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A Curved Body with Tail Design for Piezoelectric Energy Harvesting

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Abstract

Piezoelectric vibration energy harvesting has the potential for higher conversion efficiency, and higher output voltage, for MEMS systems and portable devices. Avoiding the reattachment of vortexes and increasing the pressure difference between the objects is key to effectively improve the vibration performance and output. In this paper, a curved plate with tail design is proposed, which has potential to have higher vibration frequency and larger amplitude exploiting the galloping phenomenon. The design has been compared with a curved plate design by simulation, and it shows better performance. Its average lift coefficient increases by 57.42% within a wind speed range of 1-10m/s compared to the curved plate design. The paper also studies the effect of tail length on the frequency and lift coefficient.

Keywords: energy harvesting, galloping, piezoelectric, novel design

1. Introduction

Microelectromechanical systems (MEMS) are compact devices with dimensions of a few millimeters or even smaller. Because of its small physical size, MEMS is widely used in different fields, for example, it could accurately measure stability in buildings [1], deliver drugs inside a living organism safely [2] or eliminate additional signal noise from the [3]. Since MEMS are usually embedded in the structure, they mainly rely on batteries for power supply. Similarly, there are portable devices that require battery power for many uses in everyday life. But limited battery capacity means that they require frequent charging. In remote areas, repeated charging may become a costly process and inconvenient where access to power is limited. In recent years, Energy Harvesting has attracted people's attention, and it has become a promising solution to power small devices by obtaining ambient energy.

As one kind of energy harvesting source, vibration is ubiquitous in nature, and the mechanical energy of vibration can be converted into electrical energy in a variety of ways, such as electromagnetic vibration energy harvesting, electrostatic vibration energy harvesting device and piezoelectric energy harvesting device. The most common piezoelectric energy harvesting method is wind-induced vibration and there are many designs for structures based on different vibration types. Due to efficiency or size issues, these designs are still far from commercial use.

Wind-induced vibration piezoelectric energy harvester devices generally uses a cantilever beam structure where the free end of the cantilever beam fixes the structure, and the piezoelectric device is placed at the other end of the cantilever beam. When the wind flows through the free-end structure, the vibration of the cantilever beam causes a stress change on the surface of the piezoelectric device placed at the end of the cantilever beam, thereby generating electricity.

In this work, a novel Wind-induced vibration piezoelectric energy harvester design (Curved Plate with tail design) will be presented, and the simulation result will show be shown. This design is a piezoelectric vibration energy harvesting device by harvesting operating in the galloping mode in the air flow. In contrast to existing designs, the novel design has a vibration frequency which is significantly improved, and increases the energy harvesting efficiency of the device.

2. Background

For aerodynamic energy harvesting, M Bashir et al. [4] divided this type of vibration energy harvester into three categories, motion-induced excitation energy harvester (MIEEH), instability-induced excitation energy harvester (IIEEH), and extraneously induced excitation energy harvester (EIEEH). MIEEH includes a galloping energy harvester and a flutter energy harvester. IIEEH is an energy harvester based on linear resonance, which includes vortex-induced vibration energy harvester (VIV) and buffeting energy harvester. In addition, wake galloping caused by turbulence is usually classified into EIEEH as shown in Figure 1.

Vortex-induced vibration (VIV) is one of nature's most common vibration phenomena. When a fluid with a large Reynolds number passes around a bluff body, such as a cylinder, the fluid near the boundary layer will flow at a low speed and attach to the boundary layer due to the fluid's viscosity. Then the boundary layer flow will be separated from the upper and lower surfaces of the object to form two shear layers flowing downstream. Because of the gradient pressure, discrete vortices will be generated downstream. As a result, the vortex will periodically fall out of the two sides of the object with opposite rotation and regular arrangement. This vortex generation process downstream of the bluff body is called vortex shedding. Due to the vortex shedding, there will be a low-pressure zone in the vortex area. Therefore, periodic forces will be generated on both sides of the bluff body as the vortex shedding, causing the bluff body to produce periodic vibration consistent with the vortex shedding period, which is called VIV.

