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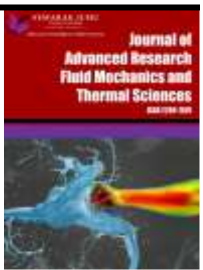

Enhancing Vibration Response through Bluff Body and Splitter Plate Interaction in Fluid Flows

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ABSTRACT

This paper explores the profound impact of bluff body design on the phenomenon of flow-induced vibration when integrated with an attached splitter plate. The main objective is to conduct an analysis of different bluff body designs equipped with splitter plates, with a specific focus on contrasting various designs of these plates. The overall goal is to identify the optimal bluff body design that maximizes vibration response. In order to accomplish this, an extensive experimental investigation is carried out in a wind tunnel environment. Three distinct bluff body shapes – cylindrical, rectangular, and elliptical were selected for the study. Vibration response measurements were performed using a triaxial accelerometer to ensure precise and reliable data collection. The findings reveal a clear correlation between bluff body geometry and subsequent vibration response. The cylindrical bluff body shows the highest vibration response of 25.7 m/s^2, followed by the rectangular bluff body of 18.9 m/s^2, while the elliptical variant records the lowest response at 15.8 m/s^2. Furthermore, within the subset of cylindrical bluff body configurations, it is evident that splitter plate A induces in average a 60% higher vibrations response than that of splitter plate B. This observation emphasizes the significance of splitter plate dimensions and bluff body shape in the context of flow-induced vibrations. The study uncovers noteworthy insights, highlighting how the elliptical bluff body's streamlined design helps to reduce vibration response. Conversely, the rectangular bluff body' sharp corners and edges amplify vibrations. Importantly, splitter plate dimensions are identified as a critical determinant of vibration response, with wider plates resulting in smaller vibration magnitudes. In conclusion, this research advances our understanding of fluid dynamics by investigating the complex interaction between bluff body design and flow-induced vibration. Beyond its academic contribution, the study holds practical implications for engineering applications. By shedding light on the factors influencing vibration response, the research informs the optimization of bluff body designs for better performance and durability.

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1. Introduction

Vibrations, which arise from the intricate interaction of fluids and structures, have garnered significant interest and research across a spectrum of engineering and scientific disciplines. These vibrations evolve from the dynamic forces, often triggered by the inherent complexity of fluid flows and their interaction with solid bodies. In general, uncontrolled vibration can yield detrimental outcomes, leading to structural fatigue, reduced efficiency, and impaired overall performance within diverse engineering systems [1]. For instance, excess vibration originating from industrial machinery like pumps and compressors can propagate through surrounding structures, resulting in malfunction, while the ensuing noise can cause discomfort to individuals. However, as the world seeks sustainable energy solutions, a unique opportunity emerges from these vibrations: the potential to harness vibrational energy as a viable and renewable energy source [2-4].

Flow-induced vibration (FIV) is a general term encompassing a variety of structural oscillations stimulated by fluid motion, includes phenomena such as vortex-induced vibration (VIV), galloping, flutter, and wake-induced vibration [5-8]. The fascinating phenomenon of FIV lies at the core of these vibrational dynamics. When fluid flows interact with structural elements, this phenomenon comes into sharp focus by inducing vibrations that resonate throughout the materials. Such interactions have a profound impact on the integrity, functionality, and safety of engineering structures [9]. From the swaying of tall buildings in the wind to the oscillations of marine structures amidst ocean currents, the effects of FIV can be felt through the very core of the built environment at every level. Over the past decade, the study of FIV has traditionally been motivated by the potential failure of engineering structures posed by fluid interactions. One of the dominant research areas has aimed to suppress FIV within structures to mitigate the risks of structural damage [10]. However, since the early 2000s, there has been a marked surge in scholarly contributions toward the realm of clean energy production from FIV [11]. Despite this new development, the challenge and opportunity to solve the complex dynamics of flow-induced vibrations, and to harness this energy source as a way to power future societies, remain vital.

At the nexus of flow-induced vibration lies the concept of bluff bodies — structures with relatively large cross-sectional areas perpendicular to the flow direction. Study of flow dynamics around bluff bodies with various cross sections such as circle, square and elliptical have been extensively investigated due to their widespread applications in aerospace, civil, mechanical and offshore engineering industries [12,13]. The design of these bluff bodies intricately influences the interaction between the fluid motion and the structures. This interaction, coupled with the presence of design elements such as splitter plates, can hold potential to disrupt and redirect fluid current, thereby amplifying vibrations in ways that challenge conventional wisdom. A simple addition or modification to the configuration of a bluff body can trigger resonances that not only enhance vibration but also offer new avenues for capturing vibrational energy. Prior research has indicated that the synchronization of flow-induced forces with the natural frequency of elastic bodies can produce significant amplitude vibrations [14].

