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Size Dependence of Vortex - Induced Vibrations Based Energy Converter Bluff Body cylinder

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Abstract
Vortex-induced vibrations (VIV) is a well-known fluid flow phenomenon studied in multiple engineering disciplines and typically sought to be eliminated or minimized. This study aims to investigate the effect of bluff body cylinder sizes on VIV based electrical energy converter from low velocity flowing water. This study is particularly important because the VIV based technology explores the vast untapped new sources of clean and renewable energy from rivers and oceans with current velocities as low as 0.514 m/s to 1.8 m/s which were previously off limit. Computer model was created using solid modelling computer aided design an engineering software and exported to ANSYS for fluid-structure interaction simulation. Three cylinder sizes, 50 mm,75 mm, and 100 mm were tested at five different velocities of between 0.514 m/s, 0.7 m/s, 1.0 m/s, 1.4 m/s, and 1.8 m/s, respectively using computational fluid dynamics (CFD) simulation. The simulation result shows that the maximum heaving force amplitude of 28N emanates from the 100mm diameter at a current velocity of 1.8m/s.
Key words: Vortex induced vibrations; Low velocity marine currents; Simulation; Heaving force amplitude; Hydrokinetic energy.

1. Introduction

The impact on the environment and limited resources of fossil fuel energies have triggered a significant research effort in the development of new and diverse technologies to produce electrical energy. Also, so much attention has also been given to systems that can produce low-cost energy to power remote or isolated devices, for which connection to the traditional electrical network is high in terms of cost or technical complexity(Doare & Michelin, 2011). These considerations have increased the attention on mechanisms able to produce self-sustained vibrations of a solid substrate on one hand and to convert the corresponding mechanical energy into electrical power on the other. The conversion into electricity of hydrokinetic energy from river flows is particularly attractive because of the large availability worldwide and the low environmental impact of this energy source(Sharma & Sharma, 2013), (Westwood, 2004). Research on fluid–structure interactions has identified several instability mechanisms that has resulted to vortex induced vibrations of a bluff body placed in a steady uniform flow. (Bernitsas & Raghavan, 2006) came up with one such fundamental instability mechanisms based on VIV. In this work, we are interested in simulating the effect of the cylinder diameter in enhancing VIV to produce electrical power from the self-sustained oscillations of the hydrokinetic energy converter resulting from this fluttering instability. Several practical applications exist that generates power using the principle of VIV, each of which are at different stages of development. These systems operate at one of several different principles, such as oscillating cylinders and vibration tensioned cables but the technology that adopts the oscillating cylinder is the one closest to commercial availability(Ball et al., 2012). The device works by securing horizontally a cylinder with elastic springs in flowing water and limiting it to a single degree of freedom, allowing it to oscillate up and down perpendicular to the water

current flow(Theophilus-Johnson et al., 2023). Alternating vortices patterns are shed systematically behind the rectangular bluff body as the water flow over it exerting fluctuating lift forces on it, pulling it up and down thus, making it to vibrate. The vibratory motion of the bluff body is converted into electricity via a power take off (PTO) device(Hall-Stinson et al., 2011).The PTO is a built-in power generation module vertically installed. Kinetic energy from the flowing fluid is captured by the flow-around structure and is then converted into electrical energy by the built-in power generation module to power the grid. The power generation module can be piezoelectric membrane or a combination of electromagnetic and coils (Zheng et al., 2020). The converter adopted is a power extraction technology based on VIV that can explore the vast untapped new sources of clean and marine renewable energy from rivers and oceans with current velocities as low as 0.514m/s to 2.57 m/s(Zahari & Dol, 2015). Such low current velocities were previously off limit to conventional turbine technologies. VIV is a well-known fluid flow phenomenon and since it was discovered, engineers and scientists have been trying to understand its operations to prevent, minimize, or suppress the effect of its power in engineering applications(Amy, 2015).To achieve the actual potential for electrical energy production by the converter, the energy loss due to conversion into electrical energy must be included in the dynamic equations of the fluid- structure system since the extracted energy is a fraction of the total energy of the structural, transmission and internal generator losses(Raghavan, 2007).
Aluminum cylinders are used to provide suitable mass that is not too heavy for the lift force of the fluid acting on the cylinder. The cylinder is designed to investigate the possible performance of VIV at low ocean current speed. The three cylinders are 1 m long with diameters of 50 mm, 75 mm, and 100 mm respectively are shown in Figure 1.

Figure 1: Various sizes of cylinders (Adapted from Zahari &Dol, 2015).

Physical Model

A simple schematic of a single physical model of the energy converter considered in this work is shown in Figure 2. The model consists of a rigid bluff body of diameter D and length L, two supporting linear springs, two vertical shafts with linear bearings. The cylinder mounted with its axis in the z-direction is to be submerged perpendicularly to the flow velocity U, which is in the x-direction and will oscillate in the y-direction on the vertical shafts using linear bearings perpendicular to its axis in z and the U velocity in x.

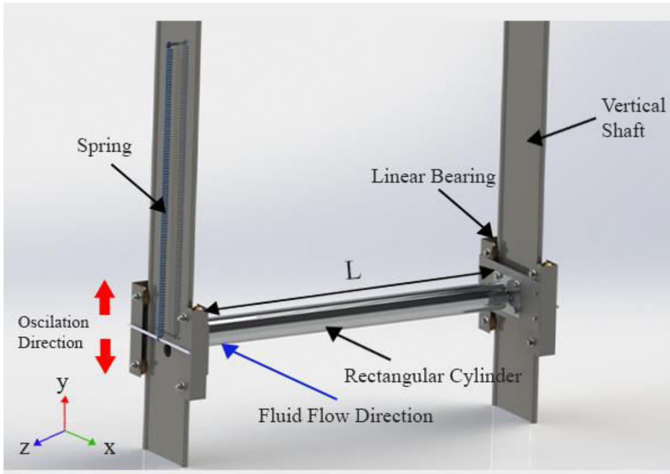


Figure 2: Simple schematic model of a rectangular prism VIVACE module.

