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Modeling and identification of circular cylinder-based piezoaeroelastic energy harvesters

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Abstract

In this paper, we develop a validated nonlinear distributed-parameter model for harvesting energy from vortex-induced vibrations. The harvester consists of a piezoelectric cantilever beam with a circular cylinder attached to its end. By using the Euler-Lagrange principle and implementing the Galerkin discretization, a reduced-order model is derived. Based on a five-mode approximation in the Galerkin approach, an identification for the van der Pol wake oscillator coefficients is performed. Further analysis is performed to investigate the effects of the cylinder's tip mass and electrical load resistance on the synchronization region and performance of the harvester. The results show that, depending on the operating freestream velocity, the cylinder's tip mass can be optimized to design enhanced piezoaeroelastic energy harvesters from vortex-induced vibrations.

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Keywords: Energy harvester, vortex-induced vibrations, experimental identification, Galerkin approach;

1. Introduction

Converting ambient and aeroelastic vibrations to usable form of electrical energy has been the subject of several studies over the past few years [1-3]. Many researchers have proposed approaches to convert wasted mechanical vibrations to electrical energy by using the piezoelectric effect as the transduction method. One of the most commonly concepts is harvesting energy from flow-induced vibrations [4-6].

Vortex-induced vibrations (VIVs) of circular cylinders, however, as one of the common phenomena of flow-induced vibrations, has been considered by several researchers in order to convert aeroelastic vibrations to usable form of electrical energy in the past few years [7,8]. A recent experimental research of a self-excited piezoelectric energy harvester subjected to a uniform flow was done by Akaydin et al. [8].

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They tested their designed harvester in a wind tunnel. In their work, however, only experimental results were performed to evaluate the performance of the harvester.

In this work, our objective is mainly to derive a nonlinear distributed-parameter model for piezoelectric energy harvesters from vortex-induced vibrations of circular cylinders, as shown in Section 2. A comparison between the obtained numerical results and the experimental measurements is performed in Section 3. In Section 4, further analysis is performed to investigate the effect of cylinder's tip mass on the performance of circular cylinder-based piezoaeroelastic energy harvester. Summary and conclusions are presented in Section 5.

2. Modeling and representation of the energy harvester

The energy harvester, under consideration, is composed of a bimorph piezoelectric cantilever beam with a circular cylinder attached to its free end, as shown in Fig. 1. The piezoelectric sheets are placed on both sides of the beam, as seen in the red wireframe. The piezoelectric sheets are bounded by two in-plane electrodes of negligible thickness connected in series to an electrical load resistance, R.

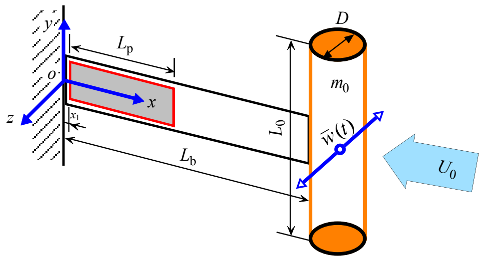

Fig. 1. Schematic of the circular cylinder based-piezoaeroelastic energy harvester.

In this study, we develop a reduced–order model of the piezoaeroelastic energy harvester by applying the Galerkin procedure to the Lagrangian and virtual work. The final governing equations are given by

$$\ddot{r}_i + 2\varsigma_i\omega_i\dot{r}_i + \left(\frac{C_D\rho_0 DU_0 L_0}{2}\left[\varphi_i(L_b) + D/2\,\varphi_i'(L_b)\right]\left[\sum_{j=1}^{n}\left(\varphi_j(L_b) + D/2\,\varphi_j'(L_b)\right)\dot{r}_j\right]\right) + \omega_i^2 r_i - \theta_i V = \alpha_i q \tag{1}$$

$$C_p\dot{V} + \frac{V}{R} + \sum_{i=1}^{n}\theta_i\dot{r}_i = 0 \tag{2}$$

$$\ddot{q} + \lambda\omega_s\left(q^2 - 1\right)\dot{q} + \omega_s^2 q = \frac{A}{D}\sum_{i=1}^{n}\left(\left[\varphi_i(L_b) + \frac{D}{2}\varphi_i'(L_b)\right]\ddot{r}_i\right) \tag{3}$$

where $q(t)$ describes the behavior of the near wake and stands for the lift acting on the cylinder; $r_i(t)$ are the modal coordinates of the displacement and $\varphi_i(x)$ are the mode shapes of a cantilever beam with a tip mass; ρ_0 is the density of fluid; C_{L0} and C_D are the steady lift and mean sectional drag coefficients which can be, respectively, considered equal to 0.3 and 1.2 in the region of well-developed wakes [9]; the values of λ and A are constants and are identified from the experimental measurements; ω_s is the vortex-shedding frequency. Some of the other physical parameters have been given in Table 1.

