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Performance Enhancement of Energy Harvesting Systems using Wake Galloping

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ABSTRACT

With the advancements in the microelectronics and the wireless sensor nodes, the issue of more reliable and clean energy harvesting has been a major concern for researchers. In order to obtain reliable and continuous power supply at unreachable locations, the wind energy has been studied to provide enough energy for the various energy harvesting devices. In this study, the wind energy is proposed to be harvested by coupling of wake galloping phenomenon and piezoelectric material based corrugated cantilever beam. Wake galloping phenomenon is known for reasonably constant vibrations after certain wind flow velocity. It is proposed to use a downstream cylinder mounted on a cantilever beam which contains a MFC which is one of piezoelectric materials. The proposed system is reliable that it provides reasonable energy at the lower wind speeds and also can be stable structure even at reasonably high wind velocities. The proposed system shows that the feasibility and sustainability in application of civil infra structures.

1. INTRODUCTION

Aerodynamic instable situation has become the biggest obstacle of civil engineering structure with the development of large civil structures, especially high-rise buildings and long span bridge. The uncertainty and variety of wind properties in the real environmental conditions and complexity of urban environments makes it one of the complex problems to solve. Large and uncertain wind vibrations caused by aerodynamic instability have raised major concerns. Furthermore, these phenomena include vortex induced vibration, flutter, buffeting and galloping. The geometry of structure and the wind flow properties make it be occurred at the same time in practical applications. In contrast with the structural instability issue, the aerodynamic instability

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can be seen as an opportunity to make useful energy based on wind power.

In this paper, the wind energy is proposed to be harvested by coupling of wake galloping phenomenon and piezoelectric material based corrugated cantilever beam. (Unimorph piezoelectric beam) We need to find a more appropriate mechanism for design of an energy harvesting system which is more stable and sustainable under all wind conditions. Wake galloping phenomenon is known for reasonably constant vibrations after certain wind. The test of proposed system was conducted in lab scale experimental condition. It is proposed to use a downstream cylinder mounted on a cantilever beam which contains a MFC sheet. The proposed system is reliable that it provides reasonable energy at the lower wind speeds and also can be stable structure even at reasonably high wind velocities.

2. PROPOSED ENERGY HARVESTING SYSTEMS

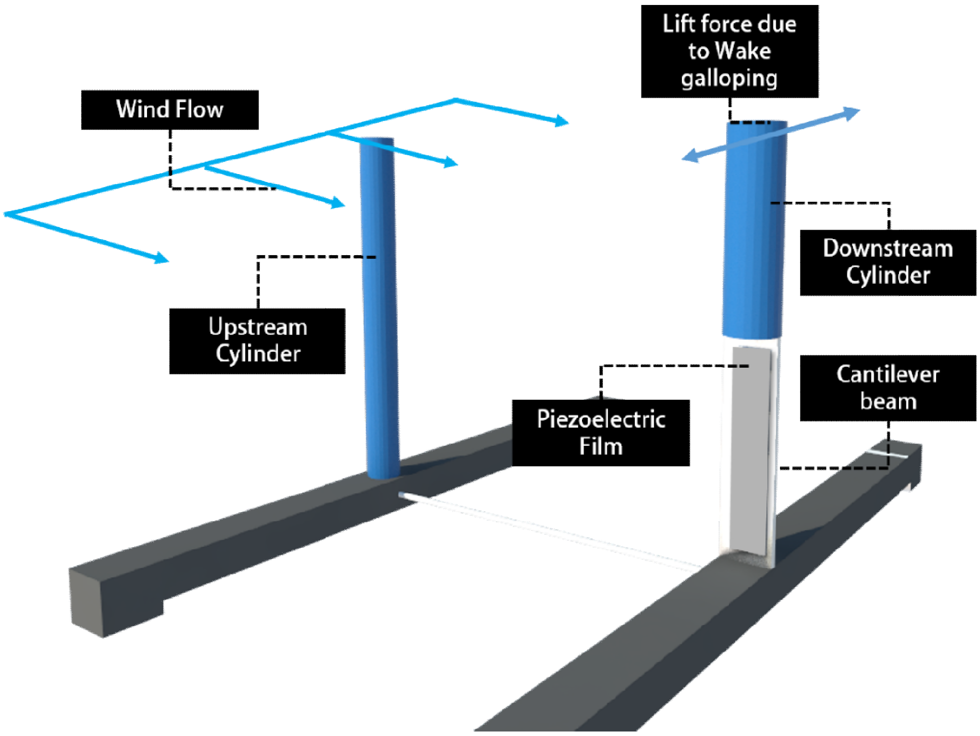

Fig. 1 The proposed energy harvesting system.

