CFD Simulation of the Galloping and Piezoelectric Energy Harvesting of a Cylindrical Body Equipped with V - Shaped Flow Control Devices

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Abstract: ***The technique to extract low velocity hydrokinetic energy through the use of a galloping piezoelectric energy harvester (GPEH) has been advanced. However, Piezoelectric energy harvesters are a novel class of power generation apparatus that can transform flow - induced vibrational energy into electrical energy. This kind of energy can be used to generate low - velocity water flow energy and different forms of wind energy in rivers and seas. This paper seeks to discuss CFD simulation of the galloping and piezoelectric energy harvesting of a cylindrical body equipped with V - shaped flow control devices. The study used an analysis of the flow patterns around a cylindrical body with V - SHAPED flow control devices attached at various circumferential points. ANYSYS FLUENT 2021 - R2, focusing on two staggered arrangements (X_3Y_0 and X_1Y_0) was used in the analysis. This was used to get insights into the flow aspects that determine how energy harvesting systems perform. There were notable fluid interactions in the X3 Y0 configuration, which was defined by a closer spacing between the two cylinders. The increased vibration amplitudes in this configuration suggest a strong interaction between the cylinders, separated shear layers, and vortex shedding. The special configuration at particular times, like t = T/4 and t = 3T/4, produced significant upward and downward forces, demonstrating the complex fluid - structure coupling. This configuration, characterized by strong fluid interactions, has the potential to maximize energy harvesting, but it needs to be carefully considered because of its structural and practical ramifications.***

Keywords: hydrokinetic energy, piezoelectric energy harvester, CFD simulation, fluid - structure interaction, energy harvesting systems

1. Introduction

The piezoelectric energy harvester is a new type of power generation equipment capable of converting vibrational energy caused by flow into electrical energy, which can be employed in the development of low velocity water flow energy and various types of wind energy in rivers and oceans. Piezoelectric energy harvesters generate electrical energy to supply energy - consuming devices such as wireless sensors, and embedded and implantable devices and this power supply technology avoids the inefficient and sometimes impossible handling and replacement of conventional batteries. The piezoelectric energy harvester not only transforms the mechanical energy of vibration directly into electrical energy, but has the advantages of simple structure, no electromagnetic interference, easy integration, and high energy density.

The piezoelectric energy harvester consists of a composite piezoelectric layer and a bluff body which accepts the flow - induced vibration (FIV) and drives the composite piezoelectric layer to generate electrical energy. Flow - induced vibration can be classified into vortex induced vibration, flutter, galloping, and wake induced vibration.

CFD Simulation

The use of CFD simulations is imperative in understanding the fluid dynamics commonly associated with galloping and piezoelectric energy harvesting configurations. Below is an analysis of the flow patterns at different circumferential locations around a cylindrical body having attached V - SHAPED flow control devices. The analysis makes use of ANYSYS FLUENT 2021 - R2, focusing on two staggered arrangements (X_3Y_0 and X_1Y_0). The key goal is to get insights into the flow aspects that determine how energy harvesting systems perform.

Computational Model

The simulation domain is based on a 45D x 30D computational space, with a 3.3% blockage ratio (See Fig.1). The cylinder is positioned at different circumferential locations. The computational model includes a no - slip interface between solid and fluid, a free - stream inlet, a stress - free outlet, and symmetrical boundaries. Simulation accuracy is ascertained by incorporating an encrypted area around the entire cylinder. Structured component and background grids are independently generated through the overset grid drawing technique.

