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Experimental validation of a novel piezoelectric energy harvesting system employing wake galloping phenomenon for a broad wind spectrum

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ABSTRACT

In this paper, a novel piezoelectric energy harvesting system using the wake galloping phenomenon is explored for the broad wind spectrum. Wake galloping is an aerodynamic instability phenomenon which has promising potential in energy harvesting. The offered advantage by the proposed system is having a wider wind speed range for a reliable and sustainable energy source for a small wireless sensor node, in addition to being simple and easily applicable to civil structures. In the proposed system, the flow of wind runs parallel to the placed cylinders with upstream cylinder fixed at one end while the downstream one is placed over an unimorph cantilever beam with piezoelectric film attached to it. To validate the effectiveness of the proposed system, several tests were conducted against wind speeds approaching till 10 m/s with varying cylinder spacing. The results revealed an optimum spacing between two cylinders of 3D and the cut-in speed was estimated to be 4 m/s. The attained results were smartly analyzed to further explore the effect of cylinder spacing on the aerodynamic vibrations and the other associated parameters.

1. Introduction

Aerodynamic instability has posed serious challenges to civil engineers with the evolution of large-scale structures, especially high-rise buildings and long-span bridges. The uncertain and variable wind properties in the real environmental conditions and the congested urban development pattern make it one of the complex problems to solve. Large and unwanted wind vibrations caused by aerodynamic instability have raised major concerns and have been thoroughly investigated over last many decades [1–6]. These phenomena include vortex induced vibration, flutter, buffeting and galloping. In practical applications, more than one of these phenomena may occur at the same time depending on the geometry of the structure and the wind flow properties. The issue of aerodynamic instability first came to limelight in 1940 when the old Tacoma Narrows Bridge in the United States of America collapsed due to torsional flutter [1]. The fundamentals of this phenomenon were later studied by Duncan [7] followed by numerous other researchers investigating more or less the similar scenarios [8–10].

In contrast to the structural instability issue, the aerodynamic instability can also be seen as an opportunity to harness useful energy based on wind power. The divergent vibration properties of this phenomenon can be used to power small wireless sensor nodes in addition to adversely affecting the serviceability of the large structures. Wireless sensor nodes have a major power concern, which has been the focus of researchers for several years [11–14]. Several power-generating devices were proposed based on flutter and other aerodynamic instability phenomena [15–20]. Among the energy harvesting devices based on such aerodynamic phenomena, the most important parameter is the limited viable range of wind speeds. Based on this parameter, various aerodynamic phenomena were compared and the wake galloping turned out to be most suitable for an energy harvesting system, because of its low cut-in speed and wider wind speed range [21]. Wake galloping is basically defined as the divergent vibrations of the downstream cylinder caused by the wake from the upstream

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cylinder. When a single cylinder with flexible base is placed in the wind and it vibrates, the vibration of the cylinder is called the galloping phenomenon. While when another cylinder with a fixed base is placed on the upstream side of the flexible base cylinder, its vibrations increase significantly due to the re-attachment of wakes from the upstream cylinder onto the downstream cylinder. This increased vibration of the downstream cylinder is termed as wake galloping [10].

Jung and Lee [21] proposed a new electromagnetic energy harvesting system based on the wake galloping phenomenon. They carried out characterization test on the wake galloping phenomenon and also proposed a system containing a permanent magnet and solenoid coil system in order to generate electrical power. Their system was tested against maximum wind speeds of up to 8–17 m/s for different configurations of cylinders. For the spacing of 3D they tested up to 10 m/s, however for the larger spacing they tested for wind speed of up to 16 m/s. They recommended a cut-in speed of 4.5 m/s. Although they tested their system for a wide range of wind speeds and validated the effectiveness of their system, still their system contains several limitations. Although their proposed system provided an efficient way of harnessing the wind-based vibration energy, they could not develop a practicable configuration of their system, which could be easily installed on a civil engineering structure. Moreover, the presence of an electromagnetic system on the structure might cause an additional vibration issue.

