Structural and numerical analysis of Bladeless Wind turbine

Omkar Pawar [1 [0009-0005-4883-9678]], Shane Aaron Amanna [1 [0009-0000-5194-8895]], Urshila Mittal [1 [0009-0008-2725-2837}],

Prashob P S[2[0000-0002-5472-4421]] and Neelesh Balki [2[0000-0003-2637-373X]]

[1] UG Student, Department of Mechanical Engineering, Mukesh Patel School of Technology Management & Engineering, SVKM's Narsee Monjee Institute of Management Studies (NMIMS) Deemed-to-University, Mumbai-400056, India
[2] Assistant Professor, Department of Mechanical Engineering, Mukesh Patel School of Technology Management & Engineering, SVKM's Narsee Monjee Institute of Management Studies (NMIMS) Deemed-to-University, Mumbai-400056, India
omkarpawar1837@gmail.com

Abstract: This report presents a comprehensive study on the structural and numerical analysis of Bladeless Wind Turbines (BWTs), with a focus on their application in a specific location in India characterized by unique wind conditions. The research involved an extensive review of relevant literature and the practical application of structural and computational methods to assess the performance of BWTs. The core principle underlying BWTs is Vortex-Induced Vibrations (VIV), an innovative approach to wind energy conversion that eliminates traditional rotor blades. The study encompasses a thorough investigation of the potential of BWTs in harnessing wind energy, with a keen interest in their suitability for the Indian environment. Structural analysis formed a pivotal component of the research, with a particular emphasis on calculating deflection to understand the behavior of these bladeless turbines under varying wind loads. This analysis sought to evaluate the structural integrity and stability of the BWTs, providing insights into their real-world performance.

Furthermore, Computational Fluid Dynamics (CFD) simulations were conducted to examine the aerodynamic characteristics and efficiency of BWTs under the specific wind conditions of the chosen Indian location. The numerical analysis shed light on their operational performance, providing a comprehensive understanding of their energy-generating capabilities. The outcomes of this research contribute to the growing body of knowledge on BWTs, offering insights into their structural behavior and numerical efficiency in the context of India's wind conditions. These findings hold significant potential for advancing sustainable energy solutions, as bladeless wind turbines continue to emerge as a promising alternative to traditional wind energy technologies.

Keywords: Vortex bladeless wind turbine, Vortex induced vibration (VIV), CFD Analysis.

1 Introduction

1.1 Renewable Energy Scenario

Renewable energy since the inception of the term, has been on the trot, roaming around the aisles of all major organizations of the world. All this notion and multiple discussions and summits later, the actual potency of the term is far from realized. It's high time we take the onus on ourselves and put a strong foot forward, to ensure that our planet has sufficient resources to fulfil the needs of our future generations. Statistically, right now only 29% of the energy needs are being met by renewable energy sources, which is just a small portion of the vastness it possesses. Of the existing renewable energy sources, Solar and wind energy makes the majority, both of which have been seeing innovation year on end to move ever so closer to the final picture of sustainability. In Solar and wind based renewable energy models, the current innovations can be looked at from a different perspective to better underline the changes.

1.2 Wind Energy

If we consider wind energy solely, the existing wind turbines and form of energy generation have multiple shortcomings, which include high initial cost of setting up, remote locations and its drastic effect on wildlife. This coupled with its odd appearance to the landscape gives us huge enough reason to innovate. The noisy aspect of the turbines is another issue with them.

1.3 Bladeless Wind Turbine

Now to counter all these issues, we have a new ground-breaking technology, namely "Bladeless-Wind turbines ". Traditional wind turbines have an efficiency of 45-50% while bladeless wind turbines are said to be 60% efficient. Bladeless technology is essentially a vertically fixed cylinder with an elastic rod. A wind range oscillates the cylinder, which creates electricity via an alternator system. It is a vortex-induced vibration resonant wind generator. The ease with which a bladeless wind turbine is made is also an added advantage as its installation and all the subsequent processes are comparatively easy to undertake when compared to the conventional wind turbines.