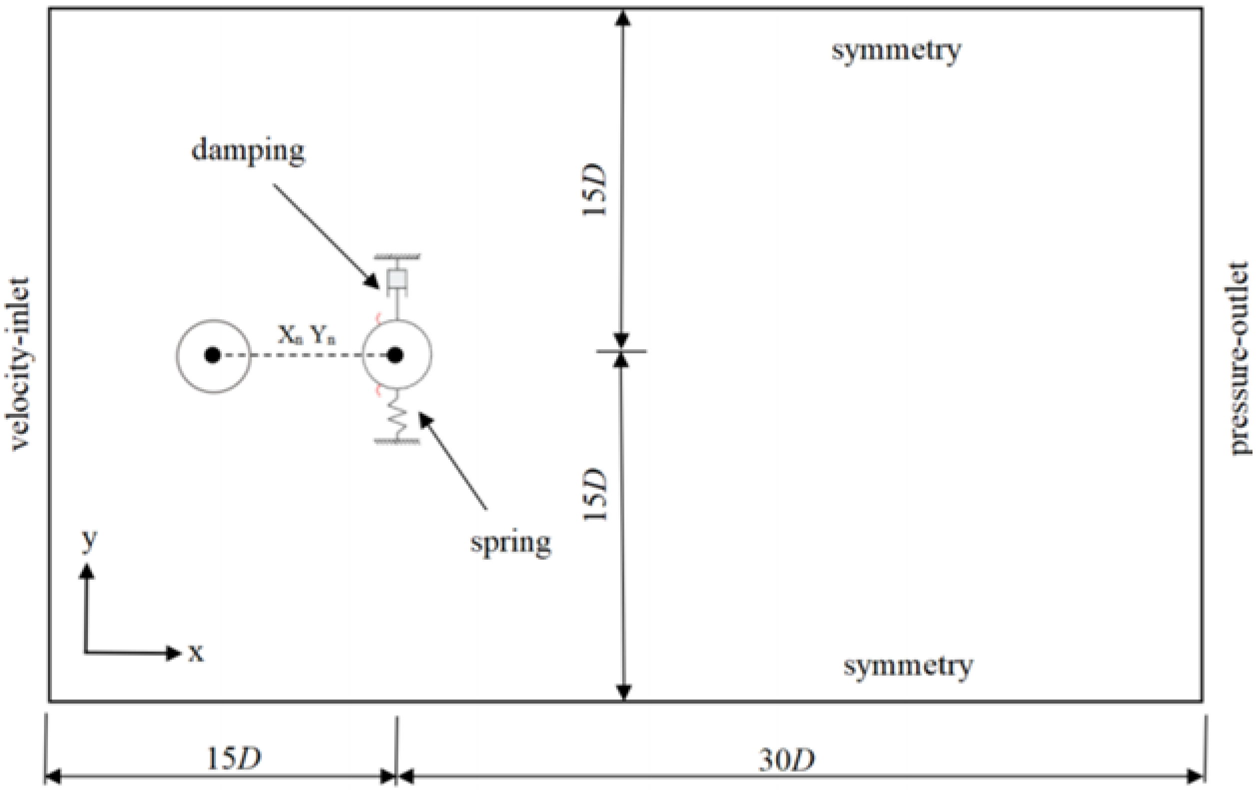

Figure 1: Computational Domain Model

Mesh Arrangement

The mesh arrangement along the splitters and cylinder entails two distinct cell heights for different wind speeds (See Fig.2). For low wind speeds (U = 0.9m/s ~ 1.8m/s), a 0.2 - mm cell height is set for the first layer. For high wind speeds (U = 2.0m/s ~ 3.0m/s), a 0.1 - mm cell height is set. The refined mesh is aimed at capturing the behavior of the flow field around the splitters and cylinder.