2. Methodology

The method adopted involves CFD analysis using ANSYS Fluent and theoretical analysis to predict the converter power.

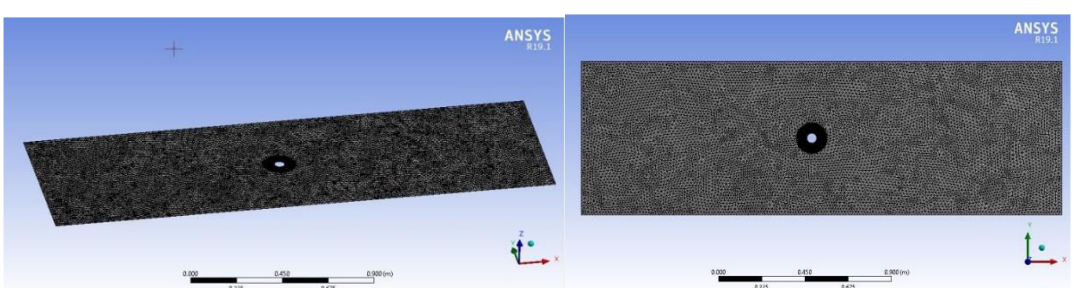
Computer Simulations

Computer models were created using solid works. The models created are exported to ANSYS for fluid-structure interaction simulations. ANSYS is a general-purpose software that enables simulation of systems, their physical, electromagnetic, thermodynamic, fluid-dynamic, vibrational, and structural behaviors. There are only a few numerical simulations suitable to predict the behavior of various hydrodynamic forces exerted on oscillating cylinders(Okajima et al., 1993).The fluid-structure interaction will be simulated and results such as pressure variation, vortex shedding, and motion of the structure are determined.

The flow around cylinders exhibits numerous important physical phenomena, such as flow separation, vortex shedding, and turbulence. Numerous practical interest fluid mechanical properties, including drag and lift forces, and pressure coefficients from instigated forces, are significantly influenced by the vortex shedding and suppression mechanism (Bimbato et al., 2011).

Model Setup

The computational domain and the boundary conditions for the simulation of the flow around circular and rectangular cylinders are shown in Figures3 (a) and (b) respectively. Longitudinal uniform velocities ranging from 0.514m/s – 1.8m/s were introduced at the inlet of the domain.



(a) (b)

Figure 3: Meshed flow domain showing (a) geometry of the model and (b) quality of mesh (Theophilus-Johnson, *et al*, 2023).

Table1shows the computational domain and the position of the body in the domain for the simulation in ANSYS workbench. The boundary condition which houses the fluid region and the bluff body as shown in Figure 4. The table further give parameters to specify the actual position of the cylinder within the computational domain.

Table 1: Location of body within the computationaldomain.

Parameters	Dimensions (mm)
D1	50
H3	2500
H5	500
V2	1750
V4	1000

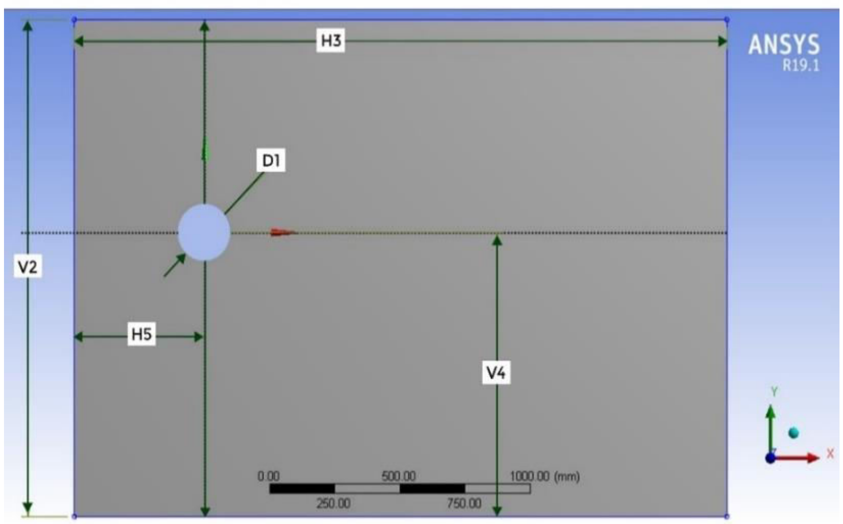


Figure 4: Sketch definition of positionof the body within the computational domain.

The optimum mesh size was selected by a mesh independent study to be 0.01m as shown in Figure 5. In the study, the mesh consisted of proximity and curvature; the size of the grid cells affects the outcome of the simulation.

The mesh cells used in this paper were refined to resolve the boundary layer separation and the wake behind the cylinders in the form of the vortex street. Meshing is one of the most important steps in obtaining an accurate boundary layer solution.

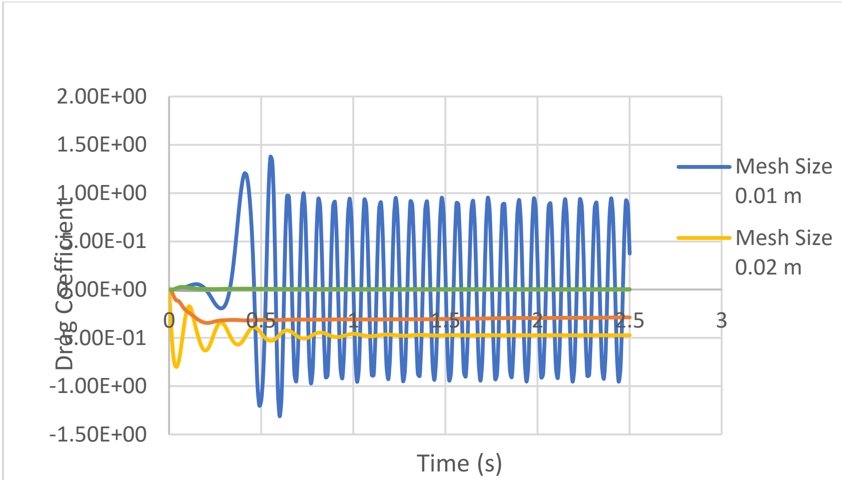


Figure 5: Chat showing C_d results for various mesh sizes.