1.4 Vortex Induced Vibration Technology (VIV)

Bladeless wind turbines capture energy from the wind using resonance and a phenomenon known as Vortex-Induced Vibration (VIV). This is achieved when air passes through a specific blunt body, altering its flow pattern to create cyclic vortices with frequencies that match or are near the structural frequency of the body. When this occurs, it causes vibration to enter into resonance with the wind. The mast geometry of these turbines has been designed to perform optimally at average wind speeds while still being able to adjust easily if there are changes in direction or turbulence usually present in urban areas.

Furthermore, due to their ability to avoid "wake effect" disturbances seen on regular turbine installations, which must be kept far from each other, bladeless ones work better when close together and function cohesively. This increased efficiency comes from its ability to capture low-pressure area's unreachable by traditional turbines. The aero dynamicity of the turbine is an added advantage. The bladeless turbine's ability to be easily installed, and run practically. The lay-man way of working of the bladeless wind-turbine is based on its movement.

1.5 Motivation and scope of the report

As aspiring engineers, it is our duty and also a purpose to be able to contribute towards the industry in a more environmentally friendly and energy efficient way, something that is of utmost importance and also within the scope of mechanical engineering. Wind Turbines are an important equipment used in majorly in the renewable energy field therefore we aim to work on its designing and optimization for more effective and efficient energy generation and optimization.

The scope of this report opens a new horizon for the existing shell and tube heat exchanger by using the different configurations that have been in this paper, by calculations conducted based on Kern's method and then processed under a thermal analysis using Computational Fluid Dynamics. This report provides a detailed outlook of the same from the inception to the results and our conclusive theory, based on the analysis done. This establishes a base for shell and tube heat exchangers to be manufactured further which can prove to be useful in the plants or industries.

1.6 Problem statement

The need for an alternative to conventional wind turbines which have its own disadvantages as stated previously, so in order to mitigate these disadvantages, a new and better wind turbine is required which is the in-development turbine called Vortex bladeless wind turbine which uses oscillatory motion to generate electricity. Since the technology is still new in India, a suitable site or place is taken into consideration and its various parameters are studied and numerical calculations are done to find the forces responsible for deformation and oscillatory motion. Along with the natural frequency of the body and vortex shedding frequency of the wind which are responsible for electricity generation.

1.7 Research Gap

After reviewing all of those mentioned publications, we identified a research gap in which no experiment utilizing Indian physical conditions has been carried out. We would love to take the effort to bring this technology to India as it is not currently available there. For this project, we used 20 years of backup data from a site to do FEA and CFD evaluations to check and improve the technology.

2 Methodology and Implementation

2.1 3D Model

Software used – SolidWorks

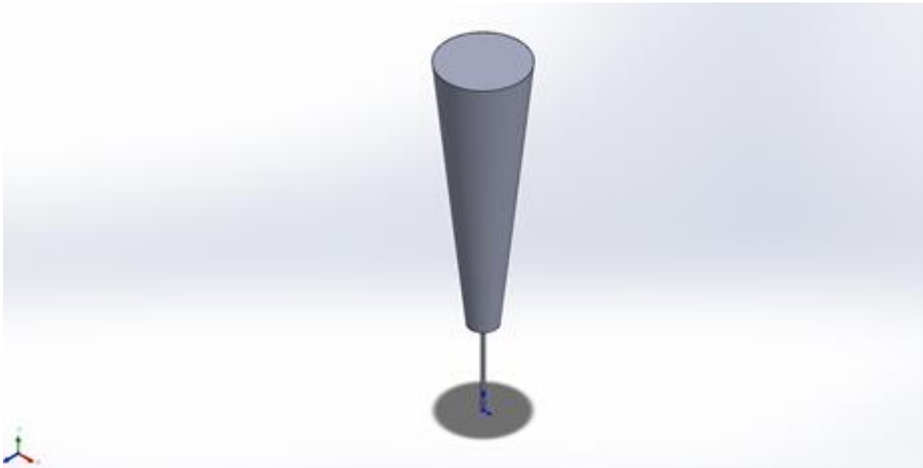

Fig. 1. 3D Model of VBT

Table 1. Dimensions of Model

Sr. No.	Name	Denotion	Value	Units
1	Length of mast	lmast	7.5	m
2	Length of rod	lrod	2.5	m
3	Max. or upper diameter of mast	dmax	0.45	m
4	Min. or lower diameter of mast	dmin	0.15	m