In this study, we propose a piezoelectric energy harvesting system based on wake galloping phenomenon. We consider the circular cross section of both cylinder and diameter of both cylinders were taken as the same. As highlighted in the previous studies that the upstream cylinder does not vibrate enough in the condition of presence of downstream cylinder, we have proposed that upstream cylinder is rigid and the energy harvesting system is only applied to the downstream cylinder.

As shown in Fig.1, the downstream cylinder is placed on top of a unimorph piezoelectric cantilever beam as a tip mass. The schematic diagram of the proposed system is shown in Fig 1. In the wake galloping aerodynamic phenomenon, the wakes are caused by the upstream cylinder and when those wakes try to move into the downstream cylinder, they make the vibration of the downstream cylinder. The force exerted on the downstream cylinder can be represented by tow orthogonal components i.e., drag and lift components, severally. One of the components, Drag force, is the one which has the same direction as the wind flow, while the other component, Lift force, is exerted in the direction perpendicular to the wind flow. Table 1 shows Characteristic of the proposed system.

Table 1 Characteristics of the proposed system.

Parameter	Unit	Value
Length of upstream cylinder	cm	25
Diameter of both cylinders	cm	3
Mass of upstream cylinder	g	249
Tip mass of downstream cylinder	g	45
Thickness of the cantilever beam	mm	0.3
MFC Film Characteristics		
Piezoelectric coefficient	pC/N	-210
Poisson's ratio(v12)		0.31
Operational bandwidth	kHz	0~10
Young's Modulus	GPa	15.857
Shear Modulus	GPa	5.512

3. Experimental Validation

3.1 Experimental Setup

Experimental tests were carried out by using the wind tunnel test equipment shown in Fig. 2. The experimental setup for this system includes the wind speed sensor, displacement sensor and voltage measurement across the MFC sheet. The speed sensor which is for using to measure the constant wind speed for each case was placed at the center of the air low channel and the displacement sensor was used to measure the displacement of the cantilever beam. The voltage at the proposed energy harvester was measured against time for each case by the voltage sensor. Fig. 2 shows the details of proposed system and sensors. The upstream cylinder is connected with the wind tunnel test equipment and downstream cylinder is placed at top of flexible cantilever beam with piezoelectric film mounted on it.