Governing Equations

The governing equations of the hydrokinetic energy converter is derived by evaluating the following parameters: natural frequency, mass ratio, reduced velocity, Reynolds number, Strouhal number, and lift force.

The cylinder is submerged in water and so its mass cannot be taken directly for calculation, thus the apparent mass of the cylinder must be considered, and it is defined by (Rao & Manur, 2013) as:

$$m_{app} = m_{obj} - m_{dis} \quad 1$$

where: m_{obj} = real mass of the cylinder

m_{dis} = mass of the fluid displaced

The real mass of the fluid displaced is given by

$$m_{dis} = \rho_{fluid} \text{ x } Vol_{cyl} \quad 2$$

$$m_{osc} = m_{app} + m_{added} \quad 3$$

To estimate the final energy output of the system, the lift force plays a vital role, and the one-degree-of-freedom equation of vibration is given by

$$m_{osc}\ddot{y} + c_{sys}\dot{y} + ky = F_{lift} \quad 4$$

where: m_{osc} = oscillating system virtual mass, which include $^{1}/_{3rd}$ of the spring mass

y = displacement perpendicular to the incident flow and the cylinder axis

c_{sys} = damping coefficient of the oscillating system

K = system spring stiffness

Linear equations for amplitude of oscillations and lift coefficient are given as

$$y(t) = y_{max} \sin(2\pi f_s t) \quad 5$$

$$c_{L(t)} = C_L * \sin(\omega t + \varphi) \quad 6$$

$$c_L(t) = C_L \sin(2\pi f_s t + \varphi) \quad 7$$

Where: y_{max} = maximum amplitude of oscillation

φ = phase angle between fluid force and displacement

c_L = time independent lift coefficient

C_L = amplitude of lift coefficient of the cylinder

The power in the fluid flowing over the cylinder whose motion is perpendicular to the fluid flow is given as

$$F_L = \frac{1}{2}\rho U^2 \times DL \times C_L \quad 8$$

$$F_L(t) = F_L \times \sin(2\pi f_s t + \varphi) \quad 9$$

$$F_{fluid}(t) = \frac{1}{2}\rho U^2 \times DL \times c_L(t) \qquad 10$$

Where: F_L =power in the fluid

$F_L(t)$ = transient fluid force

ρ = density of the fluid

D = Diameter of the cylinder

L = length of the cylinder

Note that DL is the projected area in the direction perpendicular to fluid flow available for the dynamic pressure to develop the fluid force

Work done by the fluid acting on the bluff body during a VIV cycle is given by

$$W_{VIVACE} = \int_0^{T_{cyl}} F_{fluid}\dot{y}dt \qquad 11$$

$\dot{y}$ represents the oscillation velocity in this case, the heave velocity of the oscillating cylinder.

The fluid power due to VIV is

$$P_{VIVACE} = \frac{W_{VIVACE}}{T_{cyl}} \qquad 12$$

The fluid power P_{VIVACE} from VIVACE due to VIV can be obtained using equation (13)

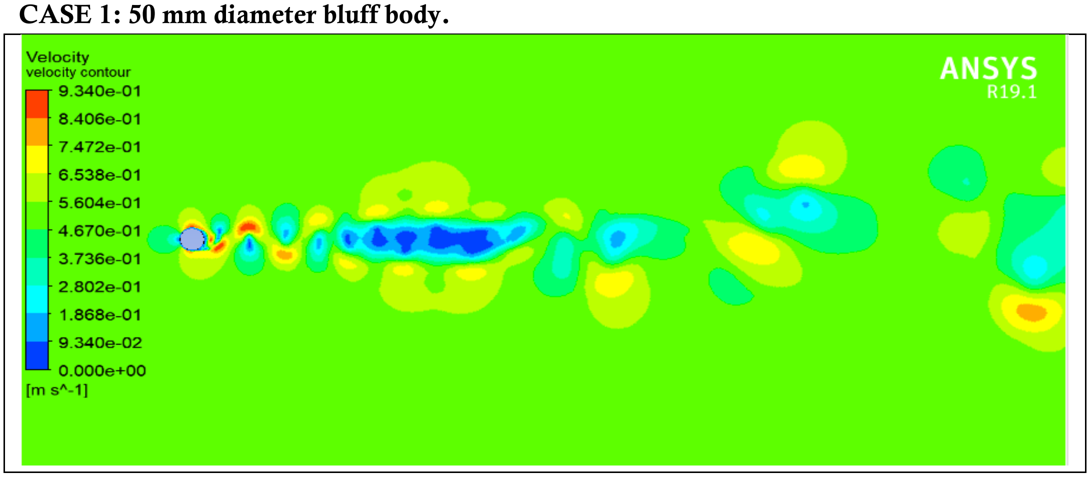
$$P_{VIVACE} = \frac{1}{2}\rho\pi U^2 C_L f_s y_{max} DLsin(\varphi) \qquad 13$$