2.2 Calculations

1. Location – Ambara, Gujrat

23.93 latitude, 69.85 longitude [20]
Ambara, Gujrat is the location which is taken for our research. We have taken last 20 years of wind data for our research in consideration. Ambara being a place medium sized village and being located approximate 90meters above sea level makes it suitable for our research.

2. Force Calculations –

Table 2. Available Data

Sr. No.	Name	Denotion	Value	Units
1	Drag Coefficient	C_d	8.4	-
2	Density of air	ρ	1.23	kg/m3
3	Maximum Velocity	Vmax	15.6	m/s
4	Minimum Velocity	Vmin	0.83	m/s
5	Average Velocity	Vavg	6.014	m/s
6	Lift Coefficient	C_l	8.18	-
7	Mass of the body	m	447.97	kg
8	Deflection	δ	0.578	m
9	Strouhal Number	St	0.2	-

The **Total Height (H)** of the VBWT Model is the summation of the height of the movable mast (l_{mast}) and the height of the rod(l_{rod}). l_{mast} is the height that is subjected to wind and is taken into consideration for calculating the loads. l_{rod} is the height of the rod that supports the structure.

$$H = l_{mast} + l_{rod} \qquad (1)$$

Since the model is tapered with a ratio of 1:3 where the lower end of the mast has a diameter (d_{min}) and the upper end of the mast has a diameter(d_{max}). Therefore, the **Average Diameter (d_{avg})** of the VBWT model is given as,

$$d_{avg} = \frac{d_{max}+d_{min}}{2} \qquad (2)$$

Considering the fact that the entire area of the model is not in contact with the wind, so the effective area is taken into consideration which is the surface area of the trapezoid. So, the area which is in contact is the **Area of Trapezoid (A)** which is given as,

$$A = \frac{1}{2} \times (d_{max} + d_{min}) \times l_{mast} \qquad (3)$$

Calculate forces and other suitable data for a range of velocities which include maximum velocity, minimum velocity and average velocity. By the use of the above-mentioned velocities in various formulas, we are able to calculate three different values of required data with the use of their respective formulas.

When the wind having a velocity range comes in contact with the model, there is a force that the wind exerts on the effective surface of the model.

So, **Drag Force (F_d)** can be calculated by using the formula mentioned below,

$$F_d = \frac{1}{2} \times C_d \times \rho \times A \times V^2 \qquad (4)$$

Where,

F_d = Drag Force in Newtons (N)
C_d = Coefficient of Drag which is obtained with the help of Ansys
ρ = Density of air (kg/m^3)
A = Surface area of the effective surface i.e trapezoid in nature (m^2)
V = Velocity of the wind (m/s)

When the wind flows over the body of the model, boundary layer separation takes place and vortices starts forming at the sides of the body due to the vibratory motion of the wind as the vortex shedding frequency of the wind resonates with the natural frequency of the body it exerts a force on the body in the perpendicular direction and that force is termed as **Lift Force (F_l)** which is given as,

$$F_l = \frac{1}{2} \times C_l \times \rho \times A \times V^2 \qquad (5)$$

Where,

F_l = Lift force acting in perpendicular direction to the wind (N)

C_l = Coefficient of lift which is obtained with the help of Ansys

The **equivalent force (F)** acting on the body is the resultant of the two forces i.e. the drag force and the lift force which is given by,

$$F = \sqrt{(F_d)^2 + (F_l)^2} \qquad (6)$$

Where,

F = Total force (N)

Moment of Inertia (I) determines whether there is uniform distribution of mass and the body's ability to resist changes in speed and is given by

$$I = \frac{1}{4} \times m \times \left({r_{max}}^2 + {r_{min}}^2 + {l_{mast}}^2\right) \quad (7)$$

