Urban Wind Harvesting Using Flow-Induced Vibrations

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ABSTRACT

The growing global interest in sustainable energy has paved the way to the rapid development of large-scale wind farms, consisting of dozens to hundreds of wind turbines. Although these large wind farms can generate enormous amount of power, they are also costly and require large areas of land or water, and thus are not suitable for urban environments. Smaller urban wind turbines have been developed for urban environments, but there are significant challenges to their widespread deployment. One of these challenges are their urban wind flows as they are strongly affected by complex building structures, producing highly turbulent flows. Any urban wind turbine would need to be designed to function efficiently and safely under these flow conditions; however, these unpredictable and turbulent winds can induce undesirable vibrations and cause early failures. Recently, bladeless wind turbines are gaining interest due to their reduced costs compared with conventional wind turbines such as the vertical-axis wind turbine and horizontal-axis wind turbine. These bladeless turbines convert flow wind energy into vibration energy, then converts the vibration energy into electricity. This paper examines the effects of force-induced vibrations on a cantilever beam system through wind tunnel experimentation. When fluid flows around a bluff body, periodic shedding of vortices may occur under the right conditions. The vortex shedding process creates an asymmetric pressure distribution on the body which causes the body to oscillate, known as vortex-induced vibrations. The purpose of the paper is to understand the factors affecting flowinduced vibrations and to improve wind energy harvesting from these vibrations. The first part of the paper focuses on wind tunnel experiments, by utilizing a cantilever beam configuration, conceptualized by previous research. Then, the experimental model was tested in different configurations, to determine the best setup for maximizing vibrations induced on the model. The long-term goal of the project was utilizing the model to optimize the system to improve efficiency of wind energy harvesting. The experimental results showed that the presence of an upstream cylinder will significantly improve the amplitude of vibration for energy harvesting, furthermore, the experiments showed that spacing in different directions also affect the amplitude of the vibrations. A two tandem cylinder system was used in this work, including a fixed rigid upstream cylinder and a downstream cylinder supported by a cantilever beam. Various configurations of these two cylinders in terms of spanwise and streamwise separation distances were studied and their maximum and root mean square displacements are reported for different wind speeds. Results showed that the presence of an upstream cylinder will significantly improve the amplitude of vibrations. This work verified that a wind energy harvester needs to consider the effects of wind speed and separation configuration of the cylinders in order to maximize the harvester's performance in urban environments.

KEYWORDS

Sustainable Energy; Energy Harvesting; Urban Environments; Bladeless Wind Turbines; Flow-Induced Vibrations; Cantilever Beam System; Wind Tunnel; Wake

INTRODUCTION

In the past century, the planet has witnessed an exponential growth in human population.¹ As the global population increases, so has the demands for energy and this trend is projected to increase with time.² In order to reduce the reliance on fossil fuels, many governments implemented policies by transitioning towards renewable energy sources.³ Wind energy is one of the fastest growing sources of renewable energy, which grew at 9.1% in 2018 to an overall capacity of 597 GW, covering close to 6% of the world's electricity demand.⁴ The primary form of harvesting wind energy is utilizing bladed turbines, as most of that energy is extracted through large wind turbines. However, conventional wind turbines are expensive, leading to the development of bladeless turbines that harvest wind energy through vibrations.^{5,6} These bladeless wind turbines harvest energy from flow-induced vibrations (FIV) and can be designed to extract from omnidirectional winds. Furthermore, winds in urban environments are affected by surrounding complex structures, inducing turbulence, making it difficult to harvest energy economically with conventional urban wind turbines.⁷ These turbulent and omnidirectional urban winds could lead to fatigue and thus early failures.⁸ In contrast, bladeless wind turbines are designed to harvest vibrational energy induced by flow instabilities.⁹ As wind flows through a bluff body, flow separations occur and vortices are induced in a periodic manner, creating pressure gradients in the transverse direction, orthogonal to the flow and undergoing vibrations.⁹ The vibrations induced by vortices are called vortex-induced vibrations (VIV).

A famous example of VIV is the Tacoma Narrows Bridge Collapse, which lead to a catastrophic failure. However, instead of damping or reducing VIV, understanding this phenomenon is important to build an efficient bladeless wind turbine for urban communities through designing and testing a mass spring damper system in order to understand how VIV in wind could be harvested efficiently.