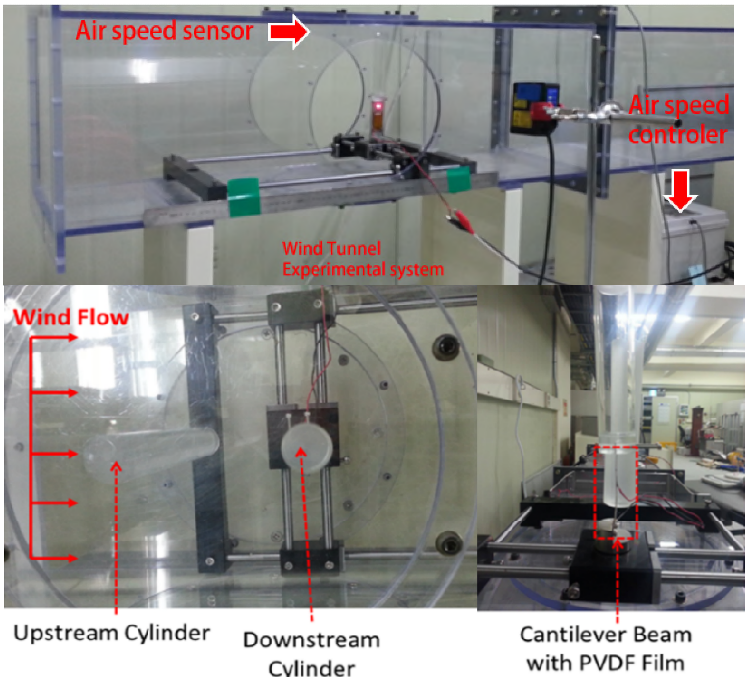

Fig. 2 Experimental setup

3.2 Experimental Results

The number of cases considered is shown in Table 2. As the wind speed increases, the stability of the vibration also increased considerably. For each time history result, the peak factor is computed and interpreted along with the apparent shape of the plot and the amplitude values.

Table 2 Experimental cases studied.

Parameter	Cases	Number of cases
Wind speed	1 m/s ~ 10 m/s	10
Spacing between both cylinders	1.73 D ~ 6 D	6
	Total cases : 60	

The peak factor is basically defined as the difference of mean extreme and maximum of mean divided by the maximum of the RMS response. That means it can be defined as the ratio of maximum fluctuating component to the standard deviation. In this study, we used a simplified method to compute the peak factor for each of the time histories, as follows:

$$Peak\ Factor = \frac{x_{max}}{x_{RMS}}$$

where x can be the time-history response of the displacement of the downstream cylinder which we are considering. For an ideal sinusoidal time-history, the peak factor is known to be exactly 1.414 and for buffeting response to the nonlinear transient winds, it is reported to be around 2.5 in Lee (2013).

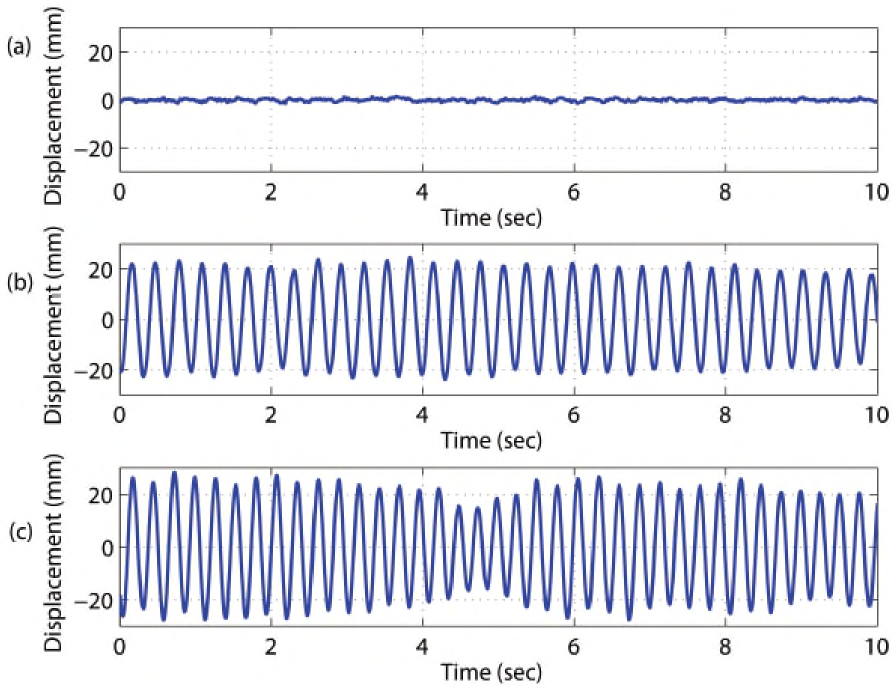

Fig. 3 The displacement time histories measured for the spacing L = 3D and (a) v = 3 m/s (b) v = 7 m/s (c) v = 10 m/s

Fig. 3 shows the time histories for the spacing L=3D and the wind speeds of 3 m/s, 7 m/s,10 m/s. Here, it is clear that the vibration is increasing directly with the increasing wind speed. Fig. 3(b) shows that there is some high frequency response at the lower wind speed of 3 m/s. The peak factor at the wind speed of 3 m/s is 2.93, it is similar to the L=1.73D case. The high frequency response and higher value of the peak factor can be explained by that for lower displacement amplitudes, the noise values in the measured signal can be more significant considering the very low values of the displacement signal itself.