Where,

I = Moment of inertia ($kg.m^2$)

M = Mass of the body (kg)

r_{max} & r_{min} = Radius of the upper and lower end of the mast (m)

l_{mast} = Length or height of the mast (m)

Spring Stiffness (K) determines the natural frequency of the body and the spring stiffness should be high enough to prevent resonance, but low enough to allow the VBWT to capture the energy from the vortex. The values of Total Force is obtained from Equation (6) and the value of deflection is obtained from ansys.

$$K = \frac{Total\ Force}{Deflection} = \frac{F}{\delta} \qquad (8)$$

Where,

F = Total force (N)

δ = Deflection (m)

Vortex Shedding Frequency (f_s) determines the rate at which the vortex is shed from the VBWT. This frequency is important for electricity generation and is given by,

$$f_s = \frac{St \times V}{d_{mast}} \qquad (9)$$

Where,

St = Strouhal number is defined as the ratio of the characteristic frequency of vortex shedding to the characteristic frequency of the flow and is a dimensionless number. It determines the vortex shedding frequency and thus alters the rate of production of electricity.

d_{mast} = Characteristic length of the body i.e. upper diameter of the mast (m).

Natural Frequency (f_n) is the frequency at which the body will vibrate when disturbed or can be defined as the frequency at which a system tends to oscillate in the absence of any driving force. This frequency is determined by the spring stiffness and mass of the body. The below equation is taken into consideration while neglecting the energy losses.

$$f_n = \frac{1}{2\pi} \times \sqrt{\frac{K}{m}} \qquad (10)$$

Where,

K = Spring stiffness (N/m)

m = mass of the body (kg).

Table 3. Calculated Values for different velocity range

Sr. No.	**Name**	**Denotion**	**Value**			**Units**
			Max Velocity (15.6 m/s)	**Min. Velocity (0.83 m/s)**	**Avg. Velocity (6.014 m/s)**	
1	Drag Force	F_d	2828.7	8.0074	420.39	N
2	Lift Force	F_l	2754.61	7.8	409.38	N
3	Total Force	F	3948.34	11.18	586.78	N

4	Spring Stiffness	K	6831.04	19.34	1015.19	N/m
5	Vortex Shedding Frequency	fs	6.93	0.37	2.67	Hz

Table 4. Calculated Values

Sr. No.	Name	Denotion	Value	Units
1	Total Height	H	10	m
2	Average Diameter	davg	0.3	m
3	Area	A	2.25	m2
4	Moment of Inertia	I	6305.82	kg.m2
5	Natural Frequency	fn	6.14	Hz