PAST EXPERIMENTAL WORK

There have been various studies focusing on harvesting wind energy through the use of VIV. In the work by Matsumoto,¹⁰ it was discussed that an excitation force was created through instabilities in the shear layer and that a cylinder can induce symmetrical vortices. Williamson et al.,¹¹ discussed the motion in which bluff bodies experience and how that motion generates different modes of vibration. Williamson et al.,¹¹ discussed the effects of vortex shedding on structures and how unsteady pressure causes bodies to undergo motion. In Sarpkaya's¹² review, he described the interactions between a bluff body and its surrounding fluid and highlighted the importance of flow separation around the cylinder as it creates eddies behind the body which causes a lift force to occur. The resulting transverse waves from multiple directions causes the bluff body to experience VIV, from which the mechanical energy then could be harvested.¹² Assi et al.,¹³ applied dimensional analysis to understand the vibration phenomenon and improve the efficiency of energy harvesting. In the work by Kim et al.,¹⁴ they conducted a series of tests using a mass spring damper system, using tripping wires to control the fluid boundary layer and thus VIV. In their experiment, it was found that when two cylinders are in tandem, the normalized distance between cylinders relative to their diameters will greatly influence amplitudes of vibration. Their experiment highlighted the importance of the spacing configuration between the cylinders. Papaioannou et al.,¹⁵ conducted wind tunnel and numerical experiments involving two cylinders in tandem, and they observed that large oscillations will occur if the natural frequency of the cylinder is close to the vortex shedding frequency. Furthermore, Mittal et al.,16 discussed how two cylinders in tandem will interact differently than just a single standalone cylinder. When the structural frequency of a cylinder is similar to the vortex shedding frequency, the cylinder experiences a lock-in, which causes the cylinder to vibrate at a much higher amplitude.¹⁶ In the experimental paper by Amandolese et al.,¹⁷ they examined the effects of VIV on a cylinder using a wind tunnel. The purpose of their experiment was to describe how the mass ratio of the structure affects the surrounding flow and how it causes the bluff body to experience oscillations.¹⁷ In the FIV work done by Kim,¹⁸ Equation 1 shows that the motion of the downstream cylinder, y, can be modeled as,

$$m\frac{\partial^2 y}{\partial t^2} + c\frac{\partial y}{\partial t} + ky = F_L$$
 Equation 1.

where m is the mass, c is the damping coefficient, k is the stiffness, and F_L is the lift force acting on the cylinder. The lift force induced by the upstream cylinder contributes to the damping of the system and could lead to oscillatory instability. This aerodynamic damping effect is described in detail in the work by Kim.¹⁸ In the work by Usman *et al.*,¹⁹ the authors conducted wind tunnel experiments with a cantilever beam system, where two cylinders are placed in tandem. The upstream cylinder is fixed, and the downstream cylinder was mounted on a cantilever beam where the flow was induced to cause vibrations on the cylinder.¹⁹ The setup by Usman *et al.*¹⁹ included an adjustable rail that would change the vertical distance between the downstream cylinder. Their study also tested the specimen under different wind speeds, which changes the oscillation of the vibrating cylinder. Their configuration primarily focused on the effect on a fixed upstream cylinder placed directly upstream of the oscillating downstream cylinder. This paper focuses on the design conceptualized by Usman *et al.*, to validate and expand upon their work using a similar experimental setup. The system designed in this work will permit various configurations of two cylinders and allow them to move in the spanwise and streamwise directions in order to test and analyze the effects of configuration on vibrational motion. The next section discusses the methods and procedures of the experimental work.

METHODS AND PROCEDURES

In this section, an experimental setup based on the work Usman *et al.*, is discussed. Similar to the two tandem cylinder setup by Usman *et al.*,¹⁸ a rail system has been built to study the effects of positioning two cylinders in tandem. The upstream cylinder is fixed in position using a 3D printed mount. The position of the downstream cylinder can be adjusted in the spanwise and streamwise directions. The downstream cylinder is attached to a cantilever beam that is mounted on a 3D printed sliding mount which allows the cylinder to change position in the spanwise direction. The downstream cylinder contained an MMA 8452Q accelerometer that is connected to an Arduino Board, that will read the output data. **Table 1** has a detailed list of the parameters of the apparatus used in this work and its specifications are listed on **Table 2**. **Figure 1** illustrates the CAD model of the experimental setup and how the device was setup. Furthermore, this paper examines the effects of wind speed range of 2.5 m/s to 10 m/s (i.e. 2.5 m/s, 3 m/s, 4 m/s, 5 m/s, 6 m/s, 7 m/s, 8 m/s, 9 m/s, and 10 m/s), with similar spacing to the work proposed by Usman *et al.*; however, in addition to the streamwise spacing, the spanwise spacing was varied from 0D to 4D (i.e. 0D, 0.5D, 1D, 2D, 3D, and 4D).