3. Results and Discussion

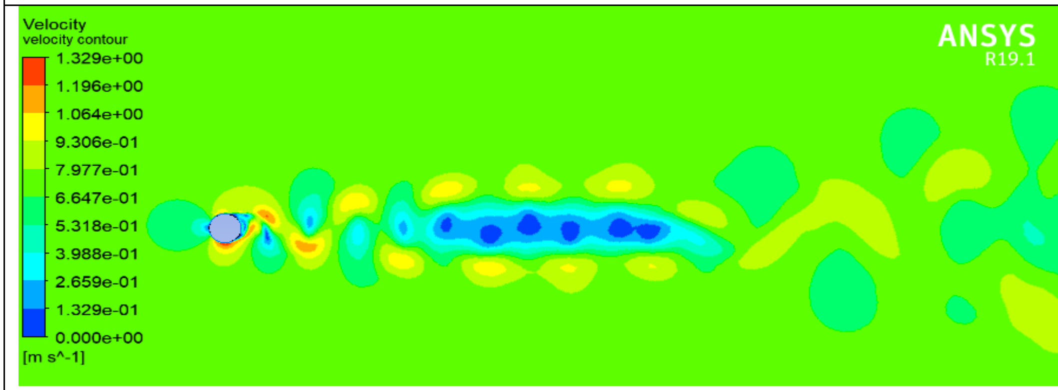
3.1 Velocity Contour Plots for Various Bluff Body sizes at Different Velocities

Figures 6, 7, and 8 show the velocity contour plots at 50 mm, 75 mm, and 100 mm cylinder diameter at different inlet velocities (i.e., 0.514 m/s, 0.7 m/s, 1.0 m/s, 1.4 m/s, and 1.8 m/s). From the contour plots, it was observed that a net pressure exists which makes the cylinder move upwards thus producing a crossflow response. As the fluid velocity increases, a higher net pressure beneath the cylinders with fully attached vortices formed from the top and bottom end of the cylinder, and a much higher formation length compared to previous cylinders with lower flow speed. The wake pattern observed in this case shows a breakdown at a much earlier stage. Result of the simulation showed a much higher velocity in the vortices formed very close to the bodies, but this velocity reduced as the flow moves further downstream and the vortices gradually diminished. This interaction between vortices makes the fluid structure interaction complicated due to the generation of radiated waves which could travel back to the body or outwards further downstream. This on the other hand would tend to increase the motion of the body.

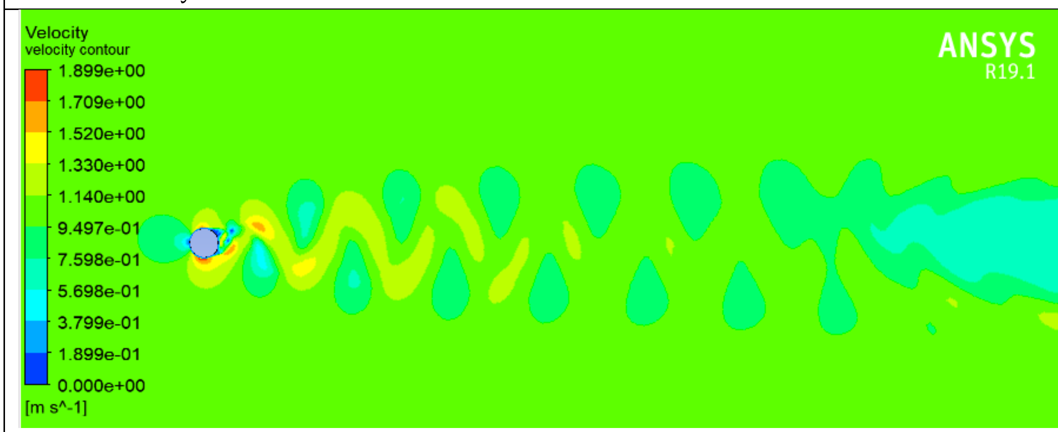
CASE 1: 50 mm diameter bluff body.