2.3 Finite Element Model

Software used – Ansys

1. **Mesh**

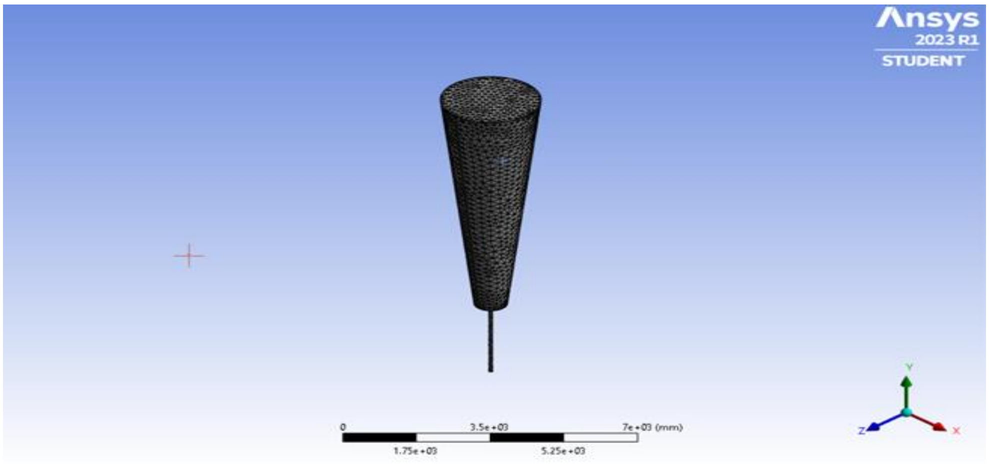

Fig. 2. Model Mesh

2. Reaction Force Direction

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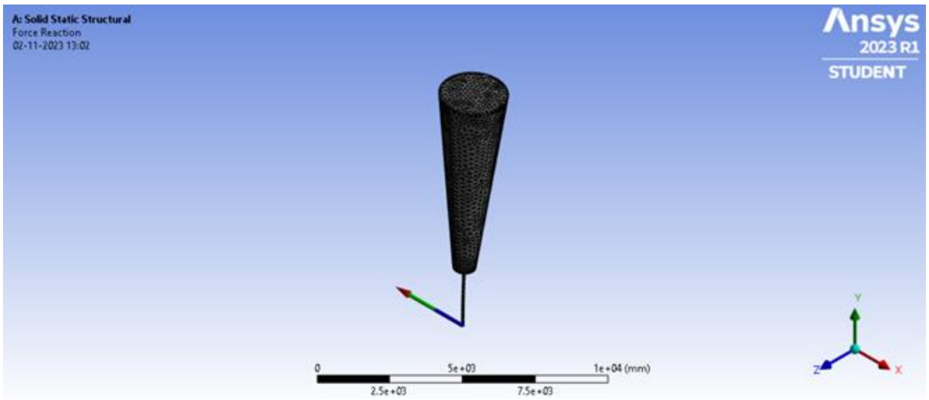

Fig. 3. Reaction Force Direction

3. Displacement Boundary Conditions

Details of "Displacement"	
Scope	
Scoping Method	Geometry Selection
Geometry	1 Edge
Definition	
Type	Displacement
Define By	Components
Coordinate System	Global Coordinate System
X Component	Free
Y Component	0. mm (ramped)
Z Component	0. mm (ramped)
Suppressed	No

Fig. 4. Applied boundary conditions

2.4 CFD Analysis

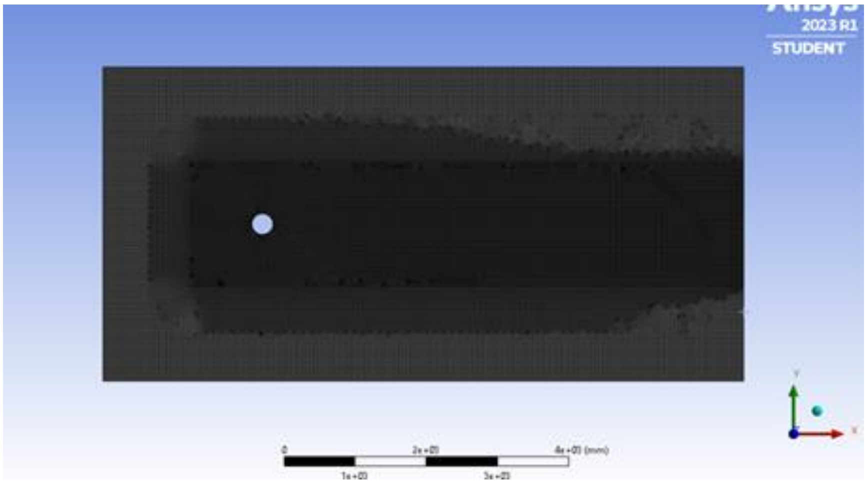

Fig. 5. CFD Meshing

Details of "Mesh"	
Display	
Display Style	Use Geometry Setting
Defaults	
Physics Preference	CFD
Solver Preference	Fluent
Element Order	Linear
Element Size	30.0 mm
Export Format	Standard
Export Preview Surface Mesh	No

Fig. 6. Mesh Conditions outer surface

Details of "Face Sizing" - Sizing	
Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Suppressed	No
Type	Element Size
Element Size	20.0 mm
Advanced	
Defeature Size	Default (0.15 mm)
Growth Rate	Default (1.1)
Capture Curvature	Yes
Curvature Normal Angle	Default (18.0°)
Local Min Size	Default (0.3 mm)