Despite of the preceding statement, the understanding of flow-induced vibration, the realm of bluff body design and its potential for harnessing vibration energy remains in its infancy [15]. Many critical questions are yet to be answered especially in relation to the physical mechanism of bluff body with splitter plates, such as the development of bluff body geometries, and their intricate interactions with splitter plate, and how all these collectively contribute to improved vibration responses and enhanced energy extraction. All these issues are remained unanswered mainly due to the lack of reliable experimental data derived from a diverse set of bluff body designs with attached splitter plates [16].

Therefore, this study embarks on a journey to uncover the intricate relationships between bluff body design, configuration of splitter plate, and the dynamics of flow-induced vibration through experimental assessment. Our objective is to delve into the concept of enhancing vibration response through interactions with bluff body, thereby pioneering a novel approach to vibrational energy harvesting that holds potential for both scientific discoveries and practical applications.

2. Flow Induced Vibration of Bluff Body

Flow-induced vibration of structures with bluff cross-sections, whether found in nature or engineered systems, is a commonplace occurrence. This phenomenon holds significance in many engineering applications. While it possesses the potential to cause structural damage, such as fatigue failure of marine risers and long flexible cylinders, it simultaneously offers the advantage of serving as a sustainable energy source for various applications [17,18]. The mechanical vibrations generated by fluid flow can be effectively harnessed and converted into usable electrical energy, thereby providing a compelling alternative to conventional power sources. Researchers have explored the potential of flow-induced vibration for energy harvesting, emphasizing its utilization in areas such as automobiles, buildings, and bridges [19,20]. By capturing and converting the abundant vibrational energy, flow-induced vibration emerges as a catalyst for sustainable power generation.

2.1 Vortex Shedding

Vortex shedding occurs when fluid flows around a bluff body, forming vortices in its wake. This remarkable phenomenon subsequently leads to flow-induced vibrations within the body itself. The frequency of these vibrations is related to the shedding frequency of the vortices.

2.2 Reynold Number

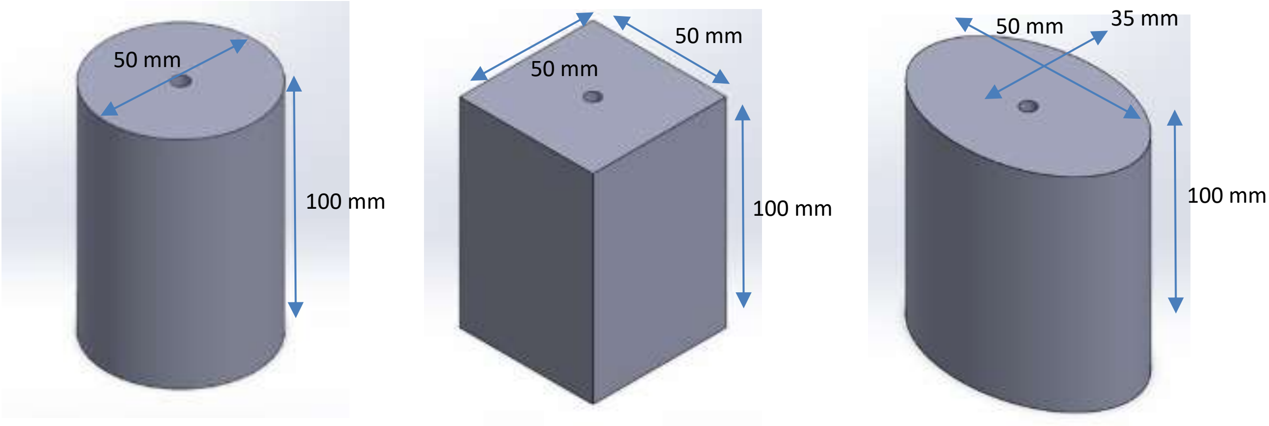
The Reynolds number denoted as Re is a dimensionless parameter used in fluid dynamics to determine whether the flow around an object or within a conduit is laminar or turbulent. It compares the importance of inertial forces (due to fluid velocity, v) to viscous forces, arising from fluid viscosity, μ. The equation is shown as follows:

$$Re = \frac{\rho v L}{\mu} \tag{1}$$

In this study, all the bluff bodies shared a consistent length of 150mm, thus ensuring a uniform Reynolds number. This decision was aimed at cultivating a turbulent flow (Re > 4000) with chaotic fluctuations. Keeping the length consistent minimized variations and allowed for a meticulous analysis of their behavior under turbulent flow conditions. As the Reynolds number increases, the flow around bluff bodies changes from orderly and steady at low numbers to turbulent and chaotic at high numbers [21,22].

