Vortex bladeless wind turbine technology An interdisciplinary and multidisciplinary approach in engineering science

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Abstract wind power is unquestionably beneficial Due to its total renewability and little greenhouse gas emissions. This study attempts to create a bladeless wind turbine made especially for cities, The methodology described in this study considers a unique wind power extraction technology known as "VBWT" that is based on the aeroelasticity phenomena known as vortex-induced vibrations (VIV), which originated in the study of flow-induced vibrations. It results from a bluff body that is subject to inertial, aerodynamic, and structural forces. Vortex Bladeless seeks to harness the induced oscillatory motion from vortex-produced vibrations to generate electricity innovatively. It's an interdisciplinary and multi-disciplinary Approach to generate electricity from wind Energy. VBWT requires less space, involves minimum maintenance, and is consequently economical. Using Ansys software, a numerical analysis was conducted to determine the forces influencing the VBWT. A Comparison between the earlier established model and the current model is performed.

1. Introduction

Wind power is unequivocally advantageous because of its negligible greenhouse gas emissions, low air pollutants, and complete renewability. Nevertheless, wind power planners or developers must be cognizant of the potential adverse impacts of wind turbines and related infrastructures, particularly on birds, bats, and other wildlife that may become disoriented by such facilities.

However, challenges still exist, and technological advancements are essential. It is crucial to address issues like variable low wind speeds, localized wind turbulence, and severe gusts to improve the reliability and efficiency of wind energy generation. Additionally, exploring unconventional wind technologies is an important area for research and development, as these innovations could offer increased power output and economic benefits while minimizing mechanical complications such as gears and bearings. In addition to technical performance, it is important to consider various other factors. These include the impact on wildlife, particularly bird migrations, the visual aesthetics of the area, issues related to electromagnetic interference (EMI) from antennas and radars, and the overall costs associated with new technologies. All these aspects are crucial for advancing wind turbine technologies and the power generation from wind. Vortex Bladeless wind turbines (VBWT) are a new wind energy harvesting technology representing a "trio" encompassing various technical disciplines, including Fluid Dynamics, Mechanics of Solids, and Electrical technical. As shown in Figure 1, the integration of Fluid Dynamics, Mechanics of Solids, and Electrical Engineering exemplifies a comprehensive methodology for the design, development, and execution of bladeless wind turbines [1]. It emphasizes the interdisciplinary character of engineering solutions designed to exploit wind energy in creative and sustainable manners. Moreover, it could be defined in other more accurate words that VBWT is a multi-disciplinary approach in the field of renewable energy engineering where Fluid mechanics, vibrational motion, fluid-solid interaction (FSI), natural science, computational fluid dynamics(CFD), harmonic response (FEA), material science, environmental impact, renewable energy generation, sustainability, urban installments, and eco-friendly science are all included in the multidisciplinary approach known as VBWT as shown in Figure 2

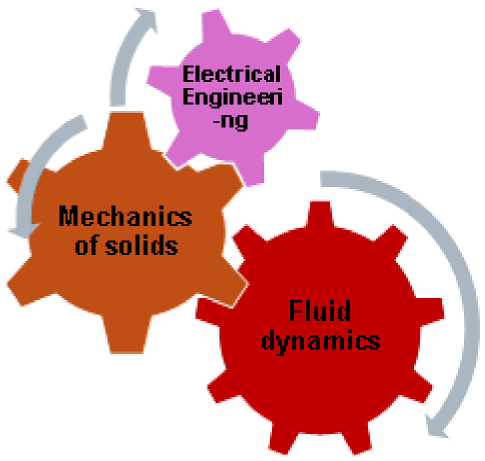


Figure 1. Interdisciplinary VBWT Approach.

