section. Under the action of vortex-induced force, the pendulum VIV-based energy harvester oscillates, alternatively bending the piezoelectric beam and hence generating a measureable voltage signal through an external electrical load resistance (R). The active length, width, and thickness of the piezoelectric beam are 62 mm, 10 mm, and 0.6 mm, respectively. The dimensions of the circular cylinder are 92 mm in length and 30 mm in diameter. The blockage ratio for the present experiments is about 11.7. A piezoelectric patch (MFC-M2807-P2, Smart Material Corp) is of negligible thickness and connected to the electrical load resistance in order to convert VIV oscillations to electrical power. The wind speed is measured by a Pitot tube anemometer and the generated voltage (V) across the load resistance is measured by the NI 9229 DAQ module.

It should be noted that the dynamics of the energy harvester can be affected with the introduction of magnets placed at a certain distance of Δx and Δy. Indeed, the magnets introduce a force dependent on Δx and Δy that opposes the elastic restoring force of the bended beam. Clearly, due to the magnetic force, the buckling instability of the piezoelectric beam can occur. This buckling effect is strongly dependent on the placement of the two magnets and hence the values of Δx and Δy.

3. Determination of damping and natural frequency for different cases

Firstly, the natural frequency and damping ratio of the proposed VIV-based energy harvesting system are obtained by free vibration tests for different cases, as shown in Tables 1 and 2, respectively. The damping ratio (ξ) for each case is obtained through the equation $\xi = \frac{\ln \eta}{\sqrt{4\pi^2 + (\ln \eta)^2}}$, in which η is the ratio between the vibration amplitudes of the former period and next period during free vibration tests. Indeed, due to the change of Δx and Δy, the natural frequency and damping ratio are lower or higher than those without magnet (case 1). It is noted that as $\Delta x = 0$, the natural frequency is decreased with the increase of Δy. This result can be explained due to the fact that all the considered Δy values are in the bistable (buckled) region. This case (when $\Delta x = 0$) is known by the presence of monostable and bistable regions depending on the placement between the two repulsive magnets. In the bistable region, it is known that a decrease of the spacing distance between the two repulsive magnets results in an increase in the natural frequency of the system which is the case in this study.