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Exploiting stiffness nonlinearities to improve flow energy capture from the wake of a bluff body

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HIGHLIGHTS

- A bi-stable restoring force is used to improve the flow energy capture from the wake of bluff body.
- The bi-stable restoring force is shown to decrease sensitivity to variations of the wind speed about the nominal design value.
- Performance improvement is demonstrated under single- and multi-frequency vortex streets.

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ABSTRACT

Fluid–structure coupling mechanisms such as wake galloping have been recently utilized to develop scalable flow energy harvesters. Unlike traditional rotary-type generators which are known to suffer serious scalability issues because their efficiency drops significantly as their size decreases; wake-galloping flow energy harvesters (FEHs) operate using a very simple motion mechanism, and, hence can be scaled down to fit the desired application. Nevertheless, wake-galloping FEHs have their own shortcomings. Typically, a wake-galloping FEH has a linear restoring force which results in a very narrow *lock-in* region. As a result, it does not perform well under the broad range of shedding frequencies normally associated with a variable flow speed. To overcome this critical problem, this article demonstrates theoretically and experimentally that, a bi-stable restoring force can be used to broaden the steady-state bandwidth of wake galloping FEHs and, thereby to decrease their sensitivity to variations in the flow speed. An experimental case study is carried out in a wind tunnel to compare the performance of a bi-stable and a linear FEH under single- and multi-frequency vortex street. An experimentally-validated lumped-parameters model of the bi-stable harvester is also introduced, and solved using the method of multiple scales to study the influence of the shape of the potential energy function on the output voltage.

1. Introduction

Today, as a result of continuous advances in the fields of microfabrication and micro-electronics, we are able to produce smaller and lower power-consumption sensors [1–4]. Unfortunately, however, operation of these sensors in their respective environment is currently being moderated by the lack of continuous scalable energy sources that can be used to power and maintain them. Batteries, which remain the most adequate power choice, have not kept pace with the sensors' demands, especially in terms of energy density [5]. In addition, their finite life span which necessitates regular replacement and/or recharging can be very costly and cumbersome which may limit the spatial-density of sensors distribution.

To overcome this critical issue, many research efforts are currently focused on the development of scalable energy generators that harvest energy from their environment to power and maintain such low-power sensors. Vibration and flow energy harvesting represent two critical technologies that have recently flourished as major thrust areas for micro-power generation. Vibratory energy harvesters (VEHs) transform mechanical vibrations into electricity; whereas flow energy harvesters (FEHs) capture and transform the kinetic energy of a moving fluid into electrical energy.

Wake-galloping represents one of the most common types of fluid–structure coupling mechanisms used for flow energy harvesting. Typically, as shown in Fig. 1(a), a wake-galloping FEH consists of a mechanical oscillator coupled to an energy harvesting

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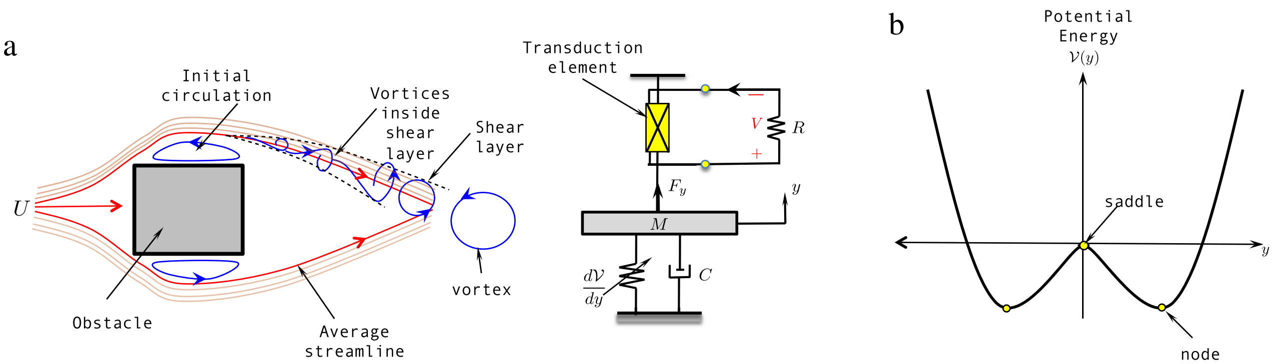

Fig. 1. (a) A schematic of a nonlinear wake-galloping energy harvester. (b) The associated potential energy function. In the figure, R represents the electric load, $\mathcal{V}(y)$ represents the potential energy function of the oscillator, C is a viscous damping coefficient, F_y is the lift force, and V is the output voltage.

