Experimental investigation of a flow-induced vibration energy converter with two mechanically coupled pivoted cylinders

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Key Words: *VIV energy converter, drag assisted, mechanically coupled two cylinders*

1. INTRODUCTION

Elastically supported cylinder undergoes vibration as respond to the cross flow passing by. In many engineering applications, such vibration must be suppressed or avoided, because large displacements may lead to catastrophic mechanical failures. The cost associated with a typical engineering structural failure can easily reach the order of one million dollars and even billions of dollars. However, instead of suppressing such vibration, recent studies consider vortex-induced vibration (VIV) as a new source for harnessing energy form water flow, because the energy source is abundant and environmentally compatible. Moreover, researches show that VIV converters are capable to harness hydrokinetic energy from slow flows staring at 0.26 m/s [3].

Bernitsas and Raghavan[3] developed an energy extraction device known as VIVACE (Vortex Induced Vibration Aquatic Clean Energy), which converts mechanical energy of the ocean and river currents into electricity. With similar concept Sung et al. [5] and Arionfard et al. [1] developed a "drag-assisted" device which utilizes the VIV motion of a pivoted cylinder. The significance of this idea is that the pivot allows the device to employ not only the lift force but drag force to improve the movement of the cylinder.

There are numerous studies done for a group of stationary cylinders in different arrangements to investigate the effect of wake and vortex interference between cylinders. Zdravkovich [7] [8] classified the interaction of two stationary cylinders into three kinds; proximity, wake, and no interference, and concluded that flow dynamics is largely determined by the gap (or pitch ratio in some studies) and Reynolds number.

The present paper describes the results of an experimental investigation of energy conversion efficiency of two mechanically coupled pivoted cylinders. The arrangement and Reynolds number are set as the main parameter to discuss. The main objective of this study is to improve the actual performance of the VIV converter for real world applications by increasing conversion efficiency. The present result is compared with the experiment done by Arionfard et al [1]. which uses similar experimental set up but with single cylinder.

The present paper is organized as follows. The experimental setup is explained in 2.1, and measurement method used in the study is explained in section 2.2. The results are presented in Section 3. Conclusive remarks are made in section 4.

2. PHYSICAL MODEL

Followings are the explanation of numbered components in Fig.1 (a). Coordinate system is defined as X; the stream-wise coordinate, Y; the cross-stream coordinate, and Z; the vertical coordinate. Fig.1 (b) illustrates the description of CG [m], Gap[m], angular position (a [rad]), and diameter of the cylinder (D [m]). Fig.1 (c) illustrates the direction of force acting on the cylinder, where stream wise force is drag force, cross-stream force is lift force, and force acting around vertical coordinate is the torque. The corresponding coefficient is given as,

$$\boldsymbol{C}_{\mathrm{L}} = \frac{\boldsymbol{F}_{\mathrm{L}}}{\frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{\rho 2DdU^2}} \quad (1)$$

$$\boldsymbol{C}_{\mathrm{D}} = \frac{\boldsymbol{F}_{\mathrm{D}}}{\frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{\rho 2DdU^2}} \quad (2)$$

$$\boldsymbol{C}_{\mathrm{M}} = \frac{\boldsymbol{M}_{\mathrm{Z}}}{\frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{\rho 2DdU^2}(|\boldsymbol{l}_{\mathrm{cy1}}| + |\boldsymbol{l}_{\mathrm{cy2}}|)} \quad (3)$$

Where $\boldsymbol{C}_{\mathrm{L}}$ is the lift coefficient, $\boldsymbol{C}_{\mathrm{D}}$ is the drag coefficient, $\boldsymbol{C}_{\mathrm{M}}$ is the moment coefficient, $\boldsymbol{F}_{\mathrm{L}}$ [N] is the lift force, $\boldsymbol{F}_{\mathrm{D}}$ [N] is the drag force, $\boldsymbol{M}_{\mathrm{Z}}$ [N•m] is the torque around Z axis, $\boldsymbol{\rho}$ [kg/$\boldsymbol{m^3}$] is the density of the fluid, $\boldsymbol{d}$ [m] is the wet length of the cylinders, $\boldsymbol{U}$ [m/s] is the velocity of the fluid flow, $\boldsymbol{l}_{\mathrm{cy1}}$ [m] is the arm length from the pivot point to cylinder at upstream, and $\boldsymbol{l}_{\mathrm{cy2}}$ [m] is the arm length from the pivot point to cylinder at downstream.

2. 1 Experimental set up

Model tests are conducted in a re-circulating free surface water channel. The channel length is 1 m with a test section of 30 cm wide and 30 cm deep. The flow velocity in the test section could be adjusted to any value between 0.024 and 0.84 m/s.