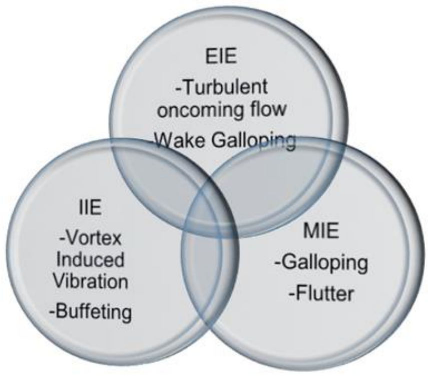

Figure 1. Different categories of aeroelastic energy harvesters

Galloping is a divergent bending self-excited vibration caused by the negative slope of the lift curve. This negative slope makes the displacement of the structure always consistent with the direction of the air force during the vibration process. As a result, the structure continuously absorbs external energy, thus forming unstable vibrations. Galloping generally occurs in flexible, lightweight structures with angular, non-streamlined cross-sections, such as cubes, as shown in Figure 2 (a). The difference with VIV is that the amplitude of galloping increases with fluid velocity, but the minimum operating fluid velocity is more significant than VIV. The curve of typical galloping vibration amplitude and fluid velocity is shown in Figure 2 (c). As shown in Figure 2 (b), it is generally assumed that the non-cylindrical bluff body is fixed on the spring, and the fluid flows from right to left at the speed of U. For galloping, the conventional cross-sectional shapes are square, triangle, and D-shaped.

In recent years, many researchers have made some novel designs for square cross-sections based on the design concept of the square to the triangle. A funnel-shaped design was proposed in 2020 [7]. This design not only prevents the vortex from re-attaching but also leaves space for the vortex to fall off. Experimental and simulation results show that the maximum output power of the design can reach 2.34mW/cm3, while the output power of the bluff body with square and triangular cross-sections is 0.207mW/cm3 and 1.56mW/cm3, respectively. At the same time, the design also reduces the minimum operating wind speed of the energy harvester.

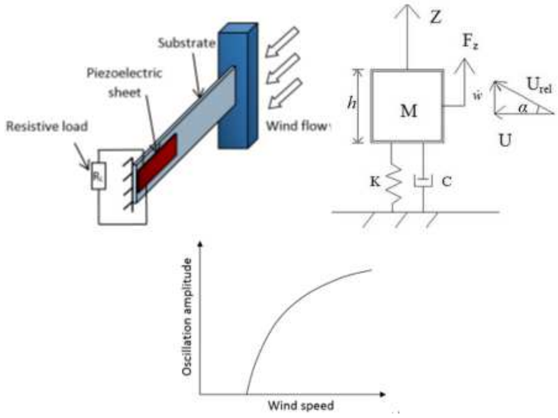

Figure 2. (a) Typical galloping piezoelectric energy harvester (b) The governing equation of galloping motion (8) (c) Typical curve of galloping vibration amplitude VS fluid velocity

Similar to this design, some researchers pointed out a novel energy conversion system, which include a T-shaped bluff body. The T-shaped design is composed of two planes with a thickness of 0.01m. Two planes are perpendicular to each other to form a "T-shaped" structure. Two planes on both sides are used to reduce the influence of the boundary. This system has a maximum output power of 21.23W at a flow rate of 12.25m/s [9].

C. Zhou [10] proposed a curved plate shape design and analyzed the effect of various lengths of the curved plate. In the experiment and simulation, the average power output of the structure of the curved plate, Square, Triangular, and D-Shaped are compared. The average power of the Curved Plate is the highest.

3. Methodology and Results

For a square shape design, the vortex is generated at the front vertices on both sides but reattaches to the boundary layer at the back vertices on both sides. Due to the reattachment of the vortex, pressure fluctuations appear on the upper and lower sides of the square, which affects the life force of the bluff body. So, the researchers merged the upper and lower back vertices of the square to turn the square into a triangle. The triangle shape can effectively avoid the reattachment of the vortex and ensure the coordination of vortex shedding at the upper and lower sides. From a lot of design, it can be seen that avoiding the reattachment of vortexes and increasing the pressure difference between the objects could effectively improve the vibration performance.

A novel design is proposed to increase the pressure difference between the upper and lower parts of the object. The novel design is superior in concept by adding a straight plate on the back of the curved plate. The straight plate is fixed at the middle of the curved plate, and in this configuration, the vortex will not fall directly but will continue along the straight plate. It is expected to extend the time of pressure difference to increase the pressure difference. The two model configurations were created in 2D to compare the improvement and were established and analyzed using computational fluid dynamics (CFD). Ansys 2021R2 Fluent was used for the process.

The main body (Curve and Curve with tail) was enclosed within a rectangle of dimensions 200 x 100cm, and the centre of the curve was set at a rectangular horizontal middle line and had 55cm distances from the left side of the rectangle, as shown in Figure 3. The curve part of the two models was semi-circular. The size of the geometry allowed the dominant flow features to be enough to capture and avoid the air streamline near the wall affecting the bluff body. The parameter for models is shown in Table 1.