Table 1. Physical and geometric properties of the harvester

Physical properties	PZT elements	Beam	Cylinder
Length, L_p, L_b, L_0 (mm)	31.5	267	203
Width, w_p, w_b (mm)	25.4	32.5	—
Thickness, t_p, t_b (mm)	0.267	0.635	—
Diameter, D (mm)	—	—	19.8
Dentisy, ρ_p, ρ_b (kg/m^3)	7800	2730	
Mass, m_p, m_b, m_0 (g)	1.68	16	16
Young's modulus, E_p, E_b (GPa)	66	70	—
Strain coefficient, d_{31} (pmV^{-1})	-190	—	—
Permittivity at constant strain, ε_{33} (nFm^{-1})	13.28	—	—
Capacotance, C_p (nF)	20.3	—	—

3. Model validation

To determine the accuracy of the developed reduced-order model for piezoelectric energy harvesting form VIVs, we validate our numerical predictions which are based on five modes in the Galerkin approach with the experimental measurements of Akaydin et al. [8]. The coefficients λ and A are identified to be equal to 0.24 and 12, respectively. These values are in good agreement with the suggested values in [9]. In addition, the physical and geometric properties of this harvester are presented in Table 1.

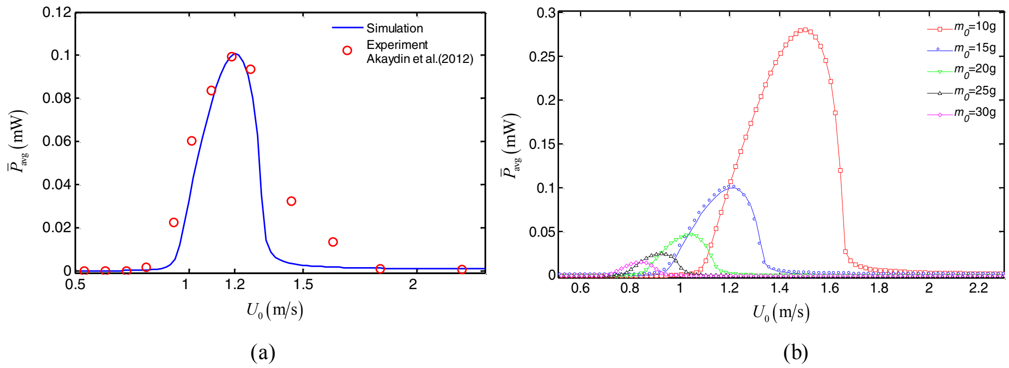

Fig. 2. (a) Comparisons of the variations of the average harvested power as a function of the freestream velocity when using the derived model (solid line) and the experimental measurements of Akaydin et al. [14] (circles); (b) Variation of the average harvested power as a function of the freestream velocity for different tip masses of the cylinder

In Fig. 2 (a), we plot the variation of the average harvested power as a function of the freestream velocity as obtained from our derived model when considering five modes in the Galerkin discretization and the experimental measurements of [8]. It is noted that there is an underestimation in the average harvested power when considering the present model for freestream velocities larger than 1.5 m/s (post synchronization region). The presence of a sudden drop in the simulated results is probably due to the accuracy of the wake oscillator model to the starting of the synchronization region and its peak.

4. Effect of the cylinder's tip mass on the performance of the energy harvester

Piezoaeroelastic energy harvesters are designed to be deployed in different locations, such as ventilation outlets, structure's surface, rivers, bridges, etc. To this end, Fig. 2 (b) shows the variation of the average harvested power as a function of the freestream velocity for different tip masses of the cylinder. Indeed, the resonant freestream velocity is decreased from about 1.4 m/s to about 0.8 m/s when the cylinder's tip mass is increased from 10 g to 30 g. These curves are plotted for the same electrical load resistance which is 2.46×10^6 Ω. At this load resistance, we note that a decrease in the cylinder's tip mass is accompanied by a wider synchronization region and higher values of the average harvested power.

5. Conclusions

We have derived a nonlinear distributed-parameter model for harvesting energy from vortex-induced vibrations of a piezoelectric cantilever beam with a circular cylinder attached to its end. Based on the Euler-Lagrange equation and Galerkin discretization, it is demonstrated that there is an excellent agreement between our derived model and experimental measurements. A parametric study was performed to investigate the effects of varying the cylinder's tip mass on the synchronization region, the performance of the harvester. The results show that a decrease in the cylinder's tip mass is accompanied by a wider synchronization region and higher values of the average harvested power.

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