Fig. 7. Mesh conditions for inner surface

Details of "Inflation" - Inflation	
Scope	
Scoping Method	Geometry Selection
Geometry	2 Faces
Definition	
Suppressed	No
Boundary Scoping Method	Geometry Selection
Boundary	1 Edge
Inflation Option	Total Thickness
Number of Layers	10
Growth Rate	1.1
Maximum Thickness	2.0 mm
Inflation Algorithm	Pre

Fig. 8. Details of inflation

2.5 CFD Boundary Condition

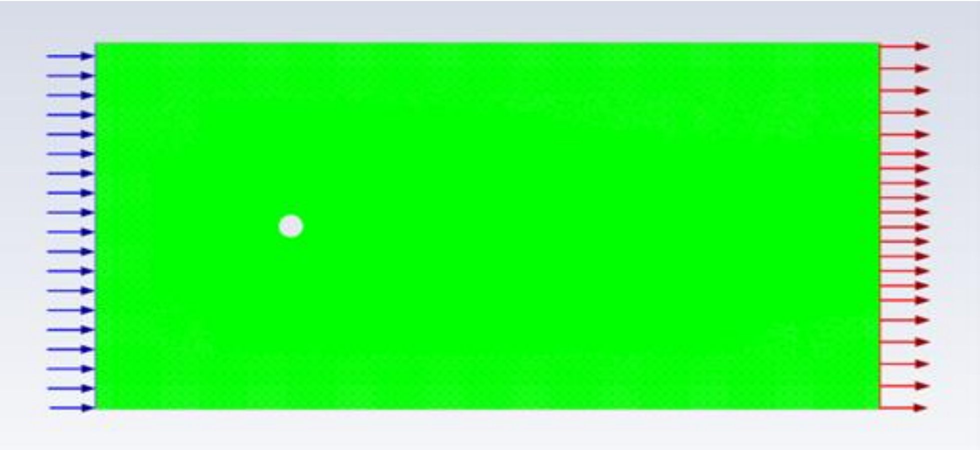

Fig. 9. CFD Boundary conditions

Inlet – Velocity 15.6 m/s
Applied velocity on Left wall and pressure on right wall

