The Controllable Turbulence Generator Based on Piezoelectric Actuation and Its Mechanical Performance Analysis

Shuai Wang, Shichen Zhou, Bo Zhou* and Shifeng Xue
College of Pipeline and Civil Engineering, China University of Petroleum (East China), Qingdao 266580, China
Email: zhoubo@upc.edu.cn

Abstract. Piezoelectric material is a kind of material that can perform electric-force conversion. Various actuators made of its inverse piezoelectric effect have been widely used in intelligent structures. In this paper, a piezoelectric actuated turbulence generator is designed, the design concept and working principle are introduced, the mechanical behavior of the piezoelectric structure is analyzed by using the finite element method, and the influence of electrical load on the deformation of the piezoelectric structure along different directions is considered. This paper can provide some theoretical basis for the design and analysis of turbulence generator.

Keywords. Piezoelectric structure, turbulence generator, finite element method, mechanical behavior.

1. Introduction
Piezoelectric material (PZT) is a material used for electrical-force conversion. When PZT is subjected to loads, charges can be generated on its surface; and when an electric field is applied to the surface of PZT, it can deform. Therefore, PZT has a positive and inverse piezoelectric effects [1-2]. In addition, PZT has high measurement accuracy and response. The advantages of fast speed and stable performance are widely used in the fields of aerospace, precision measurement and intelligent structures [3-4]. The piezoelectric composite plate is an important realization form of sensors and drivers, and currently plays an important role in energy harvesting, vibration suppression, noise control [5-6].

At present, some experts and scholars have designed and analyzed the structure of turbulence generator. Zhi L et al analyzed the working principle and structure of the turbulence generator of medium thick slurry pump, proposed a complete set of turbulence generator structure design method, designed six different structure turbulence generators and carried out finite element mechanical analysis [7]. Villamizar J et al Propagated a laser beam and built an optical turbulence generator to study the horizontal path, the experimental results showed the measurements of turbulence beam centroids fluctuations and humidity generated stronger turbulence [8]. Daoxing Y et al simplified the movement of bubbles in the rotating flow field, analyzed the force of bubbles in the turbulence generator, deduced the velocity and trajectory equation of bubbles in the process of motion, and analyzed the dynamic characteristics of bubble motion [9].

However, there are few researches on turbulence generators acted by piezoelectric composite structures. In this paper, we design a turbulence generator based on piezoelectric composite plates, by setting a few piezoelectric composite plates on the flow field, and the applied electric field can control the shape of composite plates, and Reynolds number would be changed to adjust fluid state. According
to the finite element method, the piezoelectric composite plate is analyzed, and the electric field's influence on the deformation of piezoelectric composite plate along different directions is studied.

2. Design of Controllable Turbulence Generator

Figure 1 shows three views of piezoelectric composite plates. We can see that piezoelectric patches are arranged on the upper and lower sides of the substrate plate respectively. The piezoelectric patch is set in a semicircular shape, and polarized along the z axis. The substrate is set in a circular plate, whose front and rear edges is symmetrically cut into two rectangular sections along the transverse direction, which is convenient for installation and fixing in the pipeline. There is no piezoelectric patch on the circular plate penetrated by the front and rear rectangular sections, and the remaining positions are fully acted by the semicircular piezoelectric patches. The dimension parameters of the piezoelectric composite plate have been marked in figure 1, and the specific dimensions are shown in table 1.

![Figure 1. Three views of piezoelectric composite plate.](image)

| Dimension parameters $[\times 10^{-3} \text{ m}]$ | $D$ | $W$ | $h$ | $b$ | $d_1$ | $d_2$ |
|--------------------------------------|---|---|---|---|---|---|
| $160$ | $158$ | $10$ | $3$ | $67.5$ | $25$ |

Figure 2 shows a schematic diagram of the working principle of the turbulence generator. The contact surface between the turbulence generator and the pipeline is fixed by welding. Taking the liquid as an example, it is in a laminar flow state when it initially enters the pipe and undergoes a composite without voltage action. The Reynolds coefficient is small, and its viscous force on the fluid is greater than the inertial force, the liquid still maintains a laminar flow state, and a small amount of bubbles can be generated. When the laminar fluid continues to move forward, and pass through the piezoelectric composite plate with voltage action, the Reynolds coefficient is large, the influence of inertial force is greater than the viscous force on the flow field, the liquid flow is unstable, which can form an irregular turbulent state, and generate a lot of bubbles.
3. Piezoelectric Constitutive Equations