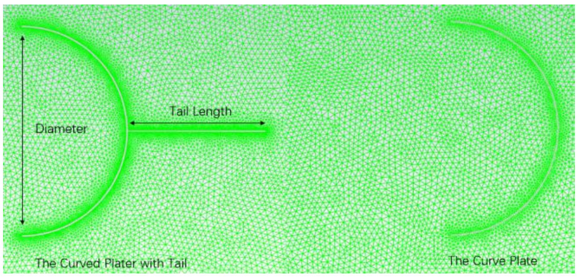

Figure 3. The 2D simulation models

The top and bottom boundaries were set as a fixed wall, and the airflow direction was perpendicular to the inlet boundary. The standard k-ε turbulence model was selected to model the wind flow according to its computational accuracy and time consumption. The turbulence intensity was 5%, and the turbulent viscosity ratio was 10. Two monitors (lift coefficient and drag coefficient) were applied to the body. Two models were simulated within the same conditions from 1 - 10 m/s of inlet boundary velocity. The other simulation solution method is shown in Table 2.

Table 1. Parameter of simulation models

Parameter	**Value**	**Unit**
Diameter	20	cm
Tail Length	13	cm
Fluid Density	1.225	kg/m3
Fluid Viscosity	1.79E-05	kg/m-s

Table 2. The simulation solution method

Catalog	**Solution Method Used**
Pressure-Velocity Coupling	Simple Scheme
Spatial Discretization	Second Order Pressure and Momentum
	First Order Upwind Turbulent Kinetic Energy
	First Order Upwind Turbulent Dissipation Rate
Transient Formulation	Second Order Implicit Option

The result shows that compared to the Curved Plate design, when the wind speed is 4m / s, its lift coefficient is the highest, it increases by 80.5%, and the average growth rate of lift coefficient is 57.42% within 10m/s as shown in Figure 4. It is also worth noting that the corresponding time of the novel design is significantly smaller than the curve plate design (see Figure 5). This means it produces more energy and has better adaptability.

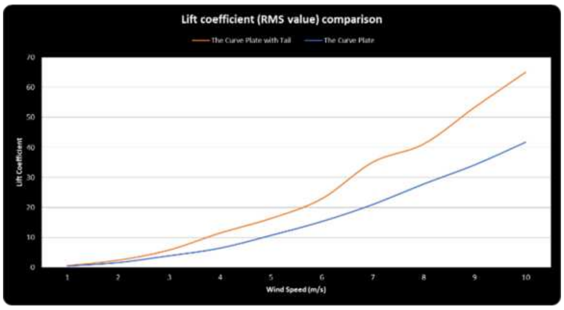

Figure 4. Lift coefficient (RMS value) comparison

Figure 5. Lift Coefficient at 6m/s

In addition, the effect of the length of the tail of the novel piezoelectric design was also analyzed with an inlet air speed of 5m/s. When the length of the tail grows continuously, the lift coefficient grows linear, but the frequency continuously declined. For example, when the tail length was increased to 60 cm, although the peak of the lift coefficient reached 77.67, the vibration frequency was reduced to 1.41 Hz, whereas the peak of the lift coefficient was 13.21, the frequency was 4.76 Hz when the tail length was 5 cm. However, it was worth noticing that before the tail length was 13cm (L / D = 0.65), the lift coefficients had increased and there was a slight decline after this point, which then recovered the upward trend again as shown in Figure 6.

The lift coefficient can be used as a reference index of the oscillation amplitude of the harvester. In general, the higher the lift coefficient, the greater the oscillation amplitude. For a piezoelectric energy harvester, the oscillation amplitude and frequency are two critical parameters that affect power output. The simulation results generally show that the maximum power output may be obtained when the tail length is 13 cm (L / D = 0.65).

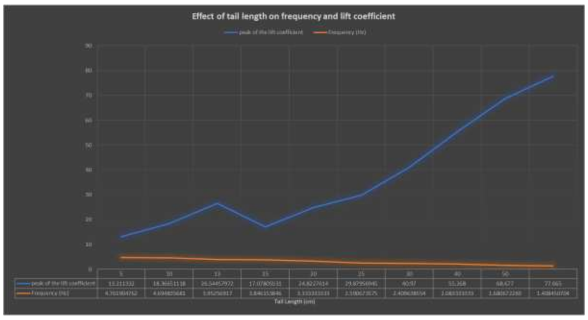

Figure 6. Effect of tail length on frequency and lift coefficient

4. Conclusion

A novel piezoelectric energy harvester design (Curved Plate with tail) has been proposed in this work. The design has a more significant lift coefficient and has the potential to have a larger energy output than the conventional designs. For the simulation study of the effect of tail length, the effect on lift coefficient and frequency has been obtained, and future experiment will be performed to validate the results from this study. The study has identified an opportunity for enhanced device efficiency by design and deployment could a contribution to tackling climate change.

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