Recently, Abdelkefi et al. [22] proposed another galloping and wake galloping based energy harvesting system. They mainly focused on a single piezoelectric beam with a square section tip mass subjected to the galloping phenomenon. They also mentioned a similar system subjected to wake galloping aerodynamic instability, in which they recommended to consider different parameters such as upstream cylinder diameter, the spacing between two cylinders, the flow speed, and the load resistance. They, however, did not try to design an optimum system based on wake galloping. The main reason why they did not proceed with the wake galloping energy harvesting system is that they only considered the low wind speed ranges. For low-speed range, the energy harvester based on galloping phenomenon performed better than the wake galloping based system. Additionally, they found that the upstream cylinder did not vibrate at all at low wind speeds. The important factor that seems missing is associated with the wind speeds that are unpredictable and vary in a very wide range. Therefore, the system designed for low wind speed might not be stable and even get damaged in higher speed ranges. For the piezoelectric energy harvesting systems based on simple galloping phenomenon, there is a major limitation of wind speed range to be less than 2.5 m/s [20].

Jung and Lee [21] have also developed awake galloping based energy harvesting system. However, this system also possesses certain reservations that need to be addressed. In their system, two parallel cylinders were used. The upstream cylinder was termed as a dummy and the downstream cylinder was taken as the main test cylinder. The downstream cylinder was connected to springs, permanent magnet and the solenoid coil. In this arrangement, the vibrations of the downstream cylinder caused the permanent magnets to oscillate with reference to the solenoid coil which in turn caused the generation of the useful energy, which can be used, for instance, to power a set of small wireless sensor nodes mounted on a cable-stayed bridge.

Although apparently the system looked simple and effective, its implication on large scale still needed serious clarifications. The proposed system was difficult to be mounted on a real structure such as a cable-stayed bridge, which ultimately reduces the effectiveness of the electromagnetic device. Furthermore, the wind load of the additional structure would impart an additional load on the original structure and might be the reason to induce additional vibrations.

1.1. Research significance

In the current research, an optimum energy harvesting system based on wake galloping using an unimorph piezoelectric beam has been proposed. The proposed system effectively addresses the aforementioned literature gaps in much effective and sustainable way by encompassing a wider range of wind speeds. The proposed system offers many advantages over the existing wake galloping based energy harvesting systems. It is easy to mount over a structure and needs minimum maintenance because of minimum vibration compared with the previously proposed system Jung and Lee [21]. Also, the adjustments of the cylinders can be made flexible in the proposed system such that the downstream cylinder is always placed on the backside of the upstream cylinder resulting in the elimination of any possible additional wind loads. The proposed system is much suitable for medium and high wind speed ranges in contrast to the previously developed system by Abdelkefi et al. [20] limited to low wind speeds. The optimum distance between the two cylinders has also been effectively evaluated in this study based on the set of experiments. In literature, the usual practice is the use of square cross-section that seem much suitable to the simple galloping based system [23], whereas in the parallel cylinder arrangement the square cross section cause more stability issue rather than ensuring sustainable vibrations. The proposed system has a configuration which is easier to implement and the size of the system is small which eliminates the possibility of causing additional vibrations to the main structure.

2. Proposed system

An effective piezoaeroelastic energy harvesting system based on wake galloping phenomenon has been successively proposed in this work. For both the upstream and the downstream cylinders, circular cross-sections of similar diameters were considered. As mentioned in the literature that the upstream cylinder does not vibrate enough in the presence of a downstream cylinder, therefore, the upstream cylinder was designed as rigid with the energy-harvesting piezoelectric system only applied at the downstream cylinder in the system proposed. The downstream cylinder was

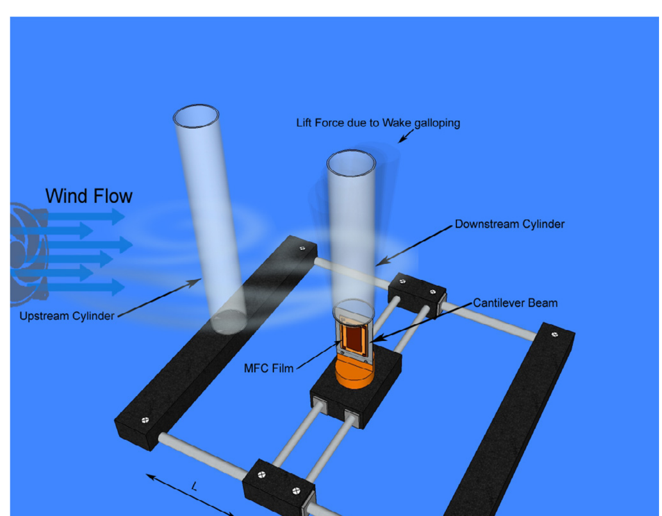

Fig. 1. Schematic diagram of the proposed system.