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A FLOW INDUCED STRUCTURE BASED KINETIC ENERGY HARVESTER

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ABSTRACT

In this paper, a strategy utilizing a pair of cylinders which are put on the both sides of the cantilever beam and perpendicular to the water flow direction to harvest the energy is demonstrated. The novel flow induced structure based energy harvester consists of a pair inducing objects (cylinders) and one L-type cantilever beam. Macro fiber composite (MFC) is attached at the fixed end of the cantilever beam to convert the kinetic energy into electric power. The structure could induce the vortex shedding from the upstream flow and harvest the energy from it. Compared with the former studies with one or series layout inducing objects, the proposed structure could both improve the power output of flow induced energy harvester and avoid the damage happening in complex working conditions. Analytical modelling and experiment methods are both utilized in the research to cross verify the results. The characteristics related with water flow speed and center distance variations between inducing objects are discussed in the paper as well. It is found that when the water flow speed is 0.2m/s and the center distance is 30mm, the output power is optimal of 0.16μW and the power density is 0.4mW/m^2.

Key words: Energy harvesting, flow induced, perpendicular to flow direction, MFC

INTRODUCTION

Currently, the structures of the international renewable energy sources are turning from simplification to diversity, more and more sources of energy have been utilized in our daily life. Renewable energies, such as wind, solar and hydrate, have been developed deeply [1]. Compared with the above large-scale power generations, which are concerned with megawatts of power, energy harvesting technology which refers to micro- or even milli- watts has got more and more attention by the scholars along with the development of NEMS and MEMS. The typical energy sources this novel technology harvests are kinetic, thermal, solar, and electromagnetic radiation. When considering to power electronic devices, kinetic energy has received the most attention because it could be found in many places where the other energy sources are not suitable [1-5]. Furthermore, compared with the other two commonly utilized transduction principles (i. g., electromagnetic and electrostatic), the piezoelectric transduction is most suitable for MEM devices and wireless sensors, mostly because it can effectively be placed in small volumes and it can be used to harvest energy over a wide range of frequency. [2, 6]

With regard to the impact factors of energy harvesting, the two most critical influences on its generated power are the quantity and the available forms of kinetic energy, and the efficiency of the power transduction. During the last decade, many studies have been concerned with harvesting energy from base vibration, significant work are related with how to enhance the level of the generated power, tune the resonance frequency of the generator, and design the broadband devices. [7, 8]

On the other hand, besides harvesting the excitation energy from the base of the structure, during the past few years, more and more scholars have paid their attention on flow induced vibration energy. From the energy harvesting point of view, the harvester is placed in a flow field and excited to undergo large limit-cycle oscillation that can be converted into electrical energy through piezoelectric transducers. [9, 10]

Classic flow induced energy harvester refers to the piezoelectric cantilever beam with the bluff body in front of it. At very slow Reynolds numbers, the streamlines of the resulting flow are perfectly symmetric as expected from potential theory. However, along with the increase of Reynolds number, the flow becomes asymmetric and the so-called Karman Vortex Street occurs [11]. The bluff body at the front converts the kinetic energy of the uniform and steady fluid flow into large temporal pressure fluctuations caused by vortex shedding based on Karman Vortex Street. The wake of vortices are periodically shed from the top and bottom of the bluff body, due to the alternating directions the vortices rotate, a flexible beam placed in the wake of the bluff body will undergo relatively large oscillations [12]. These pressure fluctuations could be converted by the piezoelectric energy harvester into electrical energy.

