Micro-energy harvesting based on vortex-induced vibration of cross-flow hydroturbine with various cantilever beam configurations

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Abstract. The cross-flow hydroturbine is a water impulse turbine with a low efficiency relatively, but it is easy to maintain and can adjust to a wide range of flow rates. Also, vortex fields are formed downstream of the cross-flow hydroturbine when the working fluid passes through an impeller, and these vortex fields can cause vibrations during electrical energy production. However, these vortex fields could gradually disappear and become a wasted, unused energy source. Therefore, amplifying and causing vortex fields continuously could result in vortex-induced vibration (VIV), which can be used as an energy source to enhance the performance of micro-energy harvesting (MEH) system. The vibration is typically converted into piezoelectric energy using a piezoelectric energy harvester, such as cantilever beam, membrane or other structure. In this study, the downstream of the cross-flow hydroturbine was equipped with a cantilever beam to harvest the vibration energy of the vortex fields. Numerical analysis was conducted using the commercial CFD code, ANSYS CFX 17.1 with a shear stress transport (SST) turbulence model. A 2-way fluid-structure interaction (FSI) analysis was also used to investigate the motion of the cantilever beam for the feasibility of using it in piezoelectric energy harvesting. As a result, the velocity vector and deformation of the cantilever beam were graphically depicted.

1. Introduction
The problem of energy disproportion due to depletion of fossil fuels has not been solved. It is a time to develop new energy that converts natural energy into electric energy. Micro-energy harvesting (MEH) is a technology that harvests energy such as light, heat, vibration, wind, and other dissipated energy generated by various machines found in the everyday environment and converts it into electric energy. Harvested energy is used in remote sensors, automobiles, wearable devices, medical devices, and military equipment, depending on the scale. As demand for energy increases, the need for innovative energy harvesting devices is increasing, and research in energy harvesting is actively being carried out [1–5]. Zhu et al. [6] experimentally studied a suitable miniature energy harvester that can capture air energy. Bryant and Garcia [7] investigated a simple cantilevered beam to find a minimum cut-in wind speed for flutter energy harvesting. Singh et al. [8] studied the feasibility of an on board vibration
energy harvesting system for a tire. Priya [9] conducted a study of the model of a wind-mill consisting of 10 piezoelectric bimorphs. In the area of fluid machines, the cross-flow hydroturbine is widely used because of its simple structure and low cost, and because it creates an unsteady phenomenon called vortex-induced vibration, in the wake of a runner. This unsteady phenomenon can be used as a source of piezoelectric energy harvesting (PEH) that harvests vibration energy, and various researches on vortex-induced vibration have been carried out. Barrero-Gil et al. [10] studied the effect of governing parameters, such as mass ratio, damping coefficient, and Reynolds numbers on energy extraction efficiency by vortex-induced vibration. Lee [11] conducted an experiment to study vortex-induced vibration in a wind tunnel, and he confirmed that vortex-induced vibration was affected by the amplitude and frequency of the cylinder attached to the shear building.

In this study, numerical analysis was conducted in an attempt to confirm the feasibility of piezoelectric energy harvesting in a cross-flow hydroturbine by using the commercial CFD code, ANSYS CFX 17.1. The downstream of a cross-flow hydroturbine was equipped with a cantilever beam to harvest the vibration energy and to make continual vortex fields. Also 2–way fluid-structure interaction (FSI) analysis was used to describe the piezoelectric energy harvesting by the motion of cantilever beams.

2. Analysis and Modelling

2.1. Reference Model

The Banki-Michell turbine [11] is used as the reference model and a detailed depiction of the cross-flow hydroturbine is shown in Figure 1. The turbine is composed of a casing, a runner, and a cantilever beam. The turbine width $W_T$ is 150 mm, the diameter ratio $D_2 / D_1$ of the runner blades is 0.67, the outer diameter $D_1$ is 290 mm, the inner diameter $D_2$ is 195 mm, the angle of attack $\alpha$ is 15°, the nozzle initial height $S_0$ is 65.685 mm, and the length of the downstream $L_1$ is 1,000 mm. In order to confirm the phenomenon of vortex-induced vibration, width and length of the downstream were designed to be large. The runner consisted of 30 blades with a thickness $t_b$ of 10.8 mm and a radius $\rho_b$ of 49.137 mm. The cantilever beam consists of a piezoelectric element that was attached to the wall of downstream. The thickness of the cantilever beam $t_c$ is 0.5 mm, width $W_c$ is 20 mm, and length $L_c$ is 40 mm. As a result of kinetic energy distribution in the cross-section of downstream, the position of cantilever beam $D_c$ was selected as 255 mm.