3. Design and Modelling

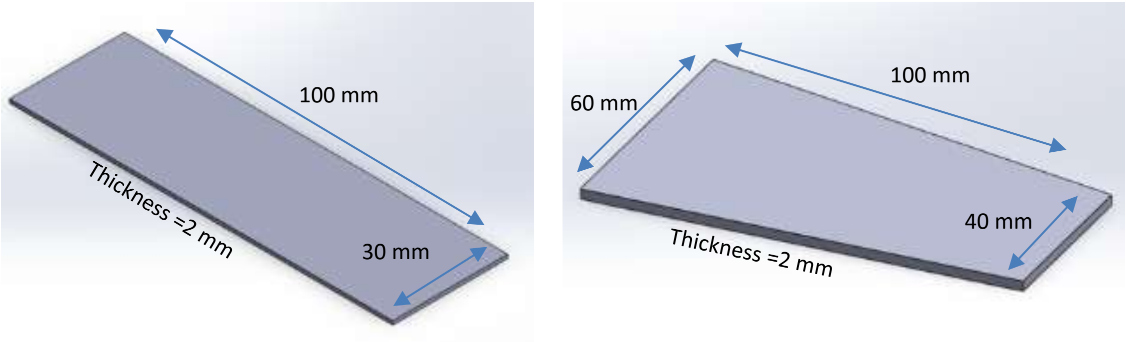
This study integrates 3D printing technology to model various bluff body designs. By leveraging 3D printing, physical models of the bluff body can be produced at different scales and complexities. The sizing of the bluff body employed in wind tunnel experiment is inherently tied to the size of the wind tunnel's test section. To ensure better resolution and accuracy of measurements, it is ordinary to opt for bluff body dimensions that are approximately 20% smaller than the test section. This is because smaller flow structures are more amenable to detection by measurement instruments. Figure 1 shows a visual representation of the bluff bodies dimensions.



(a) (b) (c)

Fig. 1. Bluff body specifications of (a) cylinder (b) rectangular (c) ellipse

Meanwhile, Figure 2 elucidates the geometry of splitter plate. In the course of experimentation, a splitter plate is introduced to measure the vibration response of a bluff body to incoming airflow. The plate functions by segmenting the main airflow into smaller streams that envelop the bluff body [23]. It helps create a realistic boundary layer flow on the bluff body, which is crucial for this study's methodology. The study aims to further investigate the impact of splitter plate size on the highest vibration response exhibited by a selected bluff body. To achieved this, we examined two distinct dimensions of splitter plates as depicted in Figure 2, in order to evaluate their respective effects.

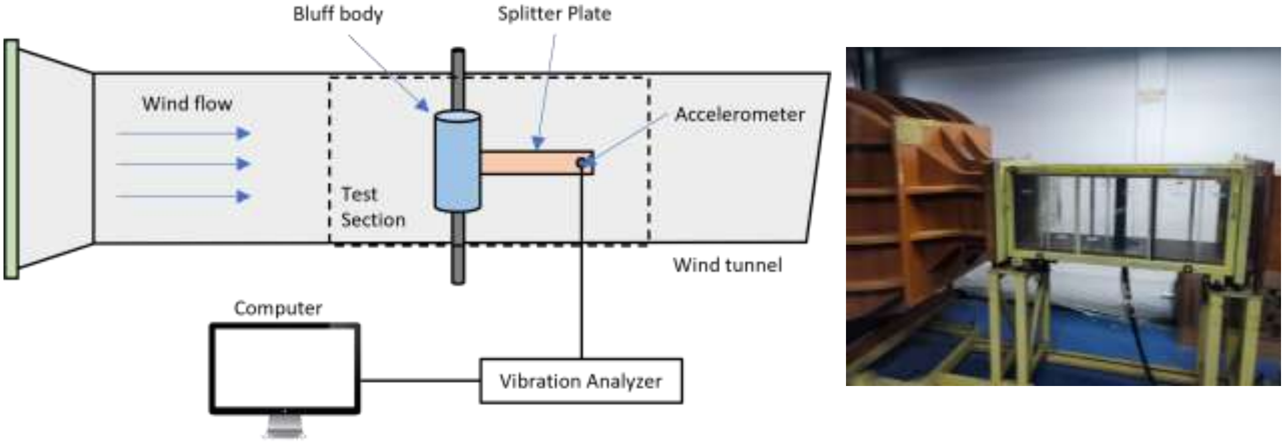


(a) (b)