(a) General Layout. (b) Accelerometer Placement. Figure 1. Proposed System Overview.

| Parameters | Dimension Values |
|---|------------------|
| Downstream Cylinder Height | 495.3 mm |
| Upstream Cylinder Height | 533.4 mm |
| Diameter of Cylinders | 44.45 mm |
| Downstream Cylinder Mass (With Mount Adapter) | 80 g |
| Height of Cantilever Beam | 107.95 mm |
| Width of Cantilever Beam | 30 mm |
| Thickness of Cantilever Beam | 0.3 mm |
| Material of Cantilever Beam | Aluminium |
| Young's Modulus of Cantilever Beam | 69 GPa |
| | |

Table 1. Apparatus Parameters.

| Capabilities |
|----------------------|
| 3 mm x 3 mm x 1 mm |
| ± 4 G |
| 1.56 Hz to 800 Hz |
| 8-bit and 12-bit |
| X, Y, Z Axes |
| 99 $\mu G/\sqrt{Hz}$ |
| |

Table 2. MMA 8452Q Accelerometer Specifications.

This paper observed the behaviour of the downstream cylinder at different spacings and wind speeds, and then find the best configuration for energy harvesting experimentally. Furthermore, this paper examined the behaviour of the downstream cylinder, using an accelerometer, which is connected to a microcontroller that is connected to a computer that outputs the reading through an interface. The acceleration data was used to study the amplitudes of oscillations of the downstream cylinder, at different flow speeds and configurations. **Figure 2** illustrates the basic overview of the experimental configuration and which parameters were changed in the experimental trials.



Figure 2. Experimental Configuration.

Experimental tests were conducted in the Aerodynamics Laboratory in California State University, Los Angeles using a subsonic wind tunnel. The wind tunnel has a test section area of 1.15 x 0.71 x 0.48 (m) and is capable of reaching speeds up to 30 m/s where the wind flows from the right to left as shown in **Figure 3**. The experimental data of this study consists of an MMA 8452Q accelerometer and a TFI Cobra Probe to measure vibration and wind speed, respectively. The TFI Cobra Probe was attached to a mounting system positioned to measure wind speed from the inflow. As illustrated in **Figure 4a**, the downstream cylinder was connected to an aluminum sheet metal cantilever beam that was mounted to the proposed system. The MMA 8452Q accelerometer was attached onto the tip of the cantilever beam, to measure the acceleration in the direction perpendicular to the wind flow. The upstream cylinder was securely fixed onto a separate beam connected to the experimental platform. The wind tunnel setup is shown in **Figure 4b**.



Figure 3. Wind Tunnel Cross-Sectional Area.



(a) General Layout

(b) Accelerometer Placement

Figure 4. Wind Tunnel Setup.

A series of experiments were conducted to determine the optimal spacing between the upstream and downstream cylinders in both the streamwise and spanwise directions. The wind speed and acceleration were measured in all cases in order to determine the optimal displacement of the cantilever beam. Once the data was collected using the Arduino Board, it was then analyzed and complied to compare the performance of the downstream cylinder based on the different configurations and wind speeds. The next section presents the complied data and examine the results.

RESULTS AND DISCUSSION

Streamwise Configuration

This subsection discusses the findings of the streamwise experiments, where the distance between the tandem cylinders are varied in the streamwise direction. The MMA 8452Q accelerometer measured the acceleration of the downstream cylinder in unit of g (acceleration of gravity). Once the data was collected from the accelerometer, it was then uploaded to an in-house MATLAB code for post-processing. This code converted the acceleration data from g to SI units, then integration was performed to obtain velocity and displacement of the downstream cylinder. To perform integration over a fixed time period, the mean acceleration over that time period must be determined. Then the acceleration data should be subtracted by the mean value and then integration can be performed to obtain velocity. This procedure was then repeated for displacement. As displacement amplitudes can vary with time, two important quantities are root mean square (RMS) displacement and a maximum peak displacement. Figure 5 illustrates the RMS displacement amplitude at various wind speeds as the downstream cylinder is aligned with the upstream fixed cylinder along the spanwise direction, with varying separation distances in the streamwise direction, ranging from 1.5D to 5D. As a benchmark, experiments without an upstream cylinder were conducted for comparison. As shown in Figure 5, the displacement of oscillation of the downstream cylinder increases with the presence of the upstream cylinder. The results show that at 3D separation, the downstream cylinder experiences larger oscillations at higher wind speeds, but the increase in displacement diminishes beyond 8 m/s or Re = 13,656. At wind speeds lower than 8 m/s, the RMS displacement at 1.5D and 2D separation seem to be the greatest, but quickly tapers off as wind speed increases. This phenomenon occurs because the strength of the oscillating vortices, downstream of the upstream cylinder, are functions of wind speed and downstream distance. Furthermore, the results indicate that the 3D spacing generates the highest RMS displacement at the higher wind speeds, e.g. greater than 8 m/s, surpassing all other configurations tested. These results are similar to the findings from Usman et al.¹⁹, as both works show that a certain configuration outputs a greater magnitude of displacement, and that the results are repeatable. One phenomenon observed at 3D separation is that between wind speeds 3 m/s to 5 m/s, the vibrational amplitude increases rapidly. Then, between 5 m/s to 7 m/s, the rate of increase declines. Beyond 7 m/s, as flow speed increases the vibrational amplitude increases rapidly again as this may occur due to the interactions between the vortices from the upstream and downstream cylinders.^{20,21} Specifically, at the first cut-in speed of 3 m/s, vortex resonance or lock-in occurs, then at the second cut-in speed of 7 m/s, galloping takes over.21