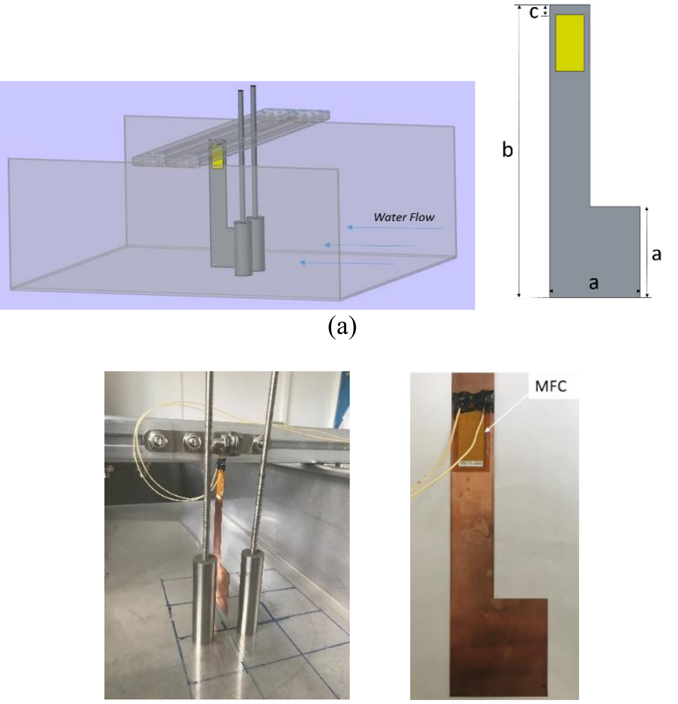
With regards to the main principle of flow induced energy harvester, when the flow through exact geometry, the alternative vortex shedding happens on the surface of the geometry. Based on the vibration generated by this shedding, we could generate power through direct effect of piezoelectric component. Some studies have been done to enhance the performance from this method. Akaydin, Elvin, and Andrepoulos designed a compact structure which combined the bluff top and the cantilever beam together [13]. By this way, the cantilever beam locating at the downstream could harvest the vibration not only from the surface of the cylinder, but also the vortices of the wake. Other scholars like Hobbs and Hu arranged a linear array of four cylinders affixed to piezoelectric energy harvester to generate and scavenged a uniform flow vibration [14]. Shan tried to test the feasibility with putting the classic structure into water flow channel with MFC material [15].

However, even the above novel methods still face great challenges of scavenging the energy from the ambient environment. First of all, the speed of the flow inside the vortex street decreases rapidly after flowing past the cylinders; besides that, along with the increase of the speed, the cantilever beam may not generate oscillating bending, it will be restricted with one side and could not rebound back; even worse, it may generate damage on key component such as piezoelectric material of the energy harvester with high flow speed. Due to the characteristic of Karman Vortex Street, the key component of energy harvester with piezoelectric material should be put totally in the downstream behind the bluff geometry, which means the energy coming from the gradient of the speed could not be utilized. The gradient of speed should be another important source of the kinetic force that generating the power in the flow induced energy harvesting field, based on Bernoulli equation. Moreover, even the arrangement of the rods are typically linear layout, there should be other efficient layout method to enhance or even amplifier the phenomenon for vortex shedding. The direction of the shedding could be induced and controlled by the exact layout of the bluff bodies.

In the following parts of the paper, we will propose a novel structure of energy harvester, which could not only improve the output of flow-induced energy harvester, but also avoid the damage happened within complex working conditions. Besides that, the novel energy harvester could make use of both the kinetic force and the pressure came for the gradient of the velocity, the direction of the shedding will be coincident.

STRUCTURE AND PRINCIPLE

Figure 1 shows the schematic diagram of our proposed structure, the entire structure could be divided into two main parts, namely L-type cantilever beam and inducing objects (cylinders) which are set on both sides of the beam and perpendicular to the flow direction. The cylinders, which are made of stainless steel, are put in front of the cantilever beam to induce the vortex shedding. The position of the cantilever beam is at the middle of the cylinders. The tip of the beam is corresponding to the cross section formed by the two axes of the cylinders. There is a piezoelectric patch (MFC) attached at the fixed end of the L-type cantilever beam to convert kinetic energy into electric power. Table 1 lists the geometric and material parameters of MFC material and energy harvester. When the laminar water flow system works, the vortex shedding from the upstream cylinders will drive the free end of cantilever beam to vibrate. The open-circuit output voltage generated by the energy harvester across the DAQ (Data Acquisition) is available. The average output power P_{av} transferred to a load resistor can be calculated by



(a)

(b)

Fig. 1. (a)Schematic diagram of a flow-induced energy harvester and (b) the photo of the prototype

$$P_{av} = \frac{V_{rms}^{2}}{R_L} \tag{1}$$

where V_{rms} is the rms voltage across the load resistor R_L. P_{av} reaches the maximum when R_L equals to its optimal value [16],

$$R_{LO} = \frac{1}{wC_P} \tag{2}$$

where ω is the vibration frequency of the energy harvesting module and C_P is the capacitance of the MFC material. Eq. (2) is used to define the optimal load resistors at different operating frequencies.

The output power P_{av} transferred to a load resistor can be calculated by

$$P_{av} = \frac{V_0^2}{2R_L[1 + (1/\ wC_P R_L)^2]} \qquad (3)$$

where V_0 is the open circuit voltage (0-peak).