Figure 2. Multi-disciplinary VBWT Approach

2. Vortex Bladeless Wind Turbine

The comprehensive strategy proposed in this study, which considers technological improvements and their wider implications, is essential for effectively incorporating renewable energy into our energy systems. Reconciling the demand for cleaner energy with environmental and social factors requires cooperation among researchers, engineers, policymakers, and communities. Ongoing study, innovation, and careful examination of the wider implications of renewable energy technology will be crucial in addressing obstacles and facilitating a successful transition to a sustainable, low-carbon energy future. The deliberate utilization of vortices for energy generation in bladeless turbines is intriguing. The device aims to harness and transform the energy generated by vortex-induced vibrations into useful electricity [2].

Bladeless turbines offer an alternative to conventional wind turbines including rotating blades. This new approach depends on the following parameters:

- Vortex-Induced Vibrations (VIV)
- Structure and Design
- Vortex Shedding
- Energy harvesting

The harmonic -oscillatory- motion of the bladeless turbine is then transformed into electrical energy via technologies such as generators or piezoelectric materials. The conversion technique is optimized for effectively harnessing energy from vortex-induced vibration. It is exhilarating to observe the continuous investigation of innovative methods such as bladeless wind turbines (BWT) in the quest for more efficient and eco-friendly wind energy alternatives. Ongoing progress in this domain may enhance the variety and optimization of renewable energy technologies, thus facilitating the shift toward a more sustainable energy framework.

3. Flow-induced vibrations

Vibrations produced by fluid flow emphasize a prevalent methodology in fluid mechanics wherein fluid and solid dynamics are frequently analyzed separately. In numerous applications, the existence of solids is accounted for by boundary conditions applied to the fluid flow. This method streamlines the analysis and facilitates the examination of fluid dynamics surrounding solid structures. In solid mechanics, fluids are frequently seen as loads exerted on solid surfaces. This method streamlines the analysis by considering the fluid as an external force that affects the deformation or movement of the solid structure. As shown in Figure 3, Fluid-structure interaction (FSI) denotes the reciprocal influence between a fluid and a structure during their interaction. In scenarios where fluid and solid dynamics are intricately interconnected, such as in the design and analysis of Vortex Bladeless Wind Turbines, it is essential to solve the fluid and solid equations concurrently [3].

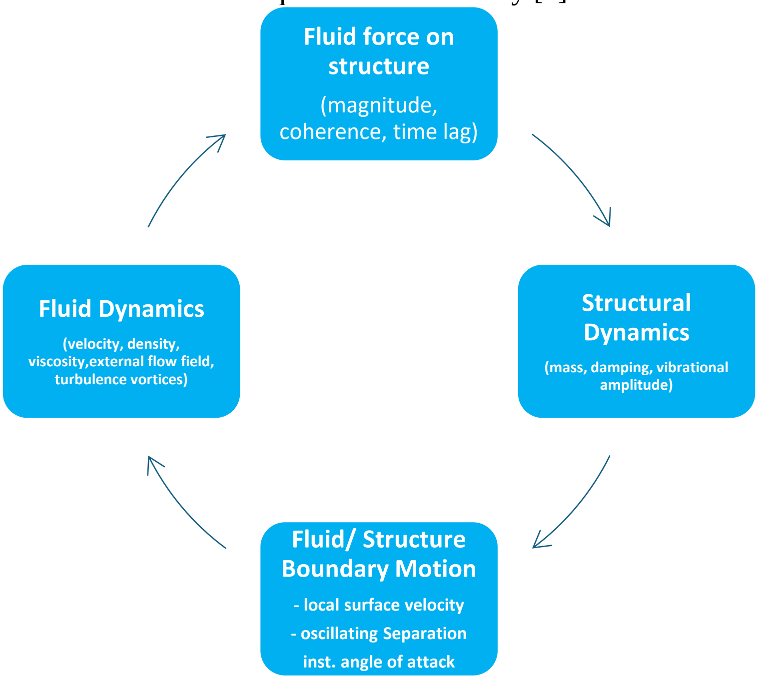


Figure 3. Fluid-structure interaction mechanism [3]