Fig. 2. Geometry of (a) splitter plate A (b) splitter plate B

4. Experimental Method

Figure 3(a) displays the experimental configuration of the wind tunnel used for this study. This apparatus, as shown in Figure 3(b) played a pivotal role in evaluating the effect of the bluff body on the system. Within this setup, airflow velocity of 20 m/s originating from the inlet crosses through the wind tunnel, encountering the bluff body along its path. Notably, the bluff body is securely fixed within the test section, with an accelerometer attached to the terminal end of the splitter plate to facilitate precise measurements. The accelerometer was attached to the terminal end of the splitter plate because this position is highly sensitive to vibration, capturing the maximum response. This strategic placement ensures accurate assessment of the impact of bluff body shapes and splitter plate designs on the vibration response.



(a) (b)

Fig. 3. (a) Vibration experimental setup with bluff body and splitter plate (b) UTHM wind tunnel

5. Results and Discussion

5.1 Effect of Bluff Body Shapes

Figure 4 presents the results of vibration response for different bluff body shapes in the time domain. Among these shapes, the cylinder bluff body prominently stands out, exhibiting the most significant vibration response, with a distinctive waveform that oscillates between amplitudes of 17.4 to 25.7 m/s^2. These oscillations mirror the periodic shedding of vortices, creating a cyclic and rhythmic pattern. Notably, the amplitude of these oscillations demonstrates substantial variance, a reflection of the unsteady flow dynamics generated by vortex shedding.

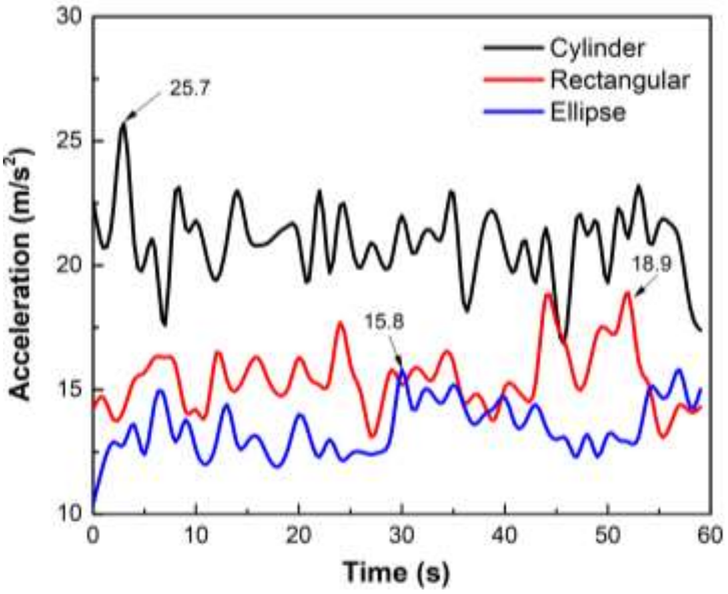


Fig. 4. Transient vibration response for cylinder, rectangular and ellipse bluff body

Shifting attention to the rectangular and elliptical bluff bodies, the time-domain analysis introduces a different visual narrative as depicted in Figure 4. For the rectangular bluff body, the vibration response traces a waveform that oscillates between 13.1 m/s² and 18.9 m/s², while elliptical bluff body waveform oscillating between 11.9 m/s² and 15.8 m/s² as tabulated in Table 1. Both of these oscillations appear less pronounced, embodying a relatively smoother pattern. For elliptical bluff body, the observation aligns with the streamlined nature of its configuration, which limits flow separation and subsequently diminishes the excitation of vibrational responses [24]. This result corroborates the study by Sun *et al.,* [25] which demonstrated the rectangular bluff body experiences unstable vortex shedding and generates higher-pressure difference at the back of bluff body, thus can induce greater excitation of the splitter plate.