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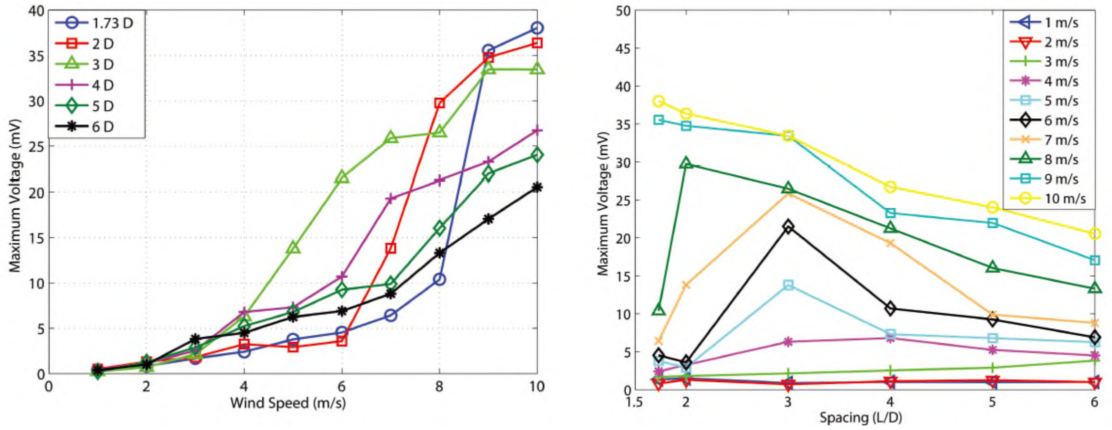

(a) (b)

Fig. 4 Experimental results. (a) Maximum voltage generated for each case against wind speed. (b) Maximum voltage generated for each case against spacing.

The spacing of the cylinders is further increased over 4D, the wake galloping phenomenon starts to fade and a transition towards the wake displacement method should be seen. When we carried out the case of 5D with the wind speed of 3 m/s, 7 m/s and 10 m/s, the maximum vibration amplitude is considerably less than the 3D case. This is can be explained by the existence of the wake displacement phenomenon

Fig. 4(b) shows the maximum voltages across the MFC film for each case. It shows the trend of the increase with increasing wind speed. In Fig. 4(b), a clear transition from galloping to wake galloping and then from wake galloping to the wake displacement can be seen. Starting from the case of 1.73D where the high cut-in speed is at around 8m/s and high peak values represent clear transitional phase from the simple galloping phenomenon to the wake galloping vibrations. Moving forward to 2D and 3D case it can be clearly seen that the vibrations are transiting towards the wake galloping vibrations, which are characterized by lower cut-in speeds and high and stable peak values. Which means that higher and more stable vibrations for a wider range of wind speeds.

4. CONCLUSIONS

A wake galloping energy harvester based using vibration is proposed with the MFC piezoelectric film. This is a very simple but reliable method to harness the naturally available wind energy. This proposed system means significant improvement compared to the previous proposed wake galloping energy harvesting system. Also, the proposed system has obvious advantages that it is easy to install and has no stability issue in higher wind speeds. In this lab scale tests, the effect of wind speed and the relative location of the downstream cylinder on the generated power has determined. The results show that the proposed system performs well for the wind speeds higher than 4 m/s and the optimum location of the downstream cylinder is equal to three times the diameter of the upstream cylinder. When two cylinders were very near, the vibration pattern showed the transition from simple galloping to wake galloping. But in medium spacing values, the pure wake galloping phenomenon was observed, while for higher spacing values, the wake displacement phenomenon was observed.

The wake galloping energy harvesting system has a lot of potential applications, especially in the large scale civil engineering structures. The issue of powering wireless sensor nodes, on such structure which are located placement difficult to access, can be solved by using this sustainable and simple energy harvesting system.

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