![Figure 1. 3-D model of the cross-flow hydroturbine.](image-url)
3. Numerical Method

3.1. Grid Systems
In this study, three-dimensional discretization has been used with the finite volume method (FVM) provided by the ANSYS CFX software. A more compact grid was constructed to confirm the accurate vortex flow at the downstream of the cross-flow hydroturbine using the body influence method, and the inflation grid condition was used at the wall of the cantilever beam. In addition, to evaluate grid dependency, a pressure used to conduct structural analysis, was considered with the variation of the number of elements from 400,000 to 2,000,000. As a result, the total number of grid elements was selected to be $1.5 \times 10^6$.

3.2. Computational Fluid Dynamics (CFD) Analysis
Numerical analysis on the cross-flow hydroturbine was carried out by solving the three-dimensional incompressible Reynolds Average Navier-Stokes (RANS) and energy equations using the commercial code, ANSYS CFX. The boundary conditions for the numerical analysis were specified in Table 1. The continuity equation and time averaged Navier-Stokes equations, with the $k-\omega$ based shear stress transport (SST) turbulence model were calculated to investigate the phenomenon of vortex-induced vibration (VIV) in the vicinity of the cross-flow hydroturbine:

i) Continuity:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$  \hspace{1cm} (1)

ii) Momentum:

$$\frac{\partial (\rho \mathbf{U})}{\partial t} + \nabla \cdot (\rho \mathbf{U} \mathbf{U}) = -\nabla p + \nabla \cdot \mathbf{\tau}_{ij}$$  \hspace{1cm} (2)

$$\mathbf{\tau}_{ij} = \mu(\nabla \mathbf{U} + (\nabla \mathbf{U})^T) - \frac{2}{3} \delta_{ij} \nabla \cdot \mathbf{U}$$  \hspace{1cm} (3)
where \( U, \rho, p, \tau_{ij}, \mu \) and \( \delta_{ij} \) are denoted as the velocity, density, pressure, stress tensor, dynamic viscosity, and Kronecker delta function, respectively.

| Boundary condition       | Value         |
|--------------------------|---------------|
| Inlet velocity [m/s]     | 6.26          |
| Rotational speed [rad/s] | 20.16         |
| Number of blades         | 30            |
| Working fluid            | Water at 25 °C|
| Analysis type            | Transient     |
| Wall condition           | No-slip wall, Free-slip wall |
| Interface                | Transient rotor stator, Periodic |

3.3. **Structural Analysis**

Structural analysis was performed using ANSYS Mechanical to confirm that the movement of the cantilever beam has a low stiffness coefficient, which means that it is frequently bent or stretched by a small force, and it is eventually broken. Thus, in order to enhance the stiffness of the cantilever beam, transient structural analysis was conducted by bonding the tantalum element to the piezoelectric element and the thickness of layer was used as a parameter [12–14]. Table 2 and Figure 3 give the descriptions of material properties and design parameters of the multi-stack layers of the modeled cantilever beam.

![Figure 3](image_url)
Table 2. Description of design parameters of the cantilever beam.

|                     | Piezoelectric element layer thickness $t_1$ [mm] | Tantalum element layer thickness $t_2$ [mm] |
|---------------------|-----------------------------------------------|-----------------------------------------------|
| Density [kg/m³]     | 5440                                          | 16650                                         |
| Young’s modulus [GPa]| 30.336                                        | 186                                           |
| Possion’s ratio     | 0.31                                          | 0.34                                          |
| Case 1              | 0.05                                          | 0.4                                           |
| Case 2              | 0.1                                           | 0.3                                           |
| Case 3              | 0.15                                          | 0.2                                           |
| Case 4              | 0.2                                           | 0.1                                           |

4. Results and Discussion

4.1. Computational Fluid Dynamics (CFD) Analysis

Figure 4 shows the transient velocity vector field of the cross-flow hydroturbine. The vortex flow that can be used for micro-energy harvesting (MEH) was confirmed at regions A and B. After the computational fluid dynamics analysis of the reference model, the cantilever beam was attached at region A to confirm the feasibility of micro-energy harvesting by realizing the motion of the cantilever beam.