Flow-induced vibrations (FIV) are a broad category of fluid-structure interactions (FSI) when an elastic or elastically mounted structure experiences oscillatory motion due to fluid flow. Designing and optimizing structures subjected to fluid dynamics, such as Vortex Bladeless Wind Turbines, requires an understanding of the various FIV categories. According to [3], FIV includes other forms of vibrations as shown in Figure 5, one of them is vortex-induced vibrations VIV which is an aero-elastic motion caused by the shedding of a vortex from a bluff body. Blevins' illustration provides a detailed explanation of how the interaction of fluid flows with a bluff body, such as a cylinder, causes the creation of a vortex street and creates vibrations in the structure. Karman [4] states the importance of the Karman vortex street core concept, which was the first to propose the concept of wake production behind the bluff body as shown in Figure 4. In fluid dynamics, vortex shedding and vortex-induced vibrations (VIV) are phenomena that can cause oscillatory motion, especially when air flows around a body. In VIV, there are two crucial elements. First, the frequency of vortex shedding shows how quickly a bluff body sheds vortices when a fluid, such as water or air, passes by it. Second, the formation and behavior of the vortex wake [4].

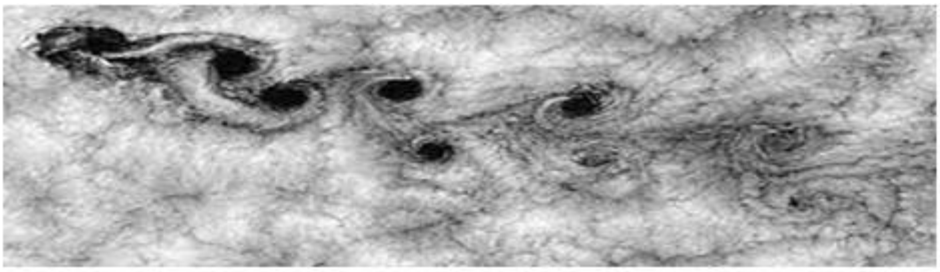


Figure 4. von - Karman vortex street [4].

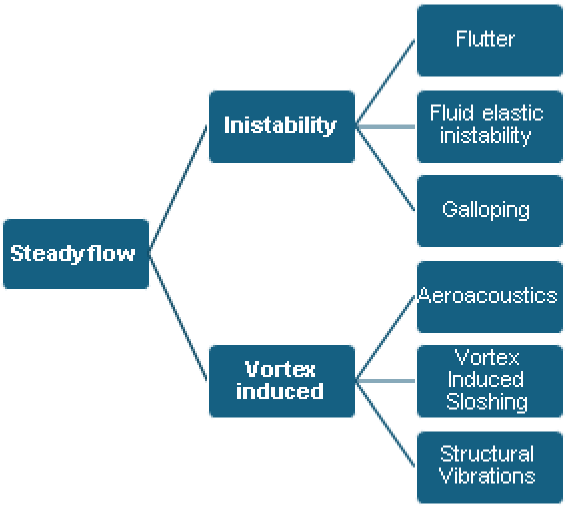


Figure 5. Steady flow-induced vibrations classification [3]

The relationship between wake width and shedding frequency, known as the Universal Strouhal number (St), was established by (Rayleigh 1894). This dimensionless parameter correlates the characteristic flow velocity and wakes width to the frequency of vortex shedding behind a bluff body. In fluid dynamics, the Strouhal number is commonly used to describe the oscillatory behavior of objects in a fluid flow, particularly when vortex shedding is present [5]. The Universal Strouhal number is valuable in predicting vortex shedding frequencies for different body configurations, making it a useful tool in fluid dynamics and aerodynamics. This understanding is applied in various fields, including the design of structures, vehicles, and other systems exposed to fluid flows. The constant value of 0.2 suggests that there is a commonality in the physics of vortex shedding across different geometries, making it a universal relationship for a wide range of bluff bodies [5]. Another dimensionless number is The Reynolds number which has a major impact on the behavior of free shear layers. Shear layers are more laminar and stable at low Reynolds numbers. It becomes increasingly unstable and turns turbulent as the Reynolds number rises, which impacts the formation of vortices and shedding [6]. Numerous experimental and computational analyses have been conducted to provide profound insights into the characteristics of flow as influenced by variations in both Reynolds and Strouhal numbers is shown in Table 1 [7].