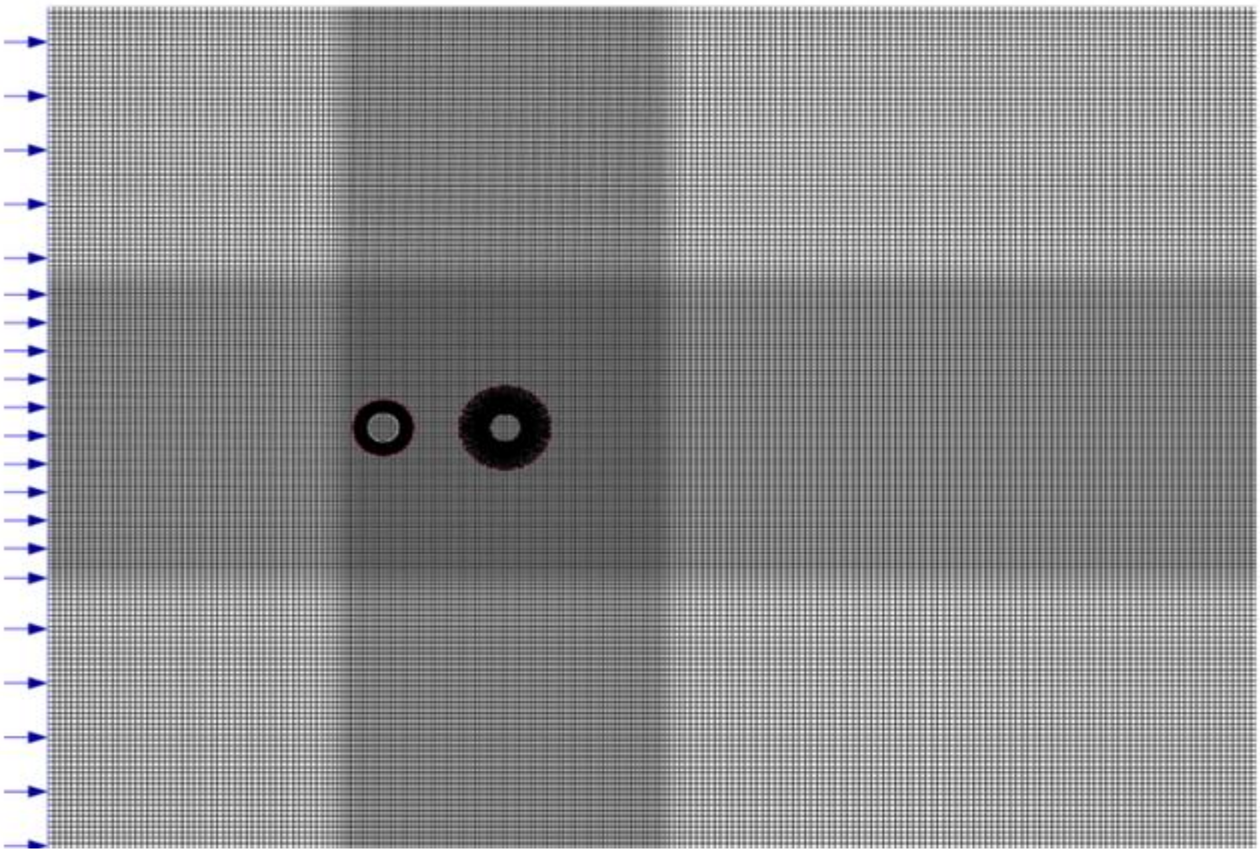

Figure 2: Computational Mesh (Entire Grid)

Two staggered arrangements (X_3Y_0 and X_1Y_0) are simulated to assess their effect on flow dynamics and the overall energy harvesting performance. X_3Y_0 (optimal) is compared against X_1Y_0 (alternative) to observe the variations in fluid interactions and vibration amplitudes.

Vibration Amplitudes and Instantaneous Vorticity Distributions

In the optimal configuration, the cylinder's vibration amplitudes are significantly greater than the ones observed in the alternative configuration. This indicates that the spatial configuration of the cylinder actually impacts their dynamic response. The X_3Y_0 configuration has a higher vorticity intensity than X_1Y_0. The heightened intensity is attributable to the shortened spacing between the cylinders. This proves that there exists a complex interplay between the cylinders themselves, separated sheet layers, and vortex shedding.

Fluid Interactions

The fluid interactions in X_3Y_0 are considerably intense and influence the motion of the downstream cylinder. At t = T/4, the shortened spacing between the cylinders provides a unique arrangement and compels the downstream cylinder's low - side separated shear layer to attach onto the lower side. This generates a considerable upward force. At t = 3T/4, a large vortex in the upstream cylinder is observed. This exerts a significant downward force on the downstream cylinder. The resulting dynamic interaction further intensifies the downstream cylinder's downward motion, reflecting the complex nature of this configuration's fluid - structure coupling.