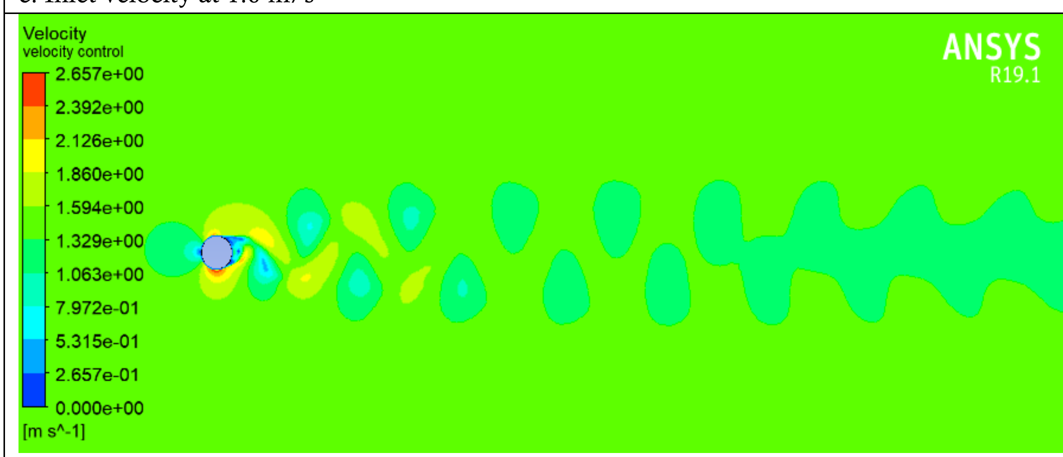
a. Inlet velocity at 0.514 m/s



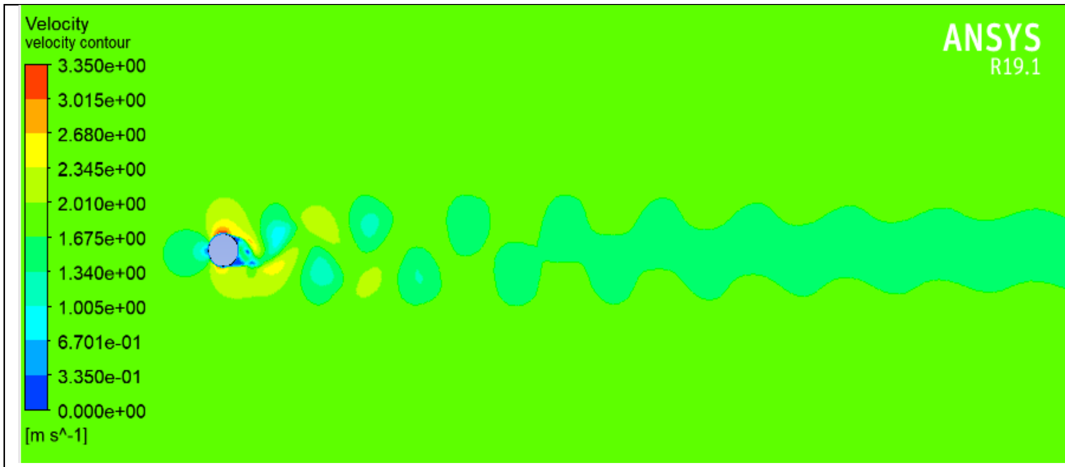
b. Inlet velocity at 0.7 m/s



c. Inlet velocity at 1.0 m/s



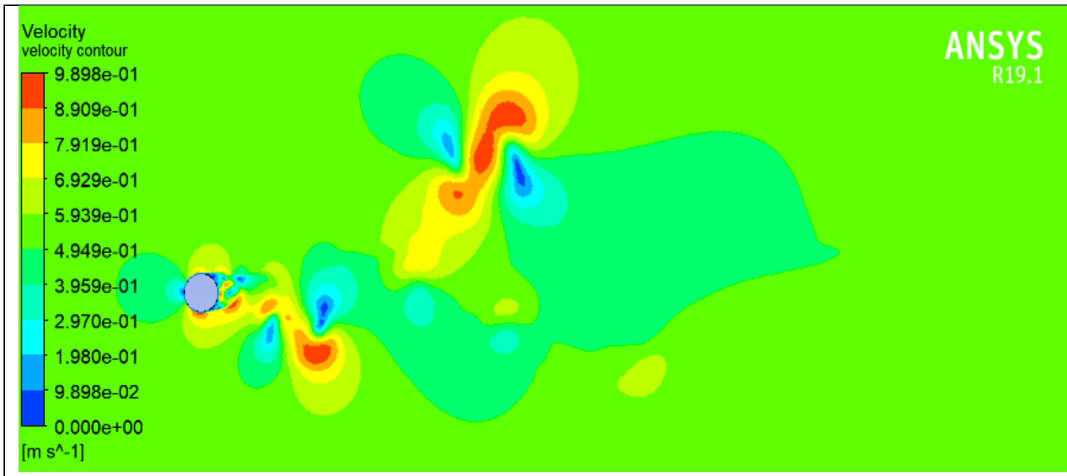
d. Inlet velocity at 1.0 m/s



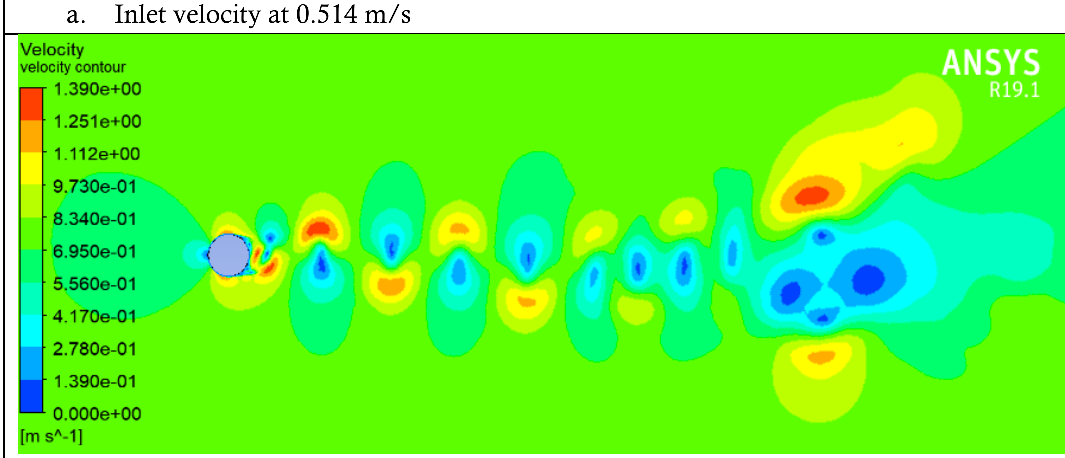
e. Inlet velocity at 1.8 m/s

Figure 6: Velocity contour plots for 50 mm cylinder diameter.

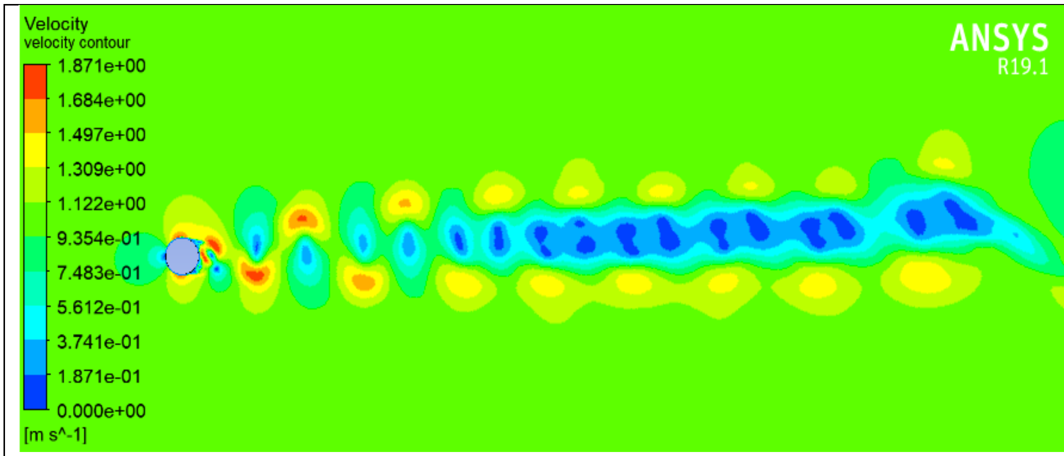
CASE 2: 75 mm diameter bluff bodies.