Table 1: Reynolds and Strouhal number on circular cylinder [7]

Reynolds number regime	Flow regime	Flow form	Flow characteristic	Strouhal number (St)	Drag coefficient (C_D)	Separation angle (Θ_s)
Re →0	Creeping flow		Steady, no wake	-	60	-
3-4 < Re < 30-40	Vortex pairs in wake		Steady, symmetric separation	-	1.5 < C_D < 4.52	130° < Θ_s < 180°
30-4 < Re < 80-90	Onset of karman street		Laminar, unstable wake	-	1.17 < C_D < 1.59	115° < Θ_s < 130°
80-90 < Re < 150-300	Pure karman street		Karman street	0.14 < St < 0.21	-	-
150-300 < Re < 1-1.3×10^5	Sub-critical regime		Laminar, with Vortex instability	St = 0.21	C_D = 1.2	Θ_s = 80°
1-1.3×10^5 < Re < 3.5×10^6	Critical regime		Laminar separation, Turbulent reattachment Turbulent separation Turbulent wake	No preferred frequency	0.2 < C_D < 1.2	80° < Θ_s < 140°

4. Vortex bladeless wind turbine (VBWT) components

It is possible to categorize the components of a vortex-bladeless wind turbine into two groups: the moving parts and the stationary elements. The moving part includes the mast and the elastic rod turbine that oscillates due to the vortex shedding phenomenon when subjected to wind exposure. The Elastic rod in bladeless turbines eliminates the necessity for conventional moving components like bearings, thereby diminishing friction, wear, and maintenance demands. The rod's elasticity facilitates the amplification of oscillations and synchronizes the wind speed with the system's natural frequency, resulting in the attainment of lock-in phase generation [8]. The fixed components offer support, stability, and enclosure for the turbine's operational elements [2]. The stator and the base structure (Static cylinder, Base, and Upper flange) are the stationary elements of the vortex-bladeless wind turbine. The base structure functions as the foundational element to securely anchor the turbine, hence assuring operational stability. designed to manage vibrations and dynamic loads while reducing environmental impact, the stator acts as Protective Housing that Encases sensitive components, including the energy conversion system -Magnet or piezo sensor-, to safeguard them from external hazards such as humidity, particulate matter, and severe temperatures or any environmental impacts as shown in Figure 6. Energy harvesting through Vortex-Induced Vibration (VIV) can be accomplished using electromagnetic devices, piezoelectric materials, or electrostatic devices. Two ways are primarily preferred: the use of a linear alternator and/or the application of piezoelectric materials.

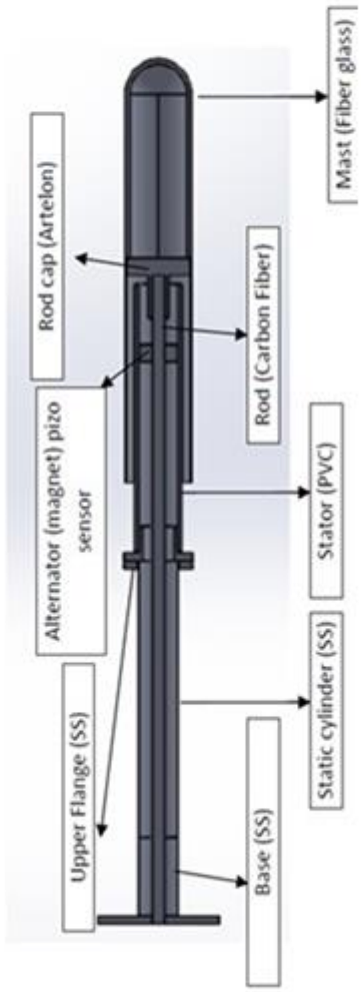


Figure 6. VBWT model parts.

Table 2: Comparison between Piezoelectric Material Sensor and Linear Alternator [9].