![Velocity vector field](image)

Figure 4. Transient velocity vector field.
4.2. Fluid-Structural Interaction (FSI)

2-way fluid-structure interaction (FSI) analysis was performed considering the influence of the piezoelectric element ratio on the deformation of the cantilever beam. Figure 5 shows the maximum and minimum deformation on the x-direction of the cantilever beam. The smallest deformation of 13.933 mm was confirmed in Case 1 (piezoelectric element layer thickness is 0.1 mm), and the largest deformation of 22.531 mm was confirmed in Case 4 (piezoelectric element layer thickness is 0.4 mm). Figure 6 shows the transient velocity distribution and deformation of the cantilever beam at the cross-flow hydroturbine in Case 4, and it was confirmed that the deformation of the cantilever beam is repeated by vortex flow.

Figure 5. Comparison results of total deformation.

Figure 6. Transient velocity distribution and deformation of cantilever beam of Case 4.
Table 3. Averaged equivalent stress and total deformation.

|                | Maximum equivalent stress of piezoelectric element [MPa] | Maximum equivalent stress of tantalum element [MPa] | Maximum deformation [mm] |
|----------------|----------------------------------------------------------|---------------------------------------------------|--------------------------|
| Case 1         | 309.4                                                    | 1496.4                                            | 13.933                   |
| Case 2         | 307.19                                                  | 1150.5                                            | 14.176                   |
| Case 3         | 467.45                                                  | 1125.3                                            | 19.274                   |
| Case 4         | 567.24                                                  | 958.57                                            | 22.531                   |

4.3. Piezoelectric Energy Harvesting (PEH)

In the cross-flow hydroturbine, piezoelectric energy harvesting is performed by bending the cantilever beam attached on the downstream. Design parameters such as the length and width of the cantilever beam and the thickness ratio of the piezoelectric element layer and non-piezoelectric element layer, are considered for enhancing the performance of piezoelectric energy harvesting. In this study, the numerical analysis is carried out according to the thickness ratio of the piezoelectric element layer and the tantalum element layer. The maximum values of equivalent stress and deformation are shown in Table 3. The deformation of the cantilever beam increased as the piezoelectric element layer became thicker, and the maximum equivalent stress of the cantilever beam decreased as the non-piezoelectric element layer which has a high elastic strength became thin. Thus, the results of the numerical analysis show that the energy harvesting efficiency enhances as the piezoelectric element layer becomes thicker at the same fluid force. Since the position where the maximum equivalent stress was applied is fixed at the end, the deformation of the free end is not affected, but fatigue failure of the piezoelectric element, which has low tensile strength, should be considered.

5. Conclusions

In this study, flow characteristics of a cross-flow hydroturbine for micro-energy harvesting (MEH) was numerically analyzed using 2-way fluid-structure interaction (FSI) analysis. The cantilever beam was attached at the downstream of the cross-flow hydroturbine to harvest the vibration energy found in the vortex-induced vibration (VIV). The cantilever beam, which consists of only the piezoelectric element, can cause the fatigue failure because of low tensile strength and high brittleness, so the cantilever beam consisted of a piezoelectric element and a non-piezoelectric element. As a numerical result, according to the layer thickness ratio of the cantilever beam, the maximum deformation of 22.531 mm was confirmed in Case 4 (piezoelectric element layer thickness is 0.4 mm), and the feasibility of piezoelectric energy harvesting in a cross-flow hydroturbine was confirmed by bending the cantilever beam by using fluid flow. Those results may give guidelines to the micro-energy harvesting of cross-flow hydroturbine and can be used to basic data when the experiment of piezoelectric energy harvesting is followed on the flow condition.

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