Two circular rigid cylinders are used in the experiment. Cylinders were made of polypropylene with the wall thickness of 2 mm, and outer diameter 30 mm. The overall length is 280 mm, and the submerged length is kept around 180 mm by controlling depth of water. The cylinders have one degree of freedom, and it is pivoted outside of water through the connector arm, using a rigid shaft and ball bearing, enabling rotation around Z axis. The top end of cylinders is fixed on the connector arm's rail by three screws, allowing us to slide the cylinder and adjust the gap and as a result, center of gravity (CG) and moment of inertia of the system. The end plate is not installed, firstly, in order to decrease the fluid damping in the system and secondly, to have the gap between the cylinder as

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Received (Filled by JASNAOE)
Read at the spring/autumn meeting (Reformed by JASNAOE)

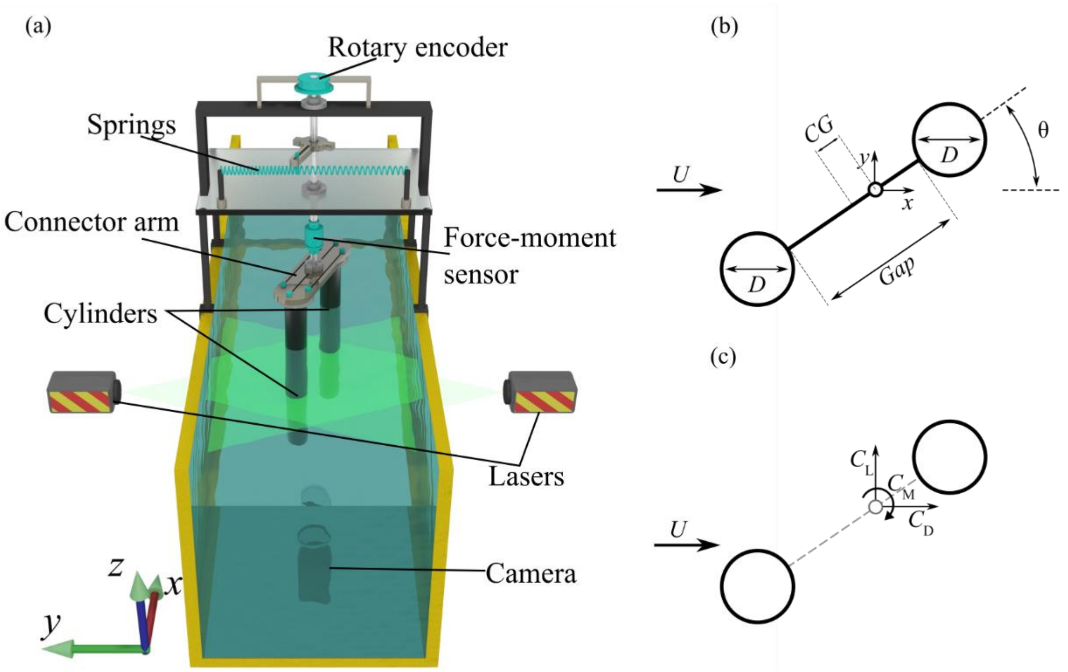

Fig. 2 3D view of the experimental setup (a). A simple schematic diagram of two cylinders (b). A simple schematic diagram of force coefficient where vector shows the direction of force acting on the cylinders (c). Note that the drawing is not to scale.