Feature	Piezoelectric Material Sensor	Linear Alternator
Energy Conversion	Mechanical stress to electrical charge	Mechanical motion to AC
Power Output	Low	High
Size	Compact and lightweight	Larger and bulkier
Durability	No moving parts, highly durable	Moving parts, subject to wear
Applications	Sensors, small-scale energy harvesting	Larger power systems, turbines
Cost	Generally lower	Higher due to complexity

To produce energy using these two applications, a cylindrical mast is (oscillator) considered a bluff body capable of oscillation. In any configuration, the body generates vibrations by the movement of air or water, depending on its orientation. The transverse displacement of the body closely resembles the sinusoidal waveform over time [9]. A coil and a magnet are utilized to generate energy with a linear alternator. As the bluff body oscillates, the magnet shifts to the coil, thereby inducing an electromagnetic field and producing an electrical current following Faraday’s law of electromagnetic induction [10].

5. Material Utilized for Vortex Bladeless Wind Turbine Components Fabrication

Selecting appropriate materials for a vortex-bladeless wind turbine is essential for ensuring durability, efficiency, and cost-effectiveness. The selection is dependent upon variables like the surrounding environment, load specifications, and the desired application (e.g., urban or rural deployment). Below is a clarification of material considerations for essential components.

The vortex bladeless mast mainly required material is fiberglass, which oscillates in the wind to utilize the vortex shedding effect. Fiberglass is recognized as a material with significant advantages over traditional alternatives, including wood, steel, and aluminum. This material possesses greater strength than sheet metal and is resistant to corrosion, making it ideal for outdoor applications or environments near water, particularly saltwater [11]. The primary advantage of fiberglass is its lower energy intensity during production, and it is widely utilized for products that reduce carbon emissions compared to materials previously employed in conventional wind turbines [12]. A carbon fiber rod at the base of the mast operates within a linear alternator that produces electricity without any touch between moving elements. Carbon fiber, or Graphite Fiber, consists of elongated strands of carbon fibers intricately woven to create a fabric-like structure. The characteristics of a carbon fiber component are comparable to those of steel, while its weight is like those of plastic. Consequently, the strength-to-weight ratio, as well as the stiffness-to-weight ratio, of a carbon fiber component significantly exceeds that of both steel and plastic. Carbon fiber possesses exceptional strength [13]. Rod cap is made of Artelón material that is favored for its affordability, lightweight nature, superior mechanical damping capacity and commendable machinability. Base structure includes a static cylinder, with the base and upper flange constructed from stainless steel material. Stainless steel possesses a range of exceptional characteristics, including attractive appearance, robust corrosion resistance, excellent impact toughness, low maintenance requirements, and high overall cost-effectiveness [14]. The stator is made from (PVC) material, PVC (polyvinyl chloride) coated polyester material is among the most prevalent materials utilized. Its popularity is mostly attributed to its advantageous pricing, excellent toughness, diverse color options, and soft texture. Moreover, it may be effortlessly folded and unfurled while exhibiting a high tolerance for cutting errors [15]. Material selection summary is shown in Table 3

Table 3. Material Selection Summary

Component	Material Options
Mast (Oscillator)	Fiber glass
Elastic Rod	Carbon fiber
Base Structure	stainless steel
Energy Conversion	Electromagnetic device
Protective Housing	PVC

6. The Lotus Effect in Materials and Its Relevance to Vortex Bladeless Wind Turbines (VBWT)

The lotus effect, derived from the surface characteristics of lotus leaves, denotes a material's capacity to reject water and self-clean, attributed to its distinctive micro- and nano-structured surface along with low surface energy, Repelling water droplets is essential for urban projects because water damage to infrastructures can result in costly insurance claims and uninsured losses for the public and private sectors [16]. This phenomenon has substantial ramifications across multiple domains, including wind turbine design, where material performance under environmental exposure is essential. In the context of vortex bladeless wind turbines, the lotus effect can boost performance and durability, The lotus effect can improve the performance efficiency and durability of vortex bladeless wind turbines [17]. Hydrophobic Mast Coating Objective to prevent water accumulation and ice development on the mast surface, particularly in regions with high humidity or precipitation, preserves aerodynamic performance by inhibiting surface irregularities caused by water or ice buildup Prolongs lifespan by reducing corrosion and material fatigue [18].

