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Simulation of Wave Energy Harvesting by Piezoelectric Seaweed

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Abstract. In the last decade, the research about energy harvesting for low-power electricity generation has received growing interest all around the world. In this study, a piezoelectric seaweed made by piezoelectric polymer (PVDF) has been used as the energy harvester. ANSYS Workbench is utilized to construct the flow domain and piezoelectric energy harvester, set up working conditions for the simulation, and calculate the power generating capacity of the piezoelectric seaweed actuated by the vibration. The results show that the maximal and minimal output voltages are 117.65V and -112.53V respectively, and it is possible to harvest energy from ocean wave using piezoelectric seaweed.

1. Introduction
In last several years, the research about energy harvesting for low-power electricity generation has received growing interest. Recent developments have renewed interest in the ocean wave energy conversion [1]. Since the frequency of ocean waves is very low, the actual operation is relatively difficult, and the current use of ocean wave energy is still lacking. With the development of science and technology, people have a good understanding of power generation with many functional materials. The capability of harvesting electrical energy from mechanical vibrations in a dynamic environment through piezoelectric transducers has been the topic of discussions for many years. Actuated by the ocean wave, the piezoelectric energy harvester can convert the ocean wave energy into electricity, while the generated energy mainly supports systems of low power consumption, such as portable electronic devices, autonomous sensors. The advantages of using a piezoelectric power supply are that it is ecological, embedded, and almost need no maintenance [2]. In this article, piezoelectric polymer (PVDF) is used as the energy harvester, and ANSYS Workbench is utilized to construct the model, set the relevant parameters, and calculate the amount of electricity generation.

2. Theory Foundation
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 [3]. The parameters of PVDF are shown in table 1.

2.2 ANSYS Workbench
ANSYS Workbench is a collaborative simulation environment combining many core simulation tools, which can carry out the structural analysis, fluid analysis, thermal analysis, coupling analysis, and so on. In ANSYS Workbench, the fluid-structure interaction can be simulated in one-way or two-way coupling methods by connecting the coupling participants to a component called system coupling [4].
### Table 1 Parameters of PVDF

| Symbol | Parameter                  | Value  | Unit     |
|--------|----------------------------|--------|----------|
| ρ      | Density                    | 1.78   | 10^3kg/m^3 |
| Y      | Young's modulus            | 2      | GPa      |
| µ      | Poisson's ratio            | 0.3    |          |
| d_{31} | Piezo strain constant      | 23     | 10^{-12} |
| g_{31} | Piezo stress constant      | 216    | 10^{-3}  |
| k_{31} | Electromechanical coupling factor | 12%  |          |

#### 2.3 Piezoelectric Equations

The piezoelectric equations are expressions that describe the relationship between the mechanical and electrical quantities of piezoelectric materials [5]. The piezoelectric effect is described by the coupling equations:

\[
\{S\} = \{s^e\} \cdot \{T\} + \{d\} \cdot \{E\} \tag{1}
\]

\[
\{D\} = \{d^t\} \cdot \{T\} + \{e^t\} \cdot \{E\} \tag{2}
\]

Where \(\{S\}\) is the elastic strain vector; \(\{T\}\) is the stress vector (N/m^2); \(\{D\}\) is the electric flux density vector (C/m^2); \(\{E\}\) is the electric field intensity vector (V/m); \(\{s^e\}\) is the compliance matrix evaluated at constant electric field, i.e. short circuit; \(\{d\}\) and \(\{d^t\}\) are the piezoelectric strain coefficient matrix (C/N), and the superscript \(\{t\}\) is the matrix transpose.

#### 2.4 Airy Wave Theory

Open channel wave boundary conditions allow one to simulate the propagation of waves, which is useful in the marine industry. Wave steepness is generally defined as the ratio of wave height to wave length, and relative depth is defined as the ratio of wave height to the liquid depth. The wave profile for a linear wave is given as [6]:

\[
\zeta(X,t) = A \cos \alpha \tag{3}
\]

where \(\alpha\) is defined as follows:

\[
\alpha = k_x x + k_y y - \omega t + \varepsilon \tag{4}
\]

\(x\) and \(y\) are the space coordinates in the \(\hat{x}\) and \(\hat{y}\) directions, respectively, \(\varepsilon\) is the phase difference, and \(t\) is the time.

The wave frequency \(\omega\) is defined as follows for shallow/intermediate waves:

\[
\omega = \sqrt{gk \tanh(kh)} \tag{5}
\]

and as follows for short gravity waves:

\[
\omega = \sqrt{gk} \tag{6}
\]

where \(h\) is the liquid height, \(k\) is the wave number, and \(g\) is the gravity magnitude [7].