2.6 Vortex Formation

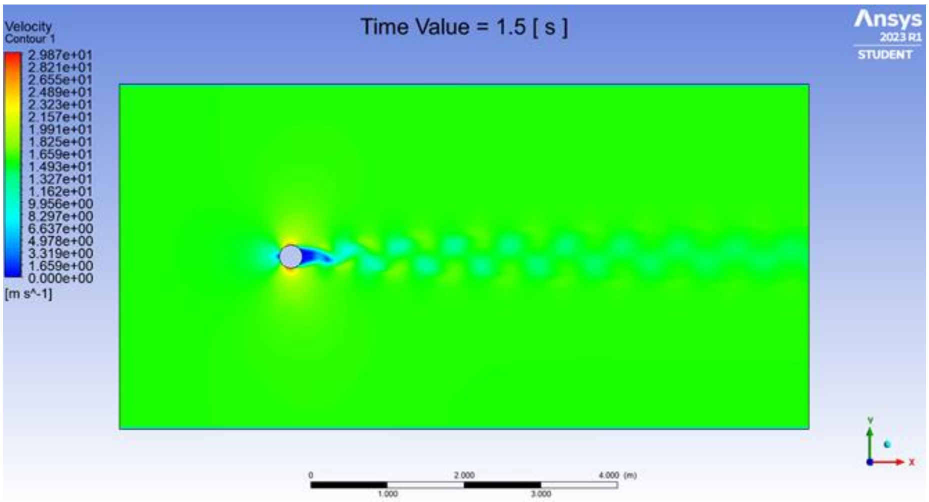

Fig. 10. Vortex Formation

3 Results and Analysis

3.1 Total Deformation

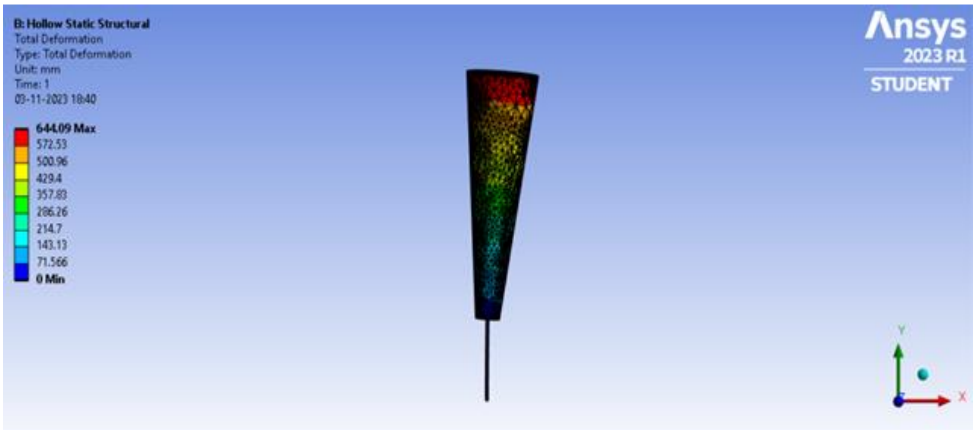

Fig. 11. Total Deformation

3.2 C_d and C_l Coefficient

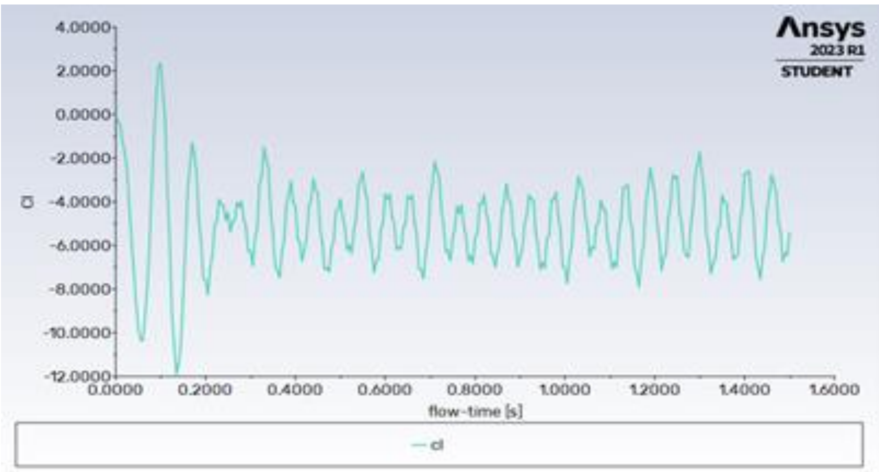

Fig. 12. C_l vs Flow time

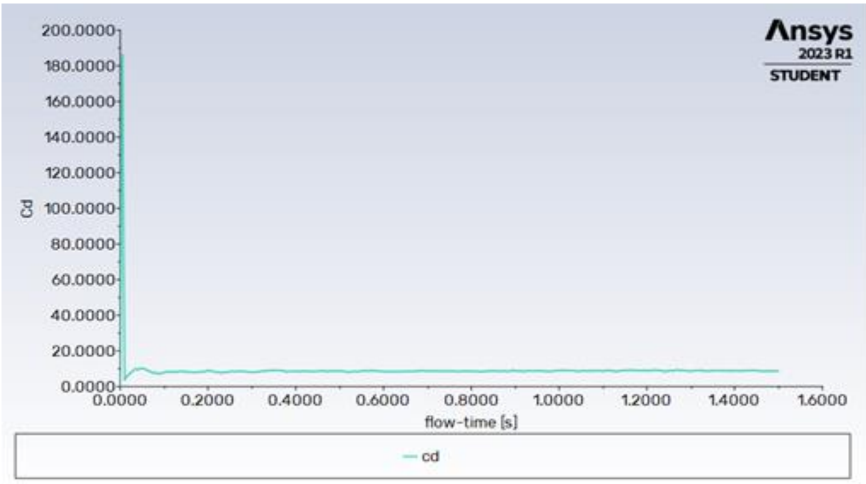

Fig. 13. C_d vs Flow time

Total Deformation – 644.09mm
C_d – 0.84 (approx.)
C_l – 0 to (-8) (approx.)
Total deformation shows the maximum movement the movable shaft can move in the direction where the force is applied.
C_l – the lift coefficient shows and gives us the movement and range of the movable shaft.