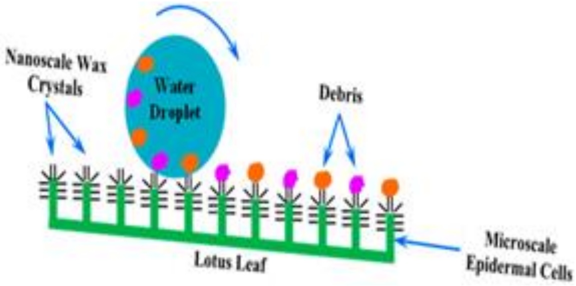


Figure 7. A simple schematic for understanding of the lotus effect. The water droplet collects the debris as it descends from the leaf. [18]

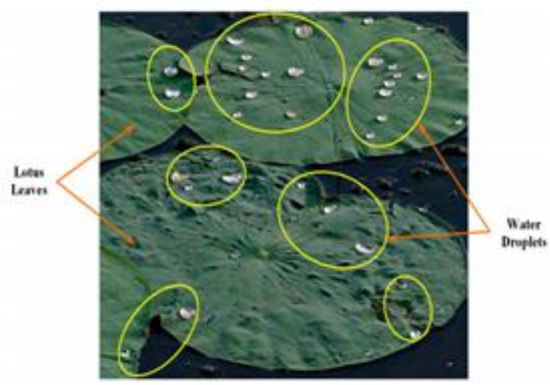


Figure 8. Lotus leaves with "lotus effect" The water droplets do not contract and remain buoyant with a spherical structure [18]

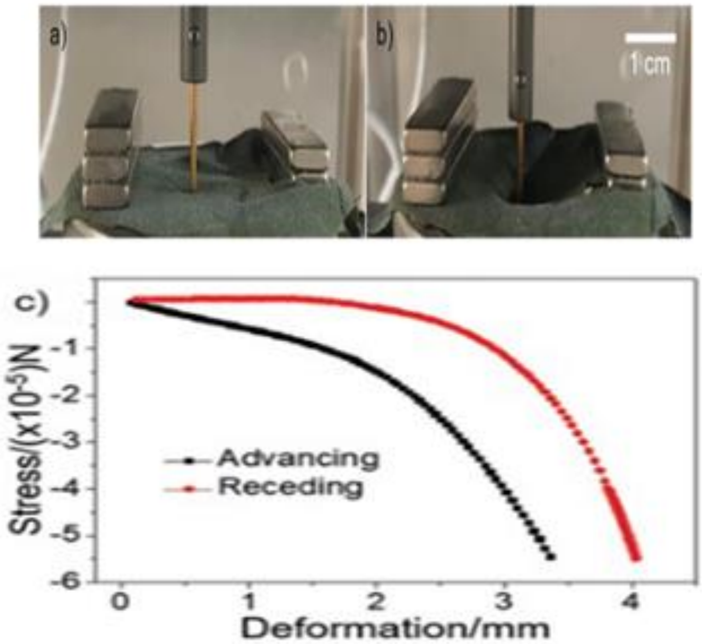


Figure 9. The mechanical test of natural lotus leaf [19]

Figure 9 shows the mechanical test of natural lotus leaf performed by [19]. a, b) Lotus leaf mechanical testing procedure where the 4 × 4 cm lotus leaf is set up on the test platform. c) The advancing and receding process of steel cylinder on the leaf surface. The lotus leaf withstands the load without breaking throughout this operation. It can deform by 4.1 mm and return to its initial state (5.6 × 10^{-5} N) when the load is removed. This gives a good indication that it Prolongs lifespan of Mast Coated Hydrophobically reducing corrosion and fatigue, increasing the sustainability of the vortex induced bladeless wind turbine. This aspect needs to be considered in upcoming research.

