Simulation and Analysis of Flexible Piezoelectric Beam under Karmen Vortex Street Effect

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Abstract. Recent years, researchers have gradually increased their research efforts on energy harvesters for low power applications. Among them, many piezoelectric energy harvesters have been widely used because of their simple structures, low energy consumption and easy miniaturization. In order to study the energy harvesting with a flexible piezoelectric beam deformed by vortex-induced vibration, this paper takes polyvinylidene fluoride as the piezoelectric beam, and relies on ANSYS simulation software, establishes a fluid-solid-piezoelectric three-field coupling model, and calculates the energy harvesting capacity of piezoelectric beam. The results show that the positive output voltage is 59.763V and the negative output voltage is -67.633V.

1. Introduction
With the development of low power electronic components, the traditional chemical batteries are facing great challenges. Because of their short service life and large space occupation, ordinary chemical batteries can’t fully meet the needs of those special projects, which provides an opportunity for the development of piezoelectric components. That makes it possible to use piezoelectric components to harvest energy instead of conventional chemical fuel cells [1].

The vibration modes in the flow field include flutter, buffeting, galloping and vortex-induced vibration [2], among which Karman vortex street vibration (a kind of vortex-induced vibration) has excellent stability and periodicity. Therefore, utilizing the Karman vortex street effect to generate electricity has become an important research hotspot for scholars. Taylor G W et al. [3] first proposed a flexible piezoelectric energy harvester, which fixed the flexible piezoelectric film behind a blunt cylinder and used the Karman vortex effect produced by the impact of water flow on the cylinder to make the film swing and generate voltage. Weinstein L A et al. [4] studied the power generation capacity of flexible piezoelectric plates at different positions of blunt bodies, and found that the electromechanical conversion rate was low, and only 0.0035% of the energy was converted into electricity.

The physical field studied in this paper is the wind field. Based on the Karman vortex street effect, the flexible piezoelectric beam is fixed at a certain distance behind the cylinder. By changing the distance, the relationship between the power generation capacity and distance is simulated and analyzed.
2. Model and Theory

2.1. PVDF

PVDF is a typical representative of piezoelectric polymers. Since PVDF has flexibility, good workability, and high piezoelectric constant, it can be made into sensors of different sizes [5]. In this paper, the overall thickness of the piezoelectric beam is 1 mm, in which the length of PVDF is 70 mm and the thickness of PVDF is 0.04 mm. The parameters of PVDF are shown in Table 1.

| Symbol | Parameter                  | Value  | Unit        |
|--------|----------------------------|--------|-------------|
| ρ      | Density                    | 1.78   | 10^3 kg/m^3|
| Y      | Young’s modulus            | 2      | GPa         |
| μ      | Poisson’s ratio            | 0.3    |             |
| d31    | Piezo strain constant      | 23     | 10^{-12}    |
| g31    | Piezo stress constant      | 216    | 10^{-3}     |
| k31    | Electromechanical coupling factor | 12%   |             |

2.2. Model

The computational domain of wind field is a 2.5D case with a length of 1500 mm, a width of 410 mm and a thickness of single layer element (5 mm). The left side of the flow field is the inlet boundary, and the right side is the outlet of the pressure outflow boundary. Both the front and back sides are the symmetrical boundary, and the top and bottom surfaces are the wall boundary. The diameter of the cylinder is 50 mm, and the left end of the flexible piezoelectric beam is fixed. The distance from the left end of the flexible piezoelectric beam to the center of the cylinder is L. When the wind flows in from the left entrance, because of the blockage of the blunt body, the Karmen vortex street effect occurs after the blunt body. The drop of the vortex street will change the pressure difference between the two sides of the piezoelectric sheet, which will cause the vibration of the flexible piezoelectric beam and generate electricity. The computational domain of wind field is shown in Figure 1, and the flow chart of system coupling simulation is shown in Figure 2.

![Figure 1. Computational domain of the model.](image-url)
2.3. Theory

The shedding frequency of the vortex street is closely related to the vibration frequency of the cantilever beam. When the shedding frequency of the vortex street reaches the resonance frequency of the piezoelectric cantilever beam, the power generation of the piezoelectric beam reaches the maximum value. The frequency of vortex shedding is defined as follows.

$$ f = \frac{S_i u}{D} $$

(1)

Where, $f$ is the shedding frequency of the vortex street; $S_i$ is the Strouhal number; $u$ is the inflow velocity; and $D$ is the diameter of the cylinder.

SST k-ω turbulence model is used to obtain more accurate pressure in fluid-structure interaction analysis. The governing equation in fluid domain is Navier-Stokes equation, which includes continuity equation and momentum equation.

$$ \frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nabla^2 u_i $$

(2)

$$ \frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nabla^2 u_i $$

(3)

Where, $u_i$ is the velocity component in the direction of $i$; $x_i$ is the coordinate component in the direction of $i$; $\rho$ is the density of the fluid, and $p$ is the pressure.

The governing equation of the piezoelectric cantilever beam trap is as follows:

$$ M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = F(t) - \Theta V_p(t) $$

(4)

$$ \Theta\ddot{x}(t) - C_p V_p(t) = Q_p(t) $$

(5)

where, $M$ is the equivalent mass of the cantilever beam; $K$ is the equivalent stiffness of the cantilever beam; $C$ is the equivalent damping of the cantilever beam; $\Theta$ is the electromechanical coupling coefficient; $C_p$ is the capacitance of the piezoelectric cantilever beam trap; $V_p$ is the output voltage of the piezoelectric cantilever beam trap; $Q_p$ is the charge generated by the piezoelectric cantilever beam trap; $F$ is the external vibration excitation; $x$ is the displacement of the piezoelectric cantilever beam trap.
2.4. Meshing of model

The ANSYS meshing is used to divide the structural grids of the model. The number of meshes after dividing is about 17,000. The key point of mesh generation is the partitioning of the model, because the difficulty is that the thickness of PVDF is only 0.04 mm, which increases the difficulty of mesh generation. The block diagram and mesh diagram of the model are as follows.

Figure 3. The block diagram of model.

Figure 4. The mesh diagram of model.

Figure 5. The mesh diagram at Cylindrical Boundary.
3. Simulation results and discuss

By changing the distance between the left side of the flexible piezoelectric beam and the center of the cylinder, the power generation results of the flexible piezoelectric beam under five different conditions have been obtained. Statistical results are shown in the following figures, where it can be seen that with the increase of distance, the output voltage amplitude decreases gradually. The positive output voltage is 59.763V and the negative output voltage is -67.633V.

4. Conclusion

The flexible piezoelectric beam can harvest energy from wind under the action of wind force. As a simple and light weight electromechanical converter, PVDF can be widely used in wind energy harvesting. Although the generated voltage is not strong (-67.633V~59.763V), it can still be used in low-power electrical equipment after signal conditioning.

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