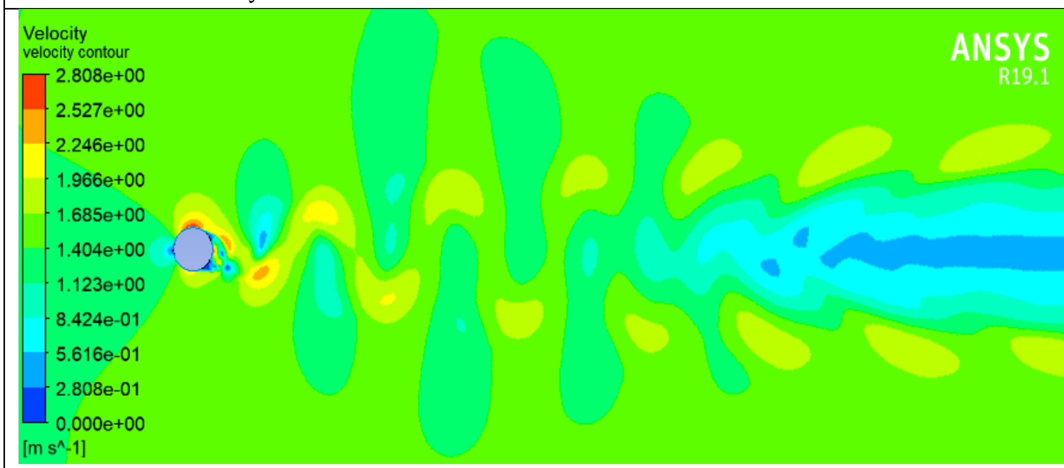
a. Inlet velocity at 0.514 m/s



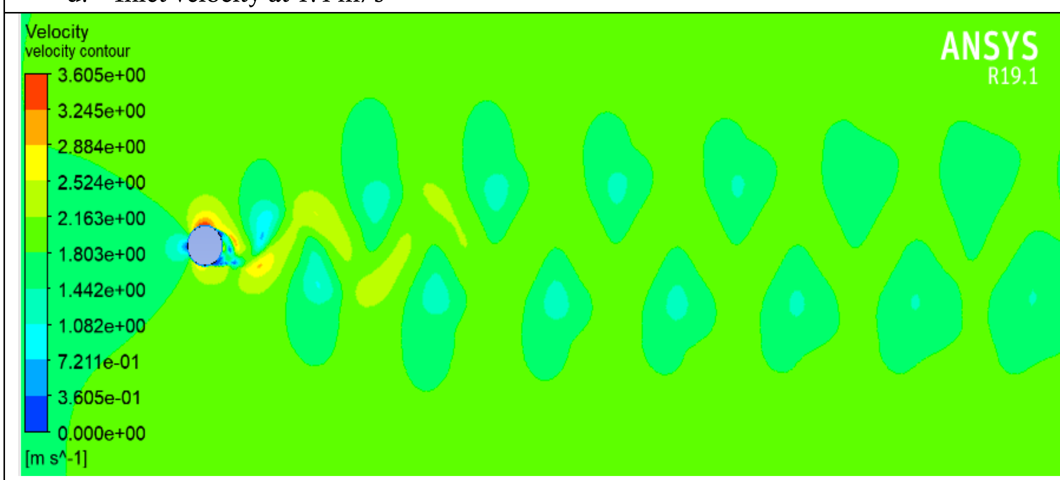
b. Inlet velocity at 0.7 m/s



c. Inlet velocity at 1.0 m/s



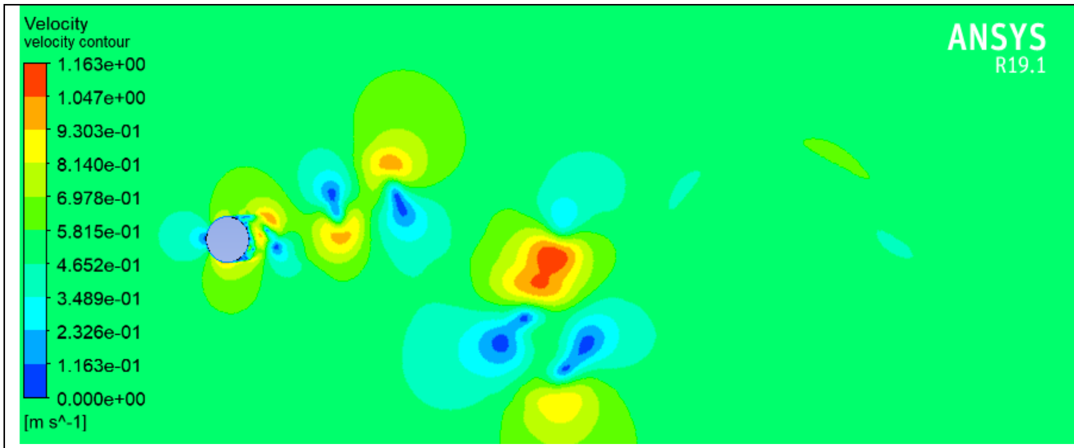
d. Inlet velocity at 1.4 m/s



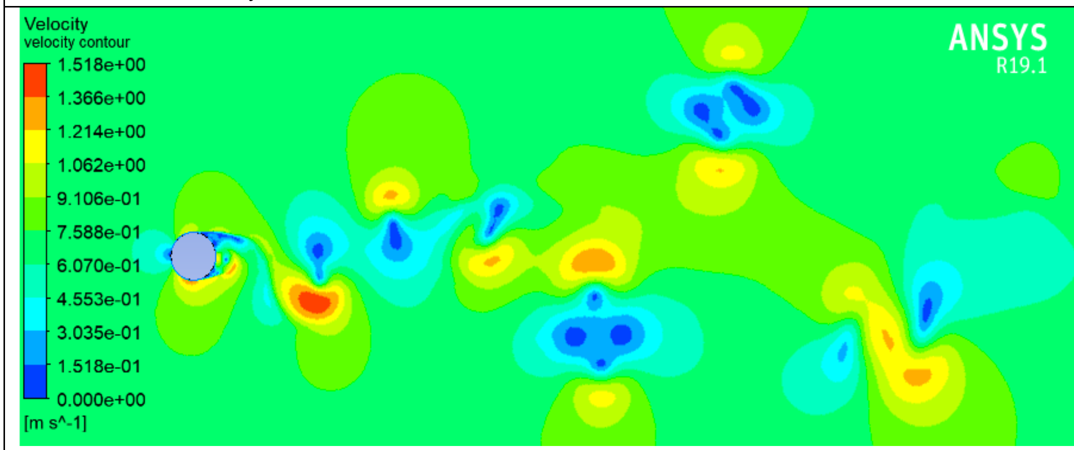
e. Inlet velocity at 1.8 m/s

Figure 7: Velocity contour plot for 75 mm cylinder diameter.