For piezoelectric materials, the piezoelectric constitutive equation describing the relationship among the electric field strength, stress, strain, and electric displacement can be expressed as

\[ \varepsilon = \sigma + d^T E \]  \hspace{1cm} (1)

\[ D = \xi E + d\sigma \]  \hspace{1cm} (2)

where \( \sigma \) and \( \varepsilon \) are the stress and strain column matrix, respectively; \( D \) and \( E \) are the electric displacement and electric field strength column matrix, respectively; \( s \) is the flexibility coefficient matrix of piezoelectric material, we can write it as

\[ s = \begin{bmatrix}
  s_{11} & s_{12} & s_{13} & 0 & 0 \\
  s_{12} & s_{22} & s_{23} & 0 & 0 \\
  s_{13} & s_{23} & s_{33} & 0 & 0 \\
  0 & 0 & 0 & s_{44} & 0 \\
  0 & 0 & 0 & 0 & s_{55} \\
  0 & 0 & 0 & 0 & 0 & s_{66}
\end{bmatrix} \]  \hspace{1cm} (3)

where \( s_{11} = s_{22}, s_{13} = s_{23}, s_{44} = s_{55} \) and \( s_{66} = 2(s_{11} - s_{12}) \); and \( \xi \) is the dielectric coefficient matrix of piezoelectric material, we can write it as

\[ \xi = \begin{bmatrix}
  \xi_{11} & 0 & 0 \\
  0 & \xi_{22} & 0 \\
  0 & 0 & \xi_{33}
\end{bmatrix} \]  \hspace{1cm} (4)

and \( d \) is piezoelectric strain coefficient matrix of piezoelectric material, we can write it as

\[ d = \begin{bmatrix}
  0 & 0 & 0 & 0 & d_{15} & 0 \\
  0 & 0 & 0 & d_{24} & 0 & 0 \\
  d_{31} & d_{32} & d_{33} & 0 & 0 & 0
\end{bmatrix} \]  \hspace{1cm} (5)

where \( d_{31} = d_{32} \) and \( d_{24} = d_{15} \).

4. Finite Element Simulation and Analysis

The piezoelectric composite plate established by ABAQUS 2018 is analyzed by finite element method. The piezoelectric patches adopt lead zirconate titanate piezoelectric ceramic (PZT-4) in reference [10]. The material parameters are shown in table 2. The substrate plate adopts purple aluminum has an elastic...
modulus of 108 GPa and a Poisson's ratio of 0.34. In the stage of defining the properties of piezoelectric materials, we can input the corresponding material parameters according to equation (3), equation (4) and equation (5), which can represent flexibility coefficient, dielectric coefficient and piezoelectric strain coefficient, respectively; then assign them to the piezoelectric patch component. In the stage of defining the element type in the grid division, the substrate plate component uses three-dimensional solid elements, and the piezoelectric patches component uses piezoelectric elements, and the element length is set to 0.5 mm. In the stage of defining boundary conditions and loading, the piezoelectric patch voltage is set to 200 V, the voltage sign on the left and right sides of composite plate are opposite. The rectangular surfaces of the middle of the substrate plate are set as fixed ends, and the contact surface of the piezoelectric patches and the substrate plate is set as a binding connection to ensure the uniqueness of the displacement field.

### Table 2. Piezoelectric ceramic (PZT-4) material parameters [10].

| Stiffness coefficient [GPa] | C_{11} | C_{12} | C_{13} | C_{22} | C_{23} | C_{33} | C_{44} | C_{55} | C_{66} |
|-----------------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                             | 126    | 77.8   | 74.3   | 126    | 74.3   | 115    | 25.6   | 25.6   | 24.1   |

| Piezoelectric strain coefficient / [C·m^{-2}] | d_{15}  | d_{24}  | d_{31}  | d_{32}  | d_{33}  | \varepsilon_{11} | \varepsilon_{22} | \varepsilon_{33} |
|-----------------------------------------------|---------|---------|---------|---------|---------|------------------|------------------|------------------|
|                                               | 0.4961  | 0.4961  | -0.1387 | -0.1387 | 0.3106  | 0.6464           | 0.6464           | 0.5622           |

Figure 3 shows the stress cloud diagram and displacement cloud diagram of the piezoelectric composite plate under electrical load. According to Von Misses, it can be seen from the displacement cloud diagram in figure 3 (a) that when the electrical load is 200 V, the maximum displacement value of the piezoelectric composite plate is located at the center of action of the piezoelectric patches, and the displacement value gradually decreases from the center of the piezoelectric patches outwards, and the overall displacement distribution has a "concave-convex" shape and is antisymmetric on both sides of the fixed end axis. It can be seen from the stress cloud diagram in figure 3 (b) that when the electrical load is 200 V, the maximum stress value of the piezoelectric composite plate is located at the corners of the four piezoelectric patches closest to the fixed end. As the distance from the fixed end increases, the stress value is gradually decreasing, and the overall stress cloud diagram is antisymmetric on both sides of the fixed end axis.