Table 1. Geometric and material parameters of MFC material and L-type beam

Parameters	Values
D_{31} (pC/N)	-1.7E02
Capacitance of MFC (nF/cm^2)	4.6
Tensile modulus of MFC (GPa)	15.857
The width of the MFC (mm)	14
The length of the MFC (mm)	28
The length of line a (mm)	45
The length of line b (mm)	145
The length of line c (mm)	5
Mass density of the beam (kg/m^3)	8900
Tensile modules of the beam (Gpa)	110
The diameter of the cylinders (mm)	20
The length of the cylinders (mm)	80

Experiment setup

Fig. 3 shows the setup of the experiment system, the width of the flow channel is 31.5cm, the flow rate could be read through flow meter, after measuring the depth of the water flow, the speed of the flow could be calculated by

$$V=Q/S \qquad (4)$$

where V is the speed of flow channel, Q is the flow rate, and S is the area of the cross section.

The length of the whole flow channel is two meters long which is to make sure the water flow is fully developed into laminar flow. It is easily to get that the water flow speed is around 0.2m/s when the flow rate is 18m^3/s and the depth of the cross section is 80mm.

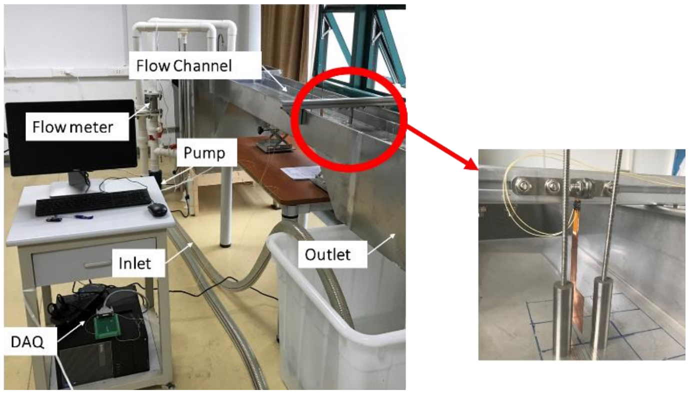
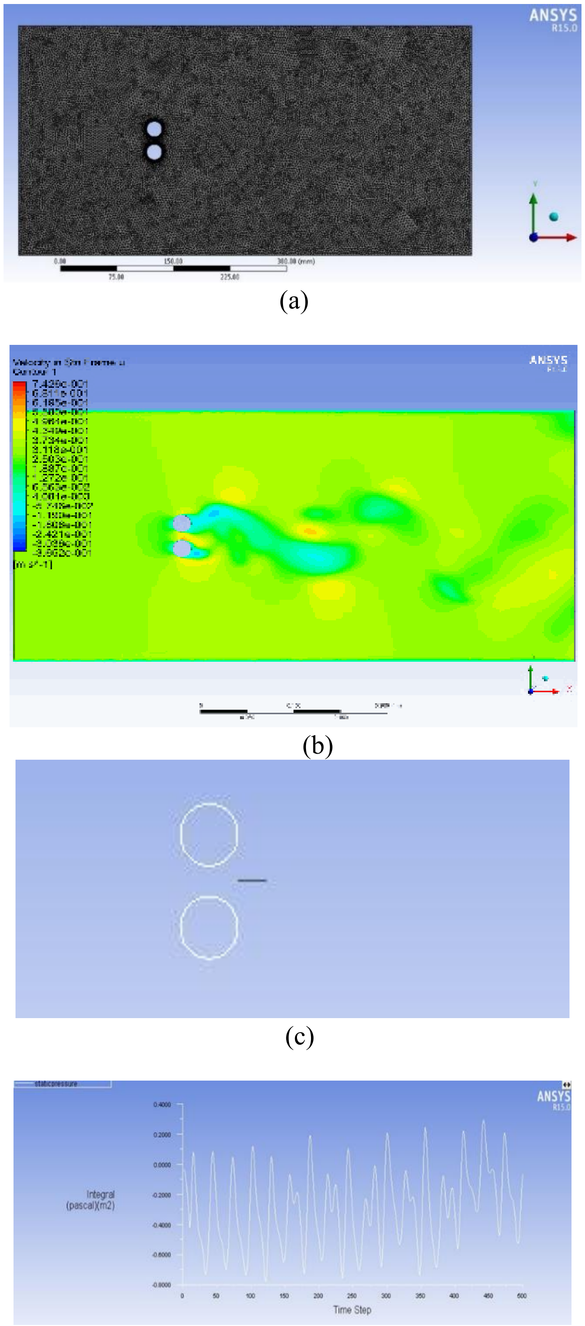


Fig. 3. Setup of the experiment system

Analytical modelling

To explain this phenomenon, we choose a finite software (FLUENT) to analyze the downstream of two cylinders (shown in Fig. 4). The inlet velocity is set as 0.2m/s and the distance between two circle centers is 30mm. From Fig. 4, it could be observed that the shedding induced through two cylinders will generate alternatively on the surface of them and remain same direction. When we insert an auxiliary line after the cylinders (shown in Fig. 3(c)), we could get the relationship between the static pressure and time. It also shows the periodic pressure fluctuation happened at the downstream of the cylinders.