In addition to the RMS displacement, the maximum displacements are also analyzed, shown in **Figure 6**, as it displays similar trends as the RMS results, but showing key differences between the two sets of data. First, at 4D and 5D separation, the maximum displacement is larger relative to the trends seen in RMS displacement at greater wind speeds. That is, the trends observed for maximum displacement do not match that of RMS displacement at 4D and 5D separation. This is in contrast with 1.5D and 2D separation, which has trends similar to the RMS results. The maximum displacement observed at 3D separation is also consistent with the RMS displacement results. The next subsection will examine the results for the spanwise experiments and observe the behavior of the downstream cylinder, when the spanwise spacing is changed.

Spanwise Configuration

The following results compare between displacement amplitude and wind speed along the spanwise direction of the downstream cylinder as illustrated in **Figure 2**, when the streamwise separation distance is at 3D. Thus, spanwise separation distances were varied at 3D streamwise separation distance. Following the same procedures done in the streamwise direction by using MATLAB, both the RMS and maximum peak displacements were observed to see if the two displacements show consistency. When observing the RMS results, illustrated in **Figure 7**, the 0D spanwise separation (3D separation in the streamwise direction) experience the highest oscillating displacement. A decreasing RMS displacement trend is observed when separation increases, especially the 1D spanwise separation. The 1D separation experiences a significant decrease in displacement due to the wake effects caused by upstream cylinder, which caused the downstream cylinder to vibrate in a non-uniform pattern, thus resulting in the significant decrease in RMS displacement. This was also observed for the other configurations from 0.5D to 4D. It was further observed that when the spanwise separation reaches 4D, the effects of upstream cylinder on the downstream cylinder is negligible. These experiments demonstrated that 0D spanwise separation produces the highest displacement, but as soon as there are deviations in alignment, there will be significant decreases in RMS displacement.



Figure 7. RMS Displacement for Spanwise Experiments.





When observing the maximum displacement results, illustrated in **Figure 8**, the trends are different compared to the RMS results. The maximum displacement at 1.5D separation becomes similar to that of 0.5D separation. Another interesting observation is that for 1D separation at wind speed of 7 m/s, there is a drop in maximum displacement. This phenomenon is due to the effects of upstream wake and can be visually observed in the experiments, as the specimen was seen to vibrate in a non-uniform pattern. Moreover, the maximum displacement results for 0.5D to 4D, are consistent with RMS displacement, as they show similar trends.

CONCLUSIONS

A VIV harvester has been built to study the potential of harvesting wind energy from flow-induced vibrations. A two tandem cylinder system was used in this work, including a fixed rigid upstream cylinder and a downstream cylinder supported by a cantilever beam. Various configurations of these two cylinders in terms of spanwise and streamwise separation distances were studied and their maximum and RMS displacements are reported for different wind speeds. Results showed that the presence of an upstream cylinder will significantly improve the amplitude of vibration. Furthermore, 0D separation in the spanwise direction produces the highest displacement at wind speeds greater than 8 m/s. Any deviation from 0D spanwise separation will decrease displacement and as the separation increases to 4D, upstream effects become negligible and the downstream cylinder behaves as if there was no upstream cylinder. This work verified that a wind energy harvester needs to consider the effects of wind speed, separation configuration of the cylinders in order to maximize the harvester's performance in urban environments.

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ABOUT STUDENT AUTHORS

Levon Ghabuzyan and Christopher Luengas just completed their Bachelor of Science in Mechanical Engineering at the California State University, Los Angeles. Currently both authors are enjoying their summer break and studying for the Fundamentals of Engineering Exam (FE) as both are planning to pursue their Master of Science in Mechanical Engineering as Levon will continue his education at California State University, Los Angeles, this upcoming Fall 2019 and Christopher will return in Fall 2020.

PRESS SUMMARY

The expansion of urban area has brought about effects on the winds that pass through and the need for more energy, highlights an opportunity for wind energy. These urban winds can be used to harvest energy by the means of vortex-induced vibrations. The purpose of the paper is to understand the factors affecting VIV and to improve energy harvesting from these vibrations, by using a cylinder-cantilever beam system to determine the most efficient setup.