**Figure 3.** Displacement cloud diagram (a) and stress cloud diagram, (b) of piezoelectric composite plate under electric load.

Figure 4 shows the displacement curve of the piezoelectric composite plate along the longitudinal axis and the transverse axis under different voltages. Figure 4 (a) shows the displacement change curve
of the piezoelectric composite plate along the transverse axis, that is, the x-axis under different voltages; figure 4 (b) shows the displacement change curve of the piezoelectric composite plate along the longitudinal axis, that is, the y-axis under different voltages. According to figure 4 (a), we can see that along the transverse axis, the displacement value presents a "decreasing-increasing-decreasing" trend with the increase of the coordinate position, which is characterized by the change of a sinusoidal function. And the displacement value of the same position increases with the applied voltage increasing. According to figure 4 (b), we can see that along the longitudinal axis, the displacement value shows an "increasing-decreasing" trend with the increase of the coordinate position, which is characterized by a parabolic change. Similarly, the displacement value at the same position increases as the applied voltage increases.

![Figure 4. Displacement curve of the piezoelectric composite plate along the longitudinal axis (a) and the transverse axis (b) under different voltages.](image)

5. Conclusion
In this paper, a turbulence generator based on piezoelectric structure is designed. A piezoelectric composite plate is formed by pasting piezoelectric patches of a specific shape on a circular substrate plate. Then it is fixed in a pipeline. When the fluid passes through the composite plate, we can change the voltage to control the shape of the piezoelectric composite plate and the Reynolds coefficient, which can be adjusted to transform the laminar flow state into the turbulent state. In this paper, the finite element method is used to simulate and analyze the piezoelectric composite plate established, and the conclusions are as follows:

1. With the increase of the coordinate value along the transverse direction, the piezoelectric composite plate first decreases, then increases, and finally decreases, and the overall change trend presents a sinusoidal function.
2. With the increase of the coordinate value along the longitudinal direction, the piezoelectric composite plate first increases and then decreases, and the overall change trend presents a parabolic shape.
3. For the same position on the piezoelectric composite plate, the magnitude of the displacement value increases with the increase of the applied voltage.

The conclusions of this paper can provide a theoretical basis for the design and analysis of turbulence generators based on piezoelectric structure.

References
[1] Li F P, Peng W P, Pan Z J and He Y N 2018 Optimization of Si/ZnO/PEDOT:PSS tri-layer heterojunction photodetector by piezo-phototronic effect using both positive and negative piezoelectric charges Nano Energy 48.
[2] Yang L Z, Zhang L L, Yu L Y, et al. 2016 An improved displacement boundary condition of piezoelectric cantilever beams ZAMM - Journal of Applied Mathematics and Mechanics / Zeitschrift für Angewandte Mathematik und Mechanik 96(1).

[3] Jia Z Y, Jin L, Liu W and Ren Z J 2019 Influence of sheet roughness on the sensitivity of piezoelectric force sensors Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture 233(1) 243-250.

[4] Hoshyarmanesh H and Abbasi A 2018 Structural health monitoring of rotary aerospace structures based on electromechanical impedance of integrated piezoelectric transducers Journal of Intelligent Material Systems and Structures 29(9) 1799-1817.

[5] Yi M H, Na W J, Hong W H and Jeon G Y 2012 Pedestrian walking characteristics at stairs according to width change for application of piezoelectric energy harvesting Journal of Central South University 19(003) 764-769.

[6] Pohl M and Rose M 2016 Piezoelectric shunt damping of a circular saw blade with autonomous power supply for noise and vibration reduction Journal of Sound and Vibration 361 20-31.

[7] Li Z, Li J, J Xu and Mo L H 2016 The structure design on turbulence generator of medium consistency pumps China Pulp & Paper Industry.

[8] Villamizar J, Herreo M, Omar T, et al. 2019 Atmospheric characterization based on relative humidity control at optical turbulence generator Atmosphere 10(9) 550.

[9] Ye D X, Li H and Lai X D 2017 Experiment on centripetal motion of air bubble in turbulence generator Journal of Drainage & Irrigation Machinery Engineering.

[10] Ding H and Liang J 1999 The fundamental solutions for transversely isotropic piezoelectricity and boundary element method Computers & Structures 71(4) 447-455.