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Role of the galloping force and moment of inertia of inclined square cylinders on the performance of hybrid galloping energy harvesters

U. Javed[a], A. Abdelkefi[b,*]

[a] Department of Mechanical and Manufacturing Engineering, Saint Cloud State University, Saint Cloud, 56301 MN, USA
[b] Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM 88003, USA

HIGHLIGHTS

- Hybrid Energy harvesting by inclined square cylinder prone to galloping oscillations is investigated.
- A reduced-order model is developed for the beam-cylinder harvester using Galerkin discretization.
- The performance of the energy harvester for various inclination angles are carried out.
- An upright zero inclined or a slight angle of cylinder is preferable for energy harvesting.
- Any backward angle of cylinder is not suitable for attaining high levels of harvested power.

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ABSTRACT

Energy harvesting by a square cross-section cylinder, inclined at different angles from the incoming wind flow, prone to galloping oscillations is investigated. The cylinder is fixed at the tip of a cantilever beam at a definite angle, to which is attached a piezoelectric layer and a permanent magnet placed in the close vicinity of a coil. Existing aerodynamic-coefficient experimental values as a function of the incident angle of attack are utilized for determining the aerodynamic force on each inclined cylinder. Seven-order polynomial is recognized to be a convenient choice for performing the analyses in this study. After establishing the galloping aerodynamic force of each case, a reduced-order model is developed for the beam-cylinder energy harvester using Galerkin discretization. Moment of inertia of each case is calculated using transformation matrix and its impact on the natural frequency is determined. It is shown that the moment of inertia affects the linear characteristics of the galloping-based energy harvester when the inclination of the cylinder is changed. The nonlinear characteristics and performance of the energy harvester for various inclination angles are carried out. It is indicated that an upright zero inclined or a slight angle of cylinder till ten or fifteen degrees towards the wind flow is preferable for energy harvesting. Any forward inclination towards the wind flow greater than that or any backward angle of cylinder away from the wind flow are not suitable for attaining high levels of harvested power. This behavior actually opens the doors for using a movable cylinder at the tip of a beam with lock mechanism that can be tilted at a high forward or backward angle for extreme windy conditions to have reasonable practical power harvesting without damaging the harvester.

1. Introduction

Localized energy production is on the rise due to the arrival and applicability of electronic gadgets, microelectro-mechanical systems, actuators [1,2], health monitoring and wireless sensors [3], and medical implants [4]. Researchers have shown tremendous interest in both base [5–7] as well as flow-induced vibrations [8–14] for effective energy harvesting. Abdelkefi [15] talks in length about utilizing aeroelastic oscillations, such as flutter exhibited by airfoil sections, galloping vibrations of prismatic cylinders, vortex-induced vibrations (VIV) present in circular cylinders, or wake galloping using different transduction mechanisms including piezoelectric [5–7], electromagnetic [8,16,17], and electrostatic [18]. The concept of using hybrid transduction comprising of a functional piezoelectric layer and an electromagnet-coil arrangement for aeroelastic oscillations have recently been proposed [16,17].

* Corresponding author.
E-mail address: abdu@nmsu.edu (A. Abdelkefi).

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The concept of energy harvesting by prismatic shaped cylinders prone to galloping oscillations due to incoming wind flow is relatively new [19–25]. High amplitude oscillations and a wide range of wind speeds over which energy can be harvested make this phenomenon an excellent choice for localized energy production. Where VIV can only harvest energy over a well- defined range of wind speeds, galloping phenomenon can be exhibited as long as the wind speed exceeds beyond a critical threshold called the onset speed of galloping denoted frequently by U_g. An interesting investigation was carried out by Sirohi and Mahadik [20,23] in which they studied the galloping response of triangular and D-section cross-section geometries that were attached at the end of a cantilever beam with piezoelectric layer on it. Zhao et al. [24] performed an experimental investigation for studying the performance of different cross-section geometries exhibiting galloping oscillations. They reported square cylinder as an efficient choice for low wind speed energy harvesting. Bibo and Daqaq [25] developed a universal relationship and curve between dimensionless output power and wind flow speed for galloping energy harvesters. Their curve only depends on the aerodynamic properties of the bluff bodies and is independent of the mechanical and electrical properties of the energy harvester. The established relationship gives an insight into the aerodynamic parameters for optimum performance and the study was therefore one step towards development of efficient energy harvesters. Dai et al. [16] explored the field of electromagnetic energy harvesting by galloping oscillations. They considered a lumped-parameter model, and developed the nonlinear normal form to characterize the type of Hopf bifurcation. Abdelmoula and Abdelkefi [26] considered a square cylinder galloping harvester with piezoelectric layer and determined the effects of capacitance and inductance in connection with an electrical load resistance in the circuitry. They concluded that the electrical capacitance and inductance are not beneficial for energy harvesting applications as they do not increase the levels of power or lower the onset speed of galloping. On the other hand, they demonstrated that the electrical capacitance and inductance are good additions for control purposes of undesirable galloping oscillations.