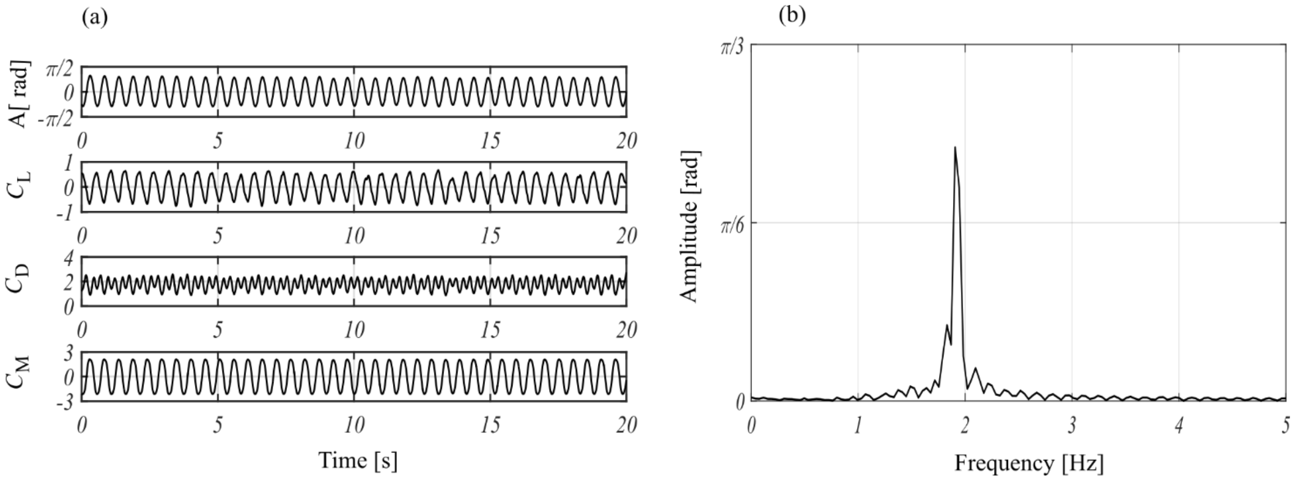

Fig. 1 The time history of amplitude and force coefficient (a). Single-sided amplitude spectrum (b).

small as possible.

The tests are conducted with gap ratio of $0 \leq \mathrm{Gap/D} \leq 4.9$, which results in 66 arrangements for the cylinder's positions. The velocity of the flow is changed within the Reynolds number $2280 \leq Re \leq 22300$. In total 401 cases are tested.

Two linear springs are connected to the shaft by using a spring connector arm to act as restoring moment. The spring stiffness are measured ($0.301 \leq k \leq 0.416$), for various angular position, where k [N•m/rad] is the equivalent torsional spring stiffness.

The equivalent torsional spring stiffness is calculated for each case from the angular position and the force acting on the cylinder, which is then averaged to obtain the total stiffness used for each case. Similar type of spring is used for the experiment. However, the rotational movement causes the linear springs to act as nonlinear between elongation and torque, resulting in variation of spring stiffness.

2. 2 Measurement method

In this section method used to obtain the angular position, forces and torque acting on the cylinder, and the method for visualizing the fluid flow for PIV analysis[4)] is presented. The measurement equipment is synchronized and external triggered at same time. Explanation of measurement method of numbered component at Fig.1 (a) is presented below.

Incremental optical rotary encoder is connected at the top end of the shaft. Rotary encoder is connected to measure the angular position of the cylinder. 1320 black lines are printed regularly on plastic disk. The disk rotates with the shaft, and when the line passes the optical sensor it sends a signal enabling one to obtain the angular position.

Fig.2 (a) shows an example of time history of an angular position when the system had maximum efficiency. (CG=0, Gap ratio=0.9, Re=1.84×10^4). Afterwards, angular velocity is calculated from angular position.

To determine the dominant frequency of the oscillating cylinder for each of the displacement time series, the Discrete Fast Fourier method is adopted. To accomplish this, the built-in discrete fast Fourier transform (FFT) function in MATLAB is used. Next, the single sided amplitude spectrum was plotted, as seen in Fig.2 (b), and the peak frequency was evaluated by

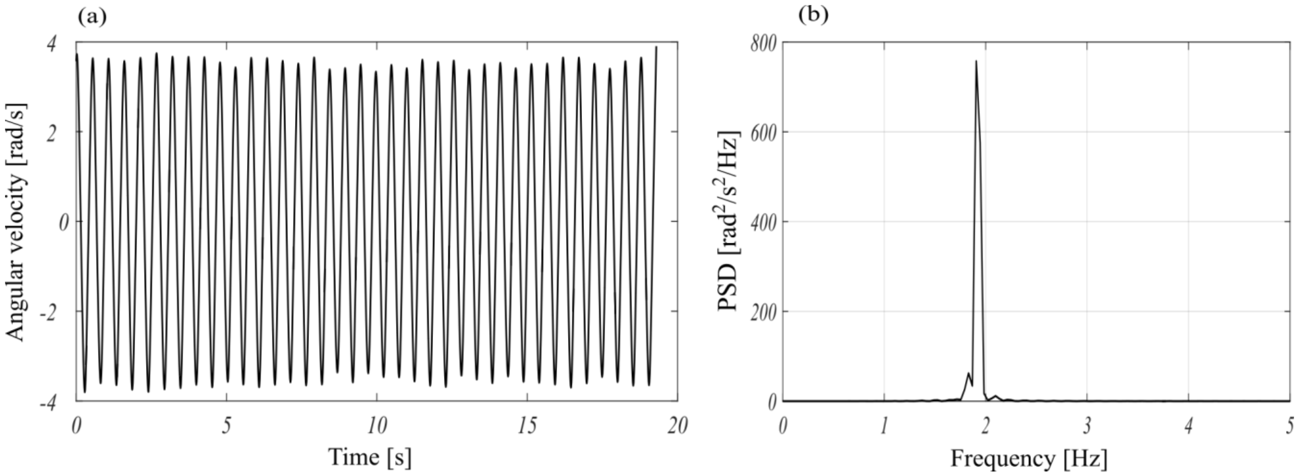

Fig. 3 Angular velocity when CG=0, Gap=0.9 (a). The power spectral density of the angular velocity, when CG=0, Gap=0.9 (b).

determining the frequency corresponding to the largest FFT amplitude.