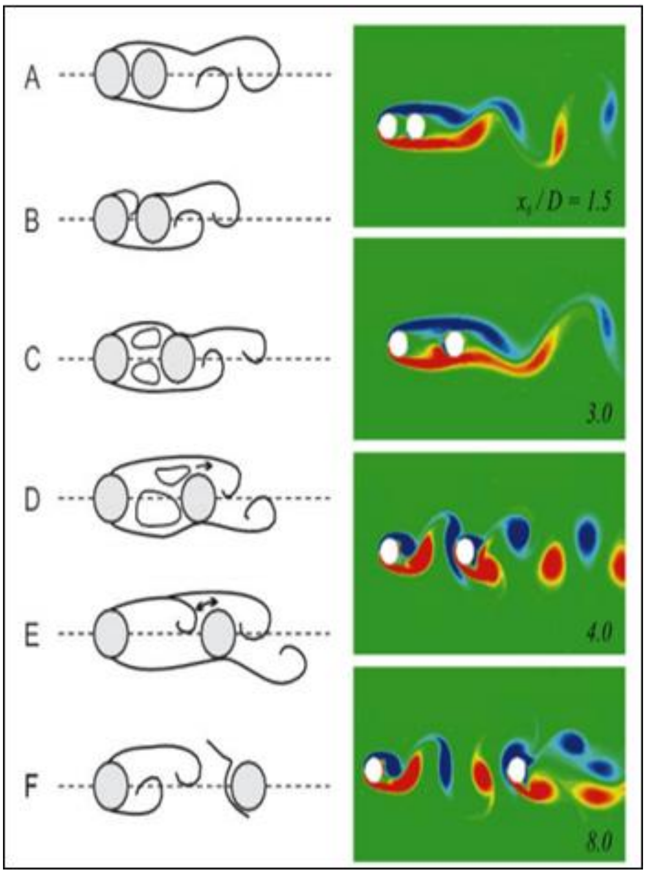

Figure 3: Flow Interactions for Tandem Cylinders for Different Separations

The other configurations exhibit much less intense glow interactions and resemble the conventional vortex shedding dynamics (See Fig.3). Flow separation from the included cylinder has a relatively moderate effect, as commonly reflected in the power generated by energy harvesters at these configurations.

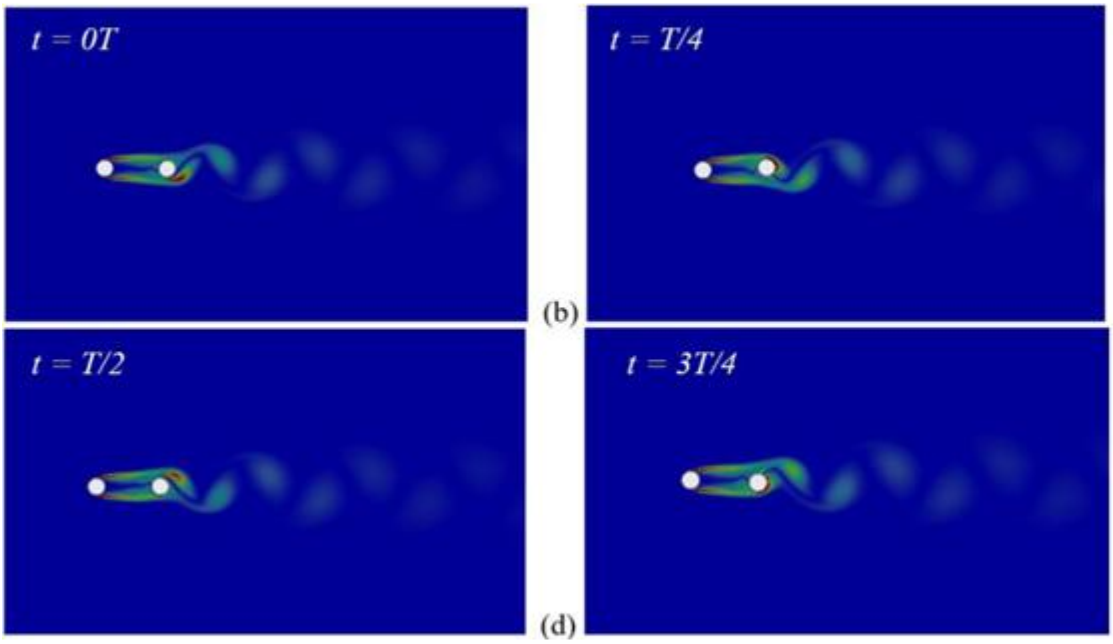

Figure 4: Temporal Evolution of Vortex Formations for Flow Over Cylinder with Optimal Configuration