In summary, the time-domain of vibration responses offers a glimpse into the continuous interaction between the fluid forces and structural behavior. Each bluff body configuration paints a distinct picture, with varying waveform patterns that reflect the underlying vortex shedding dynamics. This temporal analysis adds a layer of understanding to our comprehensive investigation, highlighting the intricate and evolving nature of flow-induced vibrations across different shapes.

Table 1
Comparison of highest and lowest vibration response of bluff bodies

Type of bluff body	Cylindrical	Rectangular	Ellipse
Highest amplitude (m/s^2)	25.7	18.9	15.8
Lowest amplitude (m/s^2)	17.4	13.1	11.9

5.2 Effect of Splitter Plate

The investigation into the effect of different splitter plate shapes on the vibration response of the cylindrical bluff body is depicted in Figure 5. Obviously, a distinct difference appears in the vibration responses obtained by splitter plates A and B. Splitter plate A yields a notably higher vibration response when compared to the response induced by splitter plate B.

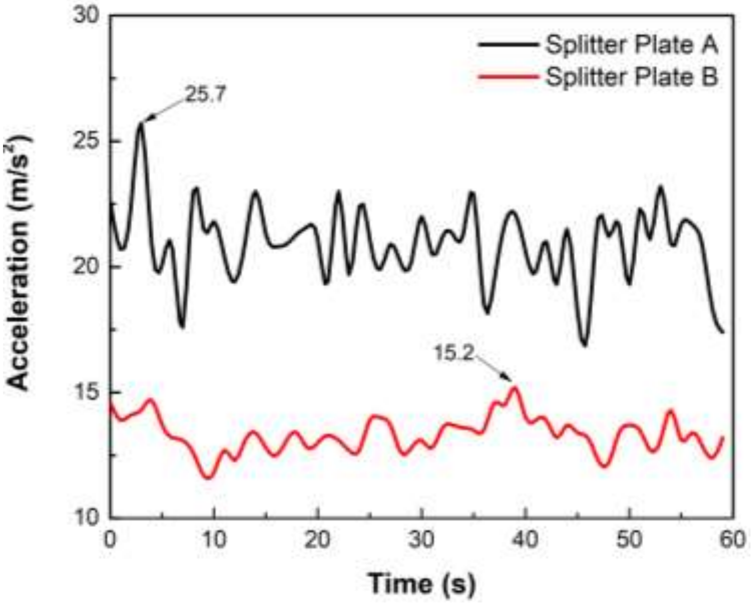


Fig. 5. Transient vibration response of cylinder bluff body with attached different splitter plate

Splitter plate A displays a substantial vibration waveform that oscillates between 17.4 m/s² and 25.7 m/s², while splitter plate B exhibits a distinct and smaller vibration waveform characterized by oscillations spanning from 11.7 m/s² to 15.2 m/s², as corroborated by the data presented in Table 2. The variance in vibration responses between the two splitter plates can be attributed to the distinct aerodynamic characteristics they introduce. Splitter plate A, characterized by a smaller surface area, leads to unsteady forces and flow separation [26]. This dynamic flow interaction produces a turbulent and complex environment that amplifies vibrations within the bluff body system. The pronounced vibration response observed with splitter plate A emphasizes the intricate balance between fluid forces and structural response.

Table 2
Comparison of highest and lowest vibration response of splitter plate

Type of splitter plate	Plate A	Plate B
Highest amplitude (m/s^2)	25.7	15.2
Lowest amplitude (m/s^2)	17.4	11.7

In contrast, splitter plate B has a different effect on the vibration behavior. Its favorable airflow patterns, coupled with reduced flow separation and minimized unsteady forces, result in a vibration response that is less strong. This matches how aerodynamics and structural dynamics, in particular the design of the splitter plate can serve as a pivotal determinant in the vibrational behavior of the bluff body system.

6. Conclusions

The experiment investigated the impact of bluff body design on flow-induced vibration of a flexible splitter plate. The results quantitatively demonstrate that the cylindrical bluff body exhibited the highest vibration response, recording a maximum amplitude of 25.7 m/s^2 followed by the rectangular bluff body, and the elliptical bluff body had the lowest response. Among the cylindrical bluff body configurations, splitter plate A induced vibrations that were 60% higher compared to splitter plate B. These findings highlight the significant influence of bluff body design, including shape and splitter plate dimensions, on flow-induced vibrations. The streamlined elliptical shape reduced vibration response, while sharp edges and corners increased vibrations in the rectangular bluff body. Furthermore, the dimensions of the splitter plate also played a crucial role in governing the vibration response.

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