(a)

(b)

(c)

(d)

Fig.4. The FEM calculation (a) Model (b) the Contour of the flow (c) the Position of auxiliary line (d) Static pressure versus time step

It is easily to understand that the vortex shedding on one cylinder will induce the other cylinder to shed vortex. In other words, the vortices shedding from the lower surface of the upper cylinder will induce the vortices shedding from the upper surface of the lower cylinder. When the two cylinders shed together at the same direction, the energy inside of the wake is higher than the single one generates, and the shedding frequency of the vortex with more energy is the same of the single shedding frequency.

Strouhal number could also be utilized to estimate the shedding frequency on smooth circular cylinder [17, 18],

$$S_t = f_s d / U \tag{5}$$

where f_s is shedding frequency, d is diameter and U is the speed of the inlet flow. Here, f_s=2Hz.

THE RESULTS AND CHARACTERISTICS DISCUSSION

The relationship between output voltage versus time with 30mm center distance of two cylinders at 0.2 m/s flow speed is shown in Fig. 5.

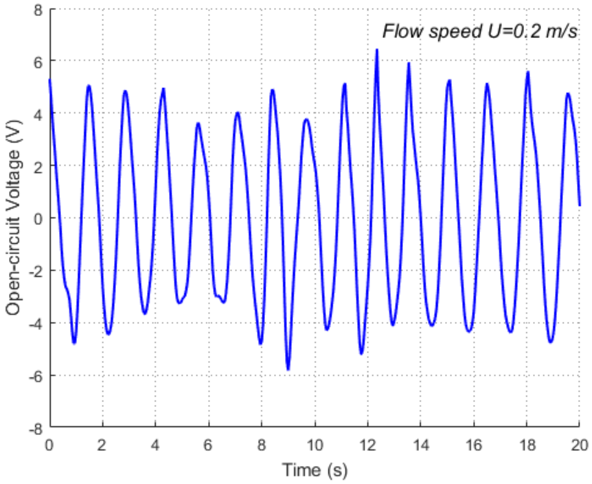


Fig. 5. Relationship between open-circuit voltage and flow time

Fig.5 indicates that the oscillating frequency is around 1.4Hz which matches the analytical modelling. The mean open-circuit voltage (0-peak) is approximately 5V. Hence, based on the equations (1-3), the optimal output power is 0.16μW and the power density is 0.4mW/m^2.

In order to measure the improvement of output power with the novel layout of the inducing objects, the structures without and with only one cylinder in front are also tested (shown in Fig. 6).

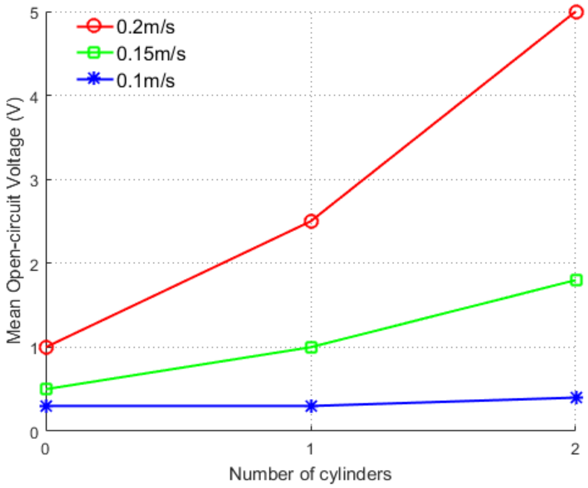


Fig.6. Relationship between volatage and number of cylinders

For the experiment with only one cylinder, it was put 66mm ahead away from the beam which was 3.3 times over the diameter of the cylinder; it was known that this distance would generate the best output at that working condition [14]. According to the fuild dynamic theory, the cantilever beam without the cylinder in front of it should not generate any vibration in laminar flow, since there is no pressure fluctuation on both sides of it. However, the fact that there is still tiny power could be observed in the experiment; it may come from the flatness of the beam not being good enough. As shown in Fig. 6, the output improved sigificantly with the effect of two cylinders in front. Since the cantilever beam was put at the middle of the cylinders, the energy it harvested was not only the pressure fluctuation from vortices street force. It is believed that, based on the Bournulli equation, along with the deformation of the cantilever beam, the flow speed on both sides of the cantilever beam will be different, the static pressure on the surface will change along with that of dynamic pressure, and the pressure difference will make the beam bend to the opposed diretion as well. Hence, one part of the pressure fluctuation comes from the gradient of velocity.