It is pertinent to mention that all the above studies related to energy harvesting from galloping oscillations considered upright cylinders. An interesting contribution in harvesting galloping energy was performed recently by Hu et al. [27] in which they considered a square cross-section cylinder inclined at different angles, towards or away to the incoming wind flow, in a wind tunnel. One end of their cylinder was free and the other was dipped in oil, acting as a damper and support. They found that as they inclined the cylinder more and more towards the incoming wind flow with forward inclination ($\alpha = +5^\circ$, $+10^\circ$, $+15^\circ$, $+20^\circ$, $+30^\circ$), the corresponding amplitude of their cylinder kept on decreasing. But when it came to backward inclination of cylinder away from the wind flow ($\alpha = -5^\circ$, -10°, -15°, -20°, -30°), they pointed out that for an optimum angle of the backward inclination, the cylinder exhibited maximum oscillation amplitude. Beyond that angle, amplitude of oscillation started to decrease. The current work is one step ahead in understanding the inclined bluff bodies exhibiting galloping oscillations but with focus on harvesting energy from them.

In the current study, a square cross-section cylinder is attached as a tip mass for an aluminum cantilever beam with a unimorph piezoelectric layer and a permanent magnet having a coil in its close vicinity, to form a hybrid galloping harvester that is subjected to wind flow. The square cross-section cylinder ensures the occurrence of galloping phenomenon as wind speed flows over, with a flow incidence angle of β from the tip-mass cylinder as long as minimum, critical, threshold wind speed gets exceeded. The square cylinder is adjusted at different angles ($\alpha = -5^\circ$ and $+5^\circ$, -10° and $+10^\circ$, -15° and $+15^\circ$, -20° and $+20^\circ$, -30° and $+30^\circ$) for inclination towards $+\alpha$ and away $-\alpha$, from wind flow, respectively. Each case would be analyzed individually and comparisons drawn amongst them for the displacement, and piezoelectric and electromagnetic-inductive levels of generated power. These cases might be considered as the same energy harvester on which each cylinder is attached at a particular inclination angle and then behavior being studied or different operating harvesters with a particular inclined cylinder.

The modeling and approximation of aerodynamic force is the trickiest part in any aeroelastic dynamical system. For this research study, the experimental results of aerodynamic coefficient as a function of incident flow angle, C_y-tan(β) of Hu et al. [27] are utilized, except the fact that for using quasi-steady approximation, the 3-D effects are neglected. Therefore, out of the eleven pressure taps used in their experiments, four taps Levels 6–9 near the center are considered. The C_y-tan(β) is then plotted and approximated by a seventh-order polynomial after which the aerodynamic force F_y is straight forward. It should be noted that $\tan(\beta) = \dot{y}/U$ where $\dot{y}$ is the speed of the oscillating cylinder and U is the incoming wind flow speed.

After establishing the aerodynamic force for each inclined case separately, a comparative performance-study between the different inclined sections would be carried out by modeling it. For that, the Galerkin discretization is employed to derive a reduced-order model for the hybrid energy harvester. We then proceed on to perform linear and nonlinear analyses using the distributed-parameter discretization with respect to different incoming wind speeds. Each cylinder inclination $+\alpha$ or $-\alpha$ case subjected to wind flow is going to be tackled separately and comparative study identifying the best inclination for effective energy harvesting would be carried out. As for the configurations that would be found unsuitable for energy harvesting due to the low responses they exhibit, they can be utilized as passive controllers. The intrinsic property of galloping systems of increasing response with increasing wind speed where on one hand is beneficial for energy harvesting purposes, on the other hand can cause structural damage and fatigue in extreme windy conditions. Furthermore, the presence of nonlinearities and high initial conditions can reduce the onset speed, and a sudden jump can occur from no oscillations to sudden high amplitude galloping oscillations. This behavior is called subcritical Hopf bifurcation and can be catastrophic for the energy harvester or any galloping dynamical system for that matter. A suitable lock and controller mechanism if put in place on the cylinder beam juncture, can activate beyond the operational wind speed range, and tilt the cylinder at an inclination angle where either the onset speed is higher or the response is low. Thus, suitable inclination for that period of stormy conditions of wind would act like a passive controller, and system can again come back to its angle of optimized performance once those set of conditions are over.

2. Impacts of the cylinder's inclination on the galloping force

The hybrid energy harvester under consideration is shown in Fig. 1. The piezoelectric layer is attached over the aluminum substrate that is induced with a strain as the beam deflects because of the incoming flowing wind U, and corresponding aerodynamic force caused over the cylinder. This strain energy gets translated into piezoelectric voltage V_p and corresponding electrical power P_p across the piezoelectric load resistance R_p. A permanent magnet of mass m_0 placed at a distance L_0 from the fixed cantilever support is attached over the surface of the beam which cuts the coil placed in its close vicinity, as the beam and tip-mass cylinder gets physically displaced. This electromagnetic induction produces electrical current i_i that flows through the coil and power P_i gets generated across the electromagnetic-inductive load resistance R_i. It should be mentioned that L_s is indicative of the length of the substrate material. L_p is the length of the piezoelectric layer whereas the L_t represents the length of the tip mass having mass M_t.

The researchers tend to unravel the governing physics of underlying aeroelastic systems whether it is for control, or for energy harvesting purposes by using experimental methods and Computational Fluid Dynamics tools. In the present work, we resort to using the experimental aerodynamic force coefficient data of Hu et al. [27] for intermediate pressure taps that give us the results of aerodynamic force coefficient for a square cylinder attached as a tip mass for a cantilever