4 Advantages, Limitations and Applications

4.1 Advantages of Vortex bladeless wind turbine

1. Safer for birds and other wildlife: VBWTs do not have blades, so they are much safer for birds and other wildlife than conventional wind turbines**.**
2. VBWTs generate less noise than conventional wind turbines, making them more suitable for use in urban and other noise-sensitive areas.
3. Less expensive to manufacture and install: VBWTs are simpler to design and manufacture than conventional wind turbines, which makes them less expensive.
4. More durable and reliable: VBWTs have fewer moving parts than conventional wind turbines, which makes them more durable and reliable.
5. More efficient in low wind speeds: VBWTs are more efficient at generating electricity in low wind speeds than conventional wind turbines.

4.2 Disadvantages of vortex bladeless wind turbines:

1. Less efficient than conventional wind turbines in high wind speeds: VBWTs are less efficient at generating electricity in high wind speeds than conventional wind turbines.
2. More difficult to control: VBWTs are more difficult to control than conventional wind turbines, which can make them less suitable for use in some applications.
3. More susceptible to damage from turbulence: VBWTs are more susceptible to damage from turbulence than conventional wind turbines.
4. Still in development: VBWTs are still in their early stages of development, and more research and testing is needed to refine the technology and improve its efficiency and performance.

5. Higher upfront cost: The upfront cost of VBWTs is currently higher than the upfront cost of conventional wind turbines.

4.3 Application of vortex bladeless wind turbines:

1. **Urban and residential areas:** VBWTs are well-suited for use in urban and residential areas due to their quiet operation and low visual impact. They could be used to power street lights, traffic signals, and other public infrastructure, as well as to charge electric vehicles and provide power to homes and businesses.
2. **Offshore applications:** VBWTs are also well-suited for offshore applications, where they can be used to generate electricity from strong winds. This could help to reduce our reliance on fossil fuels and provide a more sustainable source of energy for coastal communities.
3. **Remote areas:** VBWTs can also be used to generate electricity in remote areas, where it is difficult or expensive to connect to the grid. This could help to improve energy access and quality of life for people in these communities.
4. **Agriculture:** VBWTs could be used to power irrigation systems and other agricultural equipment, helping to reduce farmers' reliance on fossil fuels and improve their efficiency.
5. **Telecommunications:** VBWTs could be used to power telecommunications towers and equipment, ensuring that people in remote areas have access to communication services.

5 Conclusion

Thus, we can conclude that by means of analysis and numerical experimentation that the location selected is suitable for electricity generation and the design of model is safe as its natural frequency is close to the vortex shedding frequency of the wind due to which there is an ample amount of electricity generated. As per calculations performed, it can be found that there’s enough lift force to oscillate the mast and also it is seen that deformation is more at the top of the mast as compared to the bottom of the mast for a calculated drag force but not high enough to cause damage to the structure.

6 Future Scope

- Scope for future work for this project can be continued by research and development in India which can lead to the optimization of VBT designs, improved efficiency, and cost-effectiveness. Collaborations between government agencies, research institutions, and private companies can further advance the technology.
- Integrating small-scale vortex bladeless turbines into urban infrastructure and green buildings can enhance their sustainability and reduce energy consumption.
- Electrification of Remote Villages: In remote villages without access to the national power grid, these turbines can provide a reliable source of electricity for lighting, communications, and small appliances.
- VBTs can be deployed both in urban and rural settings. In urban areas, they can be installed on rooftops or within cities, offering a decentralized power generation solution. In rural areas, they can provide off-grid power for communities and agricultural purposes. With the development of VBWT, the potential applications would include inclusion of solar panels on the body of VBWT for greater electricity generation or it can be mounted on a moving vehicle and the generated electricity can be used to power the batteries etc.

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