Fig. 7 shows the relationship between the center distance of the cylinders and output; it is known that the output of the harvester increases at first and then reaches a maximum peak, and after the peak, the output of the harvester decreases with the increase of the distance. When the center distance is below critical point, the beam will touch the surfaces of the cylinders; when the center distance is larger than the critical point, it will not make contact with the surface any more. Hence, the cylinders on both sides of the cantilever beam could help to protect the beam without the damaged deformation even with complex working conditions in the ambient environment. Fig. 7 also shows that along with the increase of the flow speed, the optimal center distance would be wider. In orther words, the higher the speed, the wider optimal the center distance. It comes from the increase of the amplitude of the cantilever beam along with the increase of the flow speed.

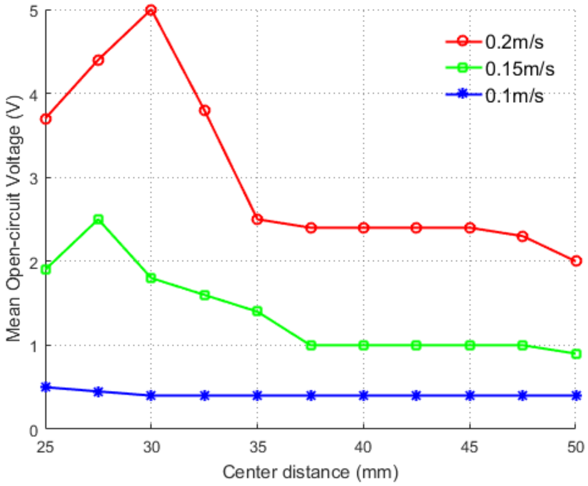


Fig. 7. Measured output versus center distance

Fig. 8 shows the influence of the flow speed on the output. It is seen that the output of this novel structure raises along with the increase of the flow speed. It could be seen that the flow speed is the critical influence factor on the output of the energy harvester, under the condition that the inducing objects are cylinders, and the higher the speed, the higher the output power. Due to the limit of the flow rate, the largest flow speed that the laminar water flow system could generate was 0.2m/s, but it could be predicted that the output could be better with higher speed.

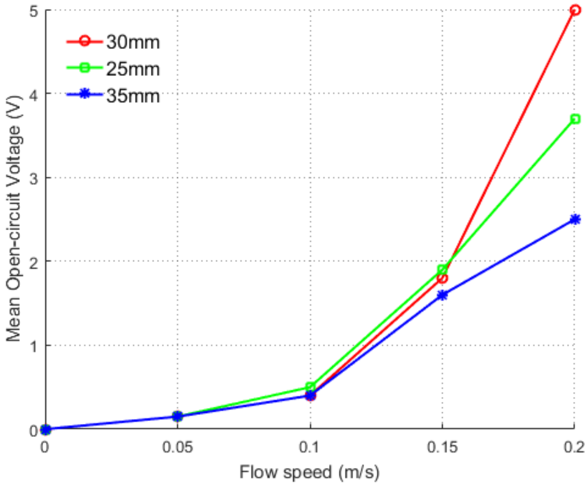


Fig. 8. Measured output versus flow speed

Regarding the classic fluid dynamic theory, the position of the shedding on the cylinder could be induced by the upstream flow. It is obvious that when the vortex hit the exact surface of the other cylinder, the shedding direction starts with that side first. Through the above layout of the cylinders, it is expected to control the shedding position on each cylinder accurately.

Based on the above experiments and analyses, it is known that potential means of improving the output characteristic include optimizing the gap distance of inducing objects, the topology of inducing objects and cantilever beam, the number of inducing objects and the position of the cantilever beam with MFC. It is believed that, based on the above optimizations, the better output of power will be generated and the safety of the key component of the structure is guaranteed.

CONCLUSION

A novel flow induced structure based energy harvester is proposed and investigated, aimed at improving the amplitude of output power. With two cylinders, perpendicular to the flow direction, the cantilever beam with MFC patch could generate higher power compared with most other flow induced structures revealed in the literature. The highest power in the experiment is 0.16μW and the power density is 0.4mW/m^2. FEM model is utilized to verify the feasibility of the structure. The characteristics with different center distances and flow speeds are investigated. The potential optimizations have been discussed.

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