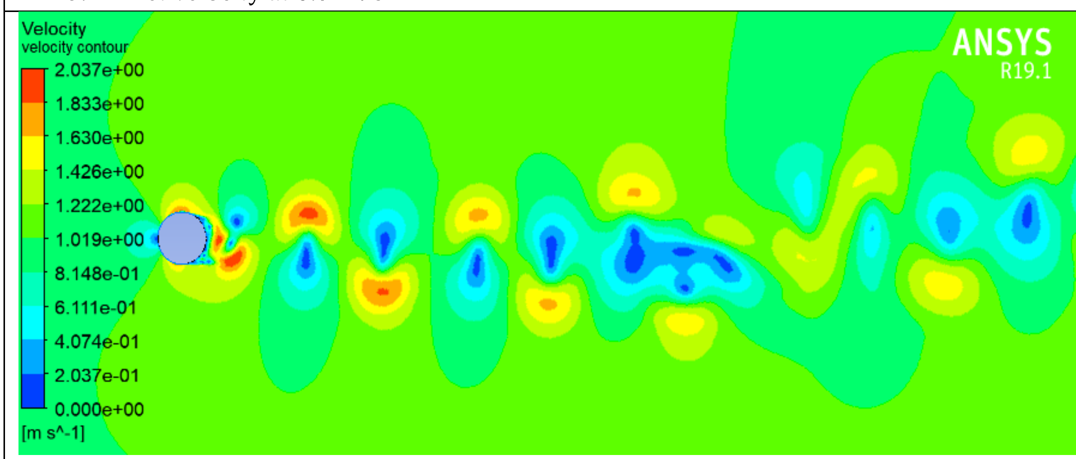
CASE 3: 100 mm diameter bluff bodies.



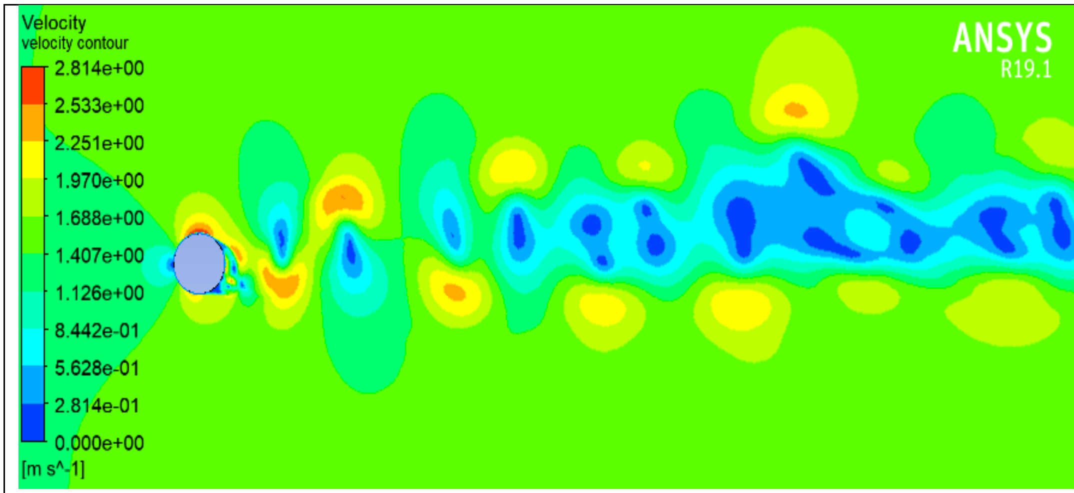
a. Inlet velocity at 0.514 m/s



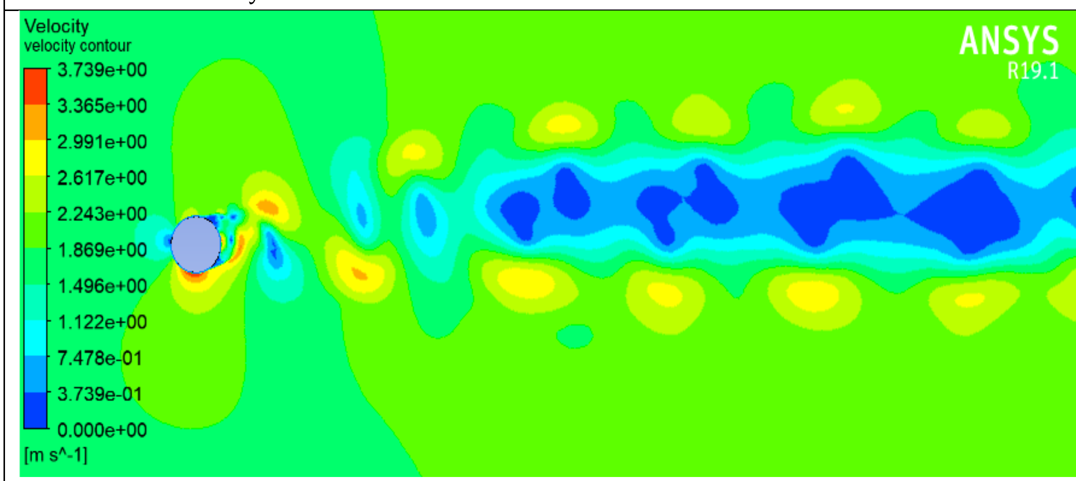
b. Inlet velocity at 0.7 m/s



c. Inlet velocity at 1.0 m/s



d. Inlet velocity at 1.4 m/s



e. Inlet velocity at 1.8 m/s

Figure 8: Velocity contour plot for 100 mm cylinder diameter.