7. Modeling simulation

A computational model of a bladeless wind turbine is established in the current study. The results obtained from the modeling process are then compared with the results obtained by the study performed by Elsayed and Farghaly et al 2022[20] that involved a VBWT with a diameter of 9 cm and a length of 1 m, subjected to flow velocities of 5 m/s. Using the commercial CFD software ANSYS FLUENT, two-dimensional transient numerical simulations were conducted to forecast the dynamic loads—specifically, drag and lift forces—imposed on the VBWT and resolve the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations turbulence model to examine the airflow dynamics and vortex-induced oscillations of the bladeless turbine. The main CAD program utilized to ascertain the model's physical properties was SolidWorks. Simulations is Done by ANSYS 2023 R2 version. After determining the aerodynamic loads, a Harmonic Study was carried out to assess the energy and power generated by the harmonic motion induced in the cylindrical turbine. The generated power was then simulated for conversion into electrical energy using piezoelectric materials alternator as shown in Figure 10. The current model, designed for test purposes, closely resembles the model developed by the [2].

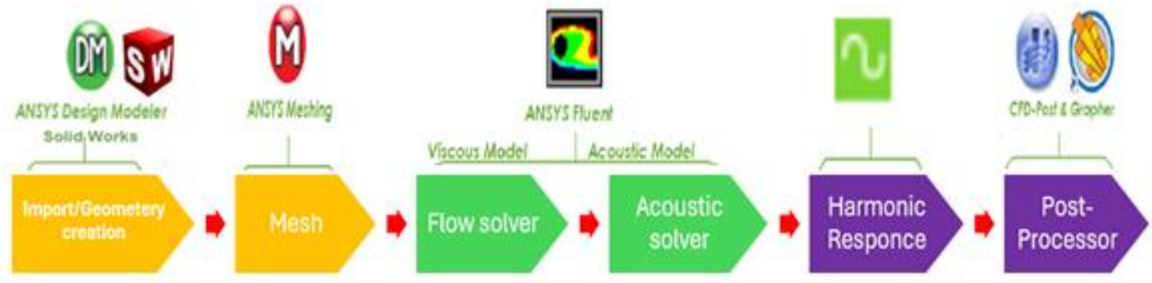


Figure 10. A flowchart outlining the computational steps in the current study

The vortex bladeless turbine design was developed in SolidWorks; this software provided the necessary flexibility and options to model complex geometries efficiently. From the initial CAD design to the final manufactured model, SolidWorks was integral in the development process. utilizing its wide range of tools for creating complex geometries as the central mast and oscillating structure are the key features of the design. The assembly process ensures proper alignment and interconnection of all components, forming the basis for the subsequent computational analysis.