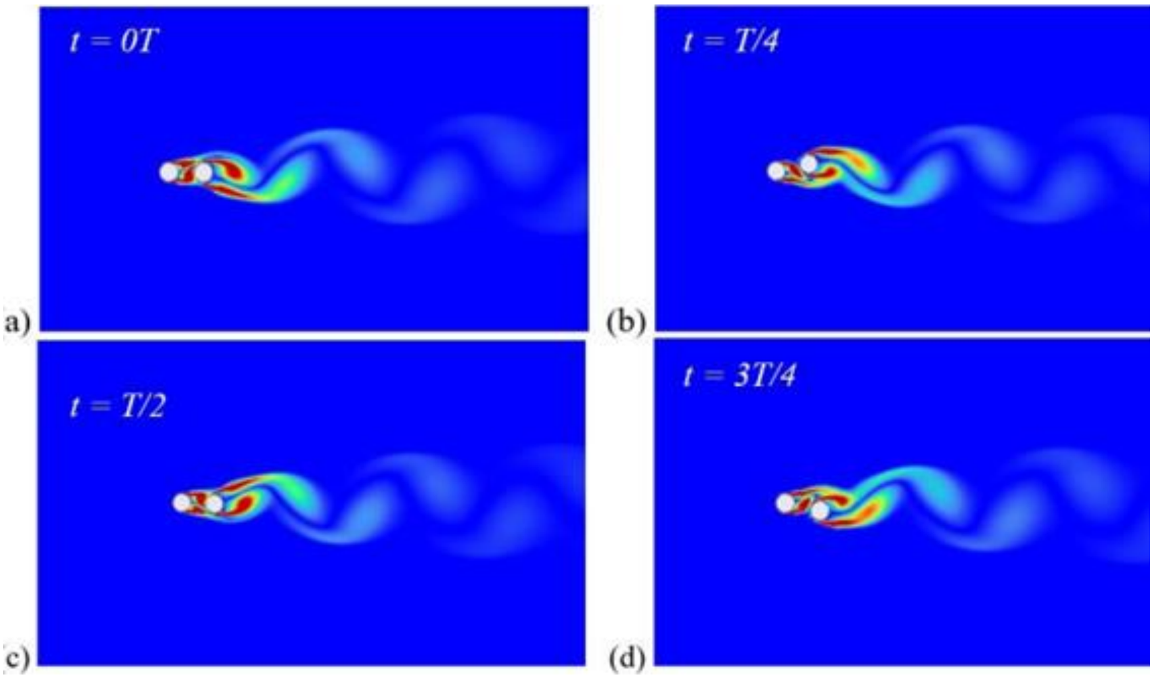

Figure 5: Temporal Evolution of Vortex Formations for Flow Over Cylinder with Alternative Configuration

2. Discussion

The X3 Y0 configuration, characterized by a closer spacing between the two cylinders, exhibited significant fluid interactions. The enhanced vibration amplitudes observed in this configuration are indicative of a compelling interplay between vortex shedding, separated shear layers, and the cylinders themselves. The unique arrangement at specific time instances, such as t = T/4 and t = 3T/4, resulted in substantial upward and downward forces, showcasing the intricate fluid - structure coupling. This configuration, marked by intense fluid interactions, holds promise for maximizing energy harvesting potential, but its practical implications and structural implications prompt for careful consideration.

The X1 Y0 configuration demonstrated less intense fluid interactions, resembling conventional vortex shedding dynamics. The spacing between the cylinders in this configuration resulted in moderate effects of flow separation from the cylinder, as reflected in the generated power of the energy harvester. While this configuration may exhibit more predictable and stable behavior, its energy harvesting efficiency may be lower compared to the X3 Y0 configuration.

Piezoelectric energy harvesting relies on the conversion of mechanical vibrations into electrical energy using piezoelectric materials [27]. In the context of the studied configurations, the enhanced vibration amplitudes observed in the X3 Y0 configuration suggest a higher potential for energy harvesting. The dynamic forces exerted on the cylinder, as induced by the fluid interactions, can lead to increased strain on the piezoelectric material, thereby generating higher electrical output. The X1 Y0 configuration, while exhibiting more stable fluid dynamics, may yield lower energy harvesting efficiency due to reduced vibration amplitudes.

The success of the computational simulation is mainly realized by the meticulous mesh arrangement, especially near the cylinder and splitters. The use of the overset grid drawing method allowed for the independent generation of structured background grids and component grids. This approach facilitates the accurate representation of the complex geometry, ensuring that the simulation captures the variations of the flow field.

The mesh arrangement, particularly the variation in cell height based on wind speed, accounts for the different scales of turbulence and flow features. Sensitivity analyses and validation against experimental data would be essential to ascertain the reliability of the simulation results. A robust validation process can help enhance the credibility of the numerical model and provides confidence in the application of findings to real - world scenarios.

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