The velocity components for the incident wave boundary condition can be described in terms of shallow/intermediate waves and short gravity waves.

#### 3. Numerical Analysis

3.1 Meshing
A 3D model is constructed by ANSYS DesignModeler, and meshed by ANSYS Meshing. As shown in figure 1, the piezoelectric seaweed is made of a sandwiched structure, including a flexible foam core of 1mm thickness and two PVDF films of 0.05mm. The length of this seaweed is 100mm. According to Ref. [8], a wave tank (figure 2) was modelled with sizes of about 1000mm long, 200mm wide, and 200mm high.

The computational domain is meshed by 7692 triangular elements for total degrees of freedom of 38462. To get better results, the element refinement has to be done at the fluid-solid interaction boundary to avoid mesh warnings, and increase the lattice density to guarantee accuracy in the coupling interface (figure 2).

### 3.2 Solution Method
The control equations are discretized to use the finite volume method based on the center of the cell. The viscous model is standard $k$-$\varepsilon$ model with enhanced wall treatment. The second order upwind differential scheme is adopted in the convective term, and the central difference scheme is adopted in the diffusion term. The system coupling analysis is carried out between transient structure and fluid.

### 3.3 Initial and Boundary Conditions
It is important to define the appropriate boundary conditions and the initialization conditions for the whole computational domain, such as the flow velocity and the outlet pressure [9]. In this study, the rigid column wall boundary condition is used. In other words, there is no slip at the interface between fluid and solid. The inlet velocity is set as 1 m/s, and the outlet is the pressure outlet. Flow domain is divided into two phases of water and air, and the initial water height is 120 mm. A sinusoidal wave boundary is simulated, whose amplitude is 50 mm, and length is 500 mm (shown in figure 3).
4. Results and Discussion

The piezoelectric seaweed is deformed by the impact of water flow, the maximum deformation is about 20.1 mm, as shown in figure 4 (a). During reciprocating oscillation, the piezoelectric seaweed recovers part of the deformation, and the corresponding maximum deformation is reduced to 18.9 mm, as shown in figure 4 (b).

![Figure 4. Deformation of piezoelectric seaweed at two extreme positions](image)

![Figure 5. Output voltage of piezoelectric seaweed at two extreme positions](image)
As shown in figure 5, the generated voltage of the piezoelectric seaweed varies with the deformation directions. Since both ends of the piezoelectric seaweed may be deformed in different directions, the maximal and minimal voltages are 117.65V and -112.53V respectively in case that the deformation occurs along the direction of the water flow (figure 5 (a)). While in figure 5(b), the maximum and minimum are 60.33V and -112.53V in the opposite swing direction. According to figure 5(b), the detailed voltage generation values are given in table 2.

**Table 2** Detailed voltage generation values of piezoelectric seaweed.

| Time(s) | Minimum(V) | Maximum(V) | Time(s) | Minimum(V) | Maximum(V) |
|---------|------------|------------|---------|------------|------------|
| 0.0     | 0          | 0          | 1.3     | -52.372    | 86.188     |
| 0.1     | -2.5200    | 14.946     | 1.4     | -39.338    | 69.447     |
| 0.2     | -11.916    | 32.797     | 1.5     | -24.968    | 52.007     |
| 0.3     | -24.883    | 52.045     | 1.6     | -12.123    | 32.823     |
| 0.4     | -39.262    | 69.637     | 1.7     | -2.7261    | 15.331     |
| 0.5     | -52.274    | 86.300     | 1.8     | -0.2479    | 0.2792     |
| 0.6     | -64.097    | 98.910     | 1.9     | -14.823    | 1.7384     |
| 0.7     | -72.758    | 108.79     | 2.0     | -33.319    | 8.4949     |
| 0.8     | -78.116    | 114.98     | 2.1     | -53.154    | 18.284     |
| 0.9     | -80.308    | 116.53     | 2.2     | -71.496    | 30.513     |
| 1.0     | -78.188    | 115.18     | 2.3     | -88.823    | 41.929     |
| 1.1     | -72.965    | 108.90     | 2.4     | -102.00    | 52.504     |
| 1.2     | -64.182    | 99.062     | 2.5     | -112.53    | 60.327     |

5. Conclusions
Driven by the wave force, the piezoelectric seaweed can harvest energy from ocean or river wave. As a simple, lightweight electromechanical converter, PVDF can be widely used in the power generation from fluid wave. Although the generated voltage is not strong (-112.53V~117.65V), after signal conditioning it still can be used for electrical equipment with low power consumption, i.e. wireless sensors.

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