circuit through an electromechanical transduction element which can either be piezoelectric, electromagnetic, electrostatic, or magnetostrictive. The oscillator is placed in the downstream of a bluff body or an obstacle. When an initially steady fluid flows over the obstacle, it may undergo symmetry breaking in the form of a Von Kármán vortex street shedding from the trailing edge of the obstacle. The range of flow velocities for which a periodic Von Kármán vortex street can be initiated depends on the Reynolds number of the flow. For circular cylinders and very small Reynolds numbers, $Re \lesssim 40$, the shear layer does not have enough energy to detach from the trailing edge and the vortices remain confined to a recirculation bubble adjacent to the obstacle walls. However, as the Reynolds number is increased beyond $Re \approx 40$, the shear layer detaches from the obstacle and periodic vortex shedding occurs as a result of a Hopf bifurcation. A fast Fourier transform of the time series of the resulting flow velocity reveals a dominant frequency up to approximately $Re \approx 10^5$ [6]. Beyond this value of the Reynolds number, quasi-periodic and chaotic flow patterns can be observed.

For the wide range of *Re* numbers where the vortex shedding is periodic, the shed vortices induce a periodic lift on the mechanical oscillator placed in the downstream of the bluff body. In the *lock-in* region, where the vortex shedding frequency is close to the natural frequency of the oscillator, the flow couples to the natural mode of the harvester resulting in large-amplitude motions. This results in kinetic energy transfer from the flow to the oscillator, which can be transformed into electricity using the electromechanical transduction element.

Wake galloping has several advantages over the traditional rotary-type generators which are known to suffer serious scalability issues because their efficiency drops significantly as their size decreases [7]. This is a result of relatively high viscous drag on the blades at low Reynolds numbers [8], electromagnetic interferences, and mechanical/thermal losses which increase as size decreases. Wake-galloping FEHs, on the other hand, operate using a very simple motion mechanism made from very few parts that would require little maintenance. They can be scaled to fit the desired application; and, most importantly, they can be designed to harvest energy from unsteady flow conditions which targets a niche market that traditional rotary-type generators do not address.

Nevertheless, wake-galloping FEHs have their own shortcomings. Typically, a wake-galloping FEH has a linear restoring force [9,10], which results in a very narrow *lock-in* region. As a result, they do not respond well to the broad range of shedding frequencies normally associated with a variable flow speed. To enhance their response bandwidth under varying flow speeds, we propose exploiting stiffness nonlinearities in the form of a bi-stable restoring force. As shown in Fig. 1(b), a bi-stable potential energy function consists of two potential wells (stable nodes) separated by a potential barrier (unstable saddle). Consequently, when the harvester interacts with the vortical structures generated by the obstacle, it can either perform small-amplitude resonant motions within a single potential well (intra-well motion); or large-amplitude non-resonant motions between the two potential wells (inter-well motion). It is widely accepted that the inter-well dynamics allow a harmonic oscillator to couple to the excitation over a wider range of frequencies.

This same concept has been used to improve the efficiacy of vibratory energy harvesters (VEHs) [11–13]. Previous research findings indicated that, a carefully-designed nonlinear vibratory energy harvester has a wider steady-state bandwidth as compared to an equivalent linear device [14–17]. Furthermore, a comparative uncertainty propagation analysis performed on linear and nonlinear VEHs indicated that the linear device is much more sensitive to uncertainties arising from imprecise characterization of the host environment and/or from manufacturing tolerances [18]. Such promising findings formed the basis of the work presented in this paper.

The main objective of this paper is to show that, by exploiting a bi-stable restoring force, the steady-state bandwidth of wake-galloping FEHs can be broadened, and, thereby their sensitivity to variations in the flow speed can be decreased. To achieve this goal, an experimental case study is carried out in a wind tunnel to compare the performance of bi-stable and linear FEHs under single- and multi-frequency vortex streets. A lumped-parameters model of the bi-stable harvester is introduced and solved using the method of multiple scales. The analytical solution is validated against experimental data and used to study the influence of the shape of the potential energy function on the output voltage of the harvester.

2. Response to a single-frequency periodic wake

2.1. Experimental investigation

In this section, we investigate the response of the bi-stable wake-galloping FEH for the range of *Re* numbers where the vortex shedding has a single dominant frequency. To this end, we construct the piezoelectric wake-galloping FEH shown in Fig. 2. The mechanical oscillator consists of a $95 \times 12.5 \times 0.2$ mm^3 stainless steel cantilever beam attached to a $25 \times 25 \times 50$ mm^3 square-sectioned bluff body at the free end. The transduction element is a piezoelectric microfiber composite (MFC) patch laminated onto the Stainless Steel beam. The obstacle, which generates the Von Kármán vortex street, is a square-sectioned cylinder of characteristics width, $D = 42.5$ mm. The bi-stable restoring force is created by using two repulsive magnets, A, and, B, placed at