Micro 6/30-A 6 axis force and moment sensor is used to measure the force and torque applied to the cylinders. The sensor is connected near the bottom end of the shaft that is connected to the connector arm.

Fig.2 (a) shows an example of time history of a lift, drag, and moment coefficient when the system had maximum efficiency.

Two focusable high power 2.5 W 450 nm blue laser module are used for visualization of the fluid flow. Each laser uses cylindrical lens to focus the light into plane instead of line. The light is then reflected to the test section by the mirror. The two lasers were placed face to each other across the water channel, so there would be less shadow of the cylinders.

Bright yellow polyethylene microspheres are used for the tracer.

CP80-3-M/C-540 (Optronis) is used for capturing images for PIV analysis [6] to evaluate the vortex shedding frequency and velocity of fluid flow. The camera is placed beneath the water channel so that it can capture the x-y plain of the fluid. The size of the captured image is 1696×854 pixel. The exposure frequency is set for 3000 μs, and exposure time to 2500 μs. The images are captured for 4 s which is 1500 frames.

3. RESULTS AND DISCUSSION

The maximum efficiency of 44.4% is observed when CG=0, gap ratio=0.9, and Re=1.84$\times \mathbf{10^4}$. The efficiency $\boldsymbol{\eta}$ is defined as the ratio of the power imparted by the flow to the body, to the total power in the flow ($\boldsymbol{P}_{\mathrm{f}} = \frac{1}{2}\boldsymbol{\rho D U^3 l_{wet}}$) [2].

$$\boldsymbol{\eta} = \frac{\boldsymbol{P}}{\boldsymbol{P_f}} \quad (4)$$

Fig.3 (a) shows the time history of angular velocity which is evaluated from angular position. Fig.3 (b) shows the power spectral density function of the angular velocity. Then, the power imparted by the flow P, is evaluated by integrating the power spectral density function (Fig.3 (b)) over the range of frequency. To carry out the integration, Trapezoidal rule is used, accordingly the power is evaluated as, $\boldsymbol{P = 0.244}$ [J/s] and from equation (4), $\boldsymbol{P}_{\mathrm{f}} \boldsymbol{= 0.549}$ [J/s].

Arionfard et al. [1] reported maximum efficiency of 31.4%, when using single cylinder with same experimental set up. 13% increase in efficiency can be confirmed when using two cylinders.

To the best of author's knowledge, there are no studies done for flow interference between two mechanically coupled pivoted cylinders. However, we interpret the increase in efficiency by referring to the discussion of Nishi et al. [4], in which when the upstream cylinder is elastically supported and downstream cylinder fixed, very large amplitude is observed due to the pressure change caused by the gap flow. When the upstream cylinder is displaced above the initial position and moving downward, the gap between two cylinders form a strong gap flow which passes along the upstream cylinder. This strong gap flow results in low pressure behind the upstream cylinder. For the front side of the upstream cylinder, high pressure region is formed because it is always exposed to the free stream. The resulting formation of pressure contrast leads to high magnitude downward lift force acting on upstream cylinder.

While the upstream cylinder is located below the initial position and moves upward, an upper shear layer interferes with the gap flow in a manner like the one described above.

This effect of high magnitude lift resulted in increase of efficiency, when comparing the case between single cylinder and two cylinders.

4. CONCLUSION

This study presented an experimental investigation on a two mechanically coupled pivoted cylinders to extract energy of the vortex induced vibration. The test was performed in a re-circulating free surface water channel in Reynolds number range of 2280≤Re≤22300. The tests were conducted with gap ratio of 0≤Gap/D≤4.9, which results in 66 arrangements for the cylinder's positions. In total 401 cases were tested. The main objective was to improve the actual performance of the VIV converter for real world applications by increasing conversion efficiency by changing the arrangements of the cylinder and Reynolds number.

44% efficiency is observed when CG=0, gap ratio=0.9, and Re=1.84×10^4. This is an increase in 13% of efficiency while comparing with single cylinder in use. The contrast in pressure field behind and in front of the upstream cylinder due to the gap flow causes high magnitude lift, resulting in higher efficiency.

ACKNOWLEDGMENT

This study was financially supported by the Grand-in-Aid for Scientific Research 15H04211.

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