Table 2 shows the optimized heave force F_L for different sizes of bluff bodies calculated using equation (9).From the graph of heave force and current velocity shown in Figure 9, the maximum heaving force of 28 N emanates from the cylinder of 100 mm diameter at current velocity of 1.8 m/s. this is followed by the 75 mm which gave a heaving force amplitude of 12.6 N at the same velocity.At a current velocity of 1.8m/s, the of 50mm diameter cylinder recorded a heaving force amplitude of 3.8N. From the foregoing, it can be deduced that the larger diameter cylinder gives the highest heaving force amplitude of oscillation of 28 N.

Table 2: Optimized heave force amplitude for different cases of bluff bodies using sum of sine fit in MATLAB Cftool.

case		velocity (m/s)	DL (m^2)	$\rho\ kg/m^3$	C_L (-)	F_L (N)
Cir0.514-50mm		0.514	0.05	995.6	0.07018	0.46149
Cir0.70-50mm		0.7	0.05	995.6	0.07105	0.86653
Cir1.0-50mm		1	0.05	995.6	0.06447	1.60466
Cir1.4-50mm		1.4	0.05	995.6	0.06062	2.95731

Cir1.8-50mm	1.8	0.05	995.6	0.05056	4.07734
Cir0.514-75mm	0.514	0.075	995.6	0.09559	0.94288
Cir0.70-75mm	0.7	0.075	995.6	0.1252	2.29043
Cir1.0-75mm	1	0.075	995.6	0.1301	4.85728
Cir1.4-75mm	1.4	0.075	995.6	0.1266	9.26416
Cir1.8-75mm	1.8	0.075	995.6	0.1143	13.8263
Cir0.514-100mm	0.514	0.1	995.6	0.1328	1.74654
Cir0.70-100mm	0.7	0.1	995.6	0.08527	2.07992
Cir1.0-100mm	1	0.1	995.6	0.1591	7.92
Cir1.4-100mm	1.4	0.1	995.6	0.1689	16.4794
Cir1.8-100mm	1.8	0.1	995.6	0.1716	27.6769

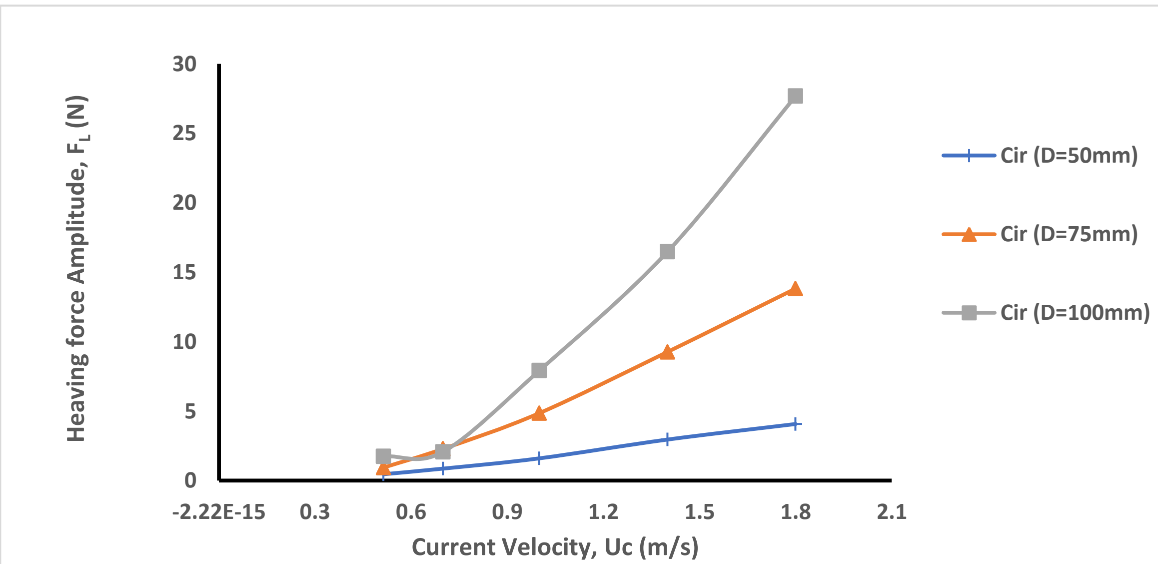


Figure 9: Plot of heaving force amplitude and velocity.

4 Conclusion

The simulation results show that with the higher cylinder diameter the energy levels produced increased. The 100mm cylinder at 1.8m/s flow velocity has a potential to generate100% more than the 75mm diameter cylinder. The results show that the hydrodynamic characteristics of oscillating cylinder strongly depend on the size of the bluff body, the forcing frequency, and the oscillating direction. It can be safely concluded that as the size of the cylinder is increased, the energy level produced by the cylinder increases. Thus, in designing a VIV based hydrokinetic energy converter a suitable size of the cylinder is very important to generate substantial energy for electricity generation.

Results in this paper provide a reference for design of VIV based energy converter considering size of the bluff bodies and range of flow velocities to obtain larger VIV responses to harness energy. It is finally recommended that experimental investigations should be carried out to validate the simulation results obtained in this paper.

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