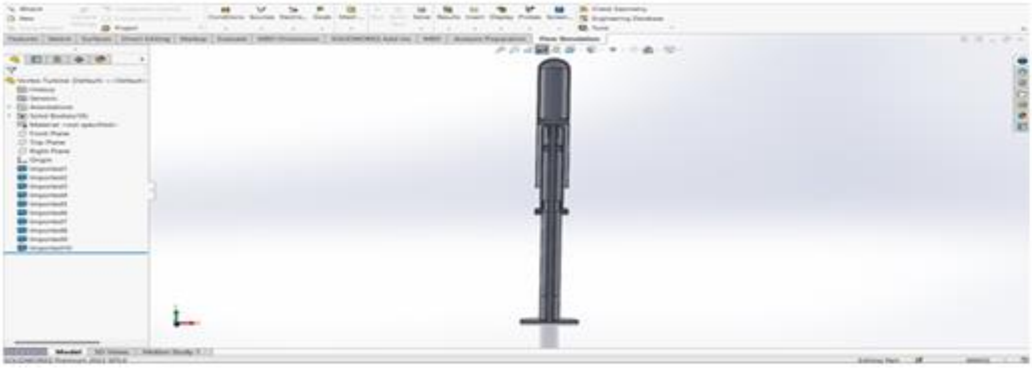


Figure 11. SolidWorks Design

The meshing process involves the use of hybrid triangular and quadrilateral elements to accurately capture complex flow dynamics around the turbine. A mesh sensitivity study ensures that the results converge with minimal error. A target y+ value of 1.8 is applied to ensure proper resolution of the boundary layer near the turbine structure. The k-omega SST turbulence model was employed to capture both the turbulent flow structures and the interaction of vortices with the turbine. The SST k-ω model was employed in this study due to its superior performance in free shear flows, adverse pressure gradients, and separated flows, as well as its prevalent application in flow simulations around wind turbines [21]. The CFD analysis was conducted under the following boundary conditions to evaluate the fluid-structure interaction with the bladeless turbine where Inlet Wind Speed is 10 m/s, Pressure outlet boundary conditions were set to simulate realistic outflow. No-slip conditions were applied on the turbine surfaces to capture realistic interactions between the fluid and the turbine's surface. To simulate the turbine's response to oscillatory wind forces, a harmonic response simulation was performed. Harmonic forces were applied based on the wind force frequency and vortex shedding frequency obtained from the CFD analysis. These oscillatory forces varied sinusoidally over time, simulating how the turbine would respond to continuous oscillations. The damping ratio of 0.05 was applied to account for energy loss due to internal material damping and air resistance, harmonic response was analyzed over a frequency range covering the natural frequency from 12 Hz and extended up to 50 Hz to capture any resonance effects. The harmonic forces were applied to the upper section of the turbine as shown in Figure 12 where the vortex shedding effects are most significant. This section undergoes the highest oscillatory motion due to aerodynamic forces. The oscillation frequency due to vortex shedding is key to evaluating the power output of the turbine. The results of the Comparison between the current study model and the model established by [20] are shown in Table 4.

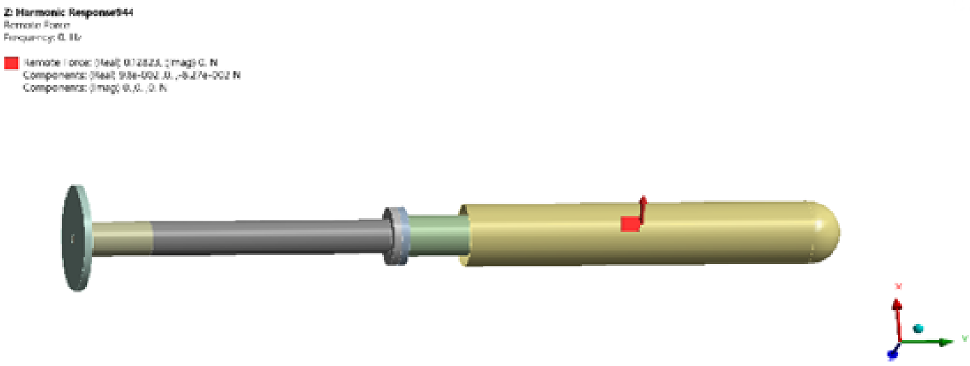
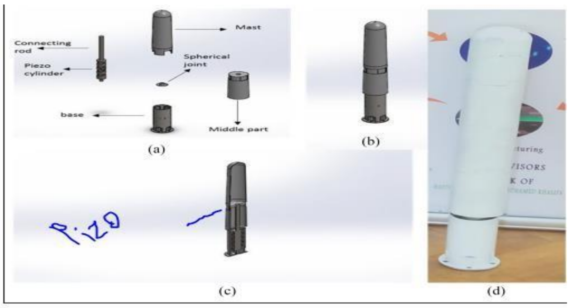
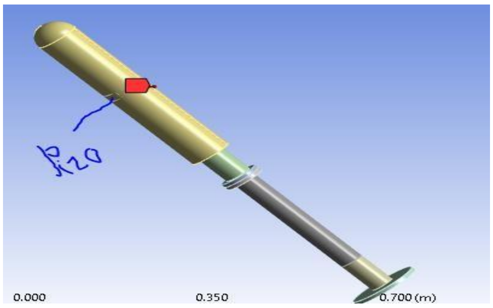


Figure12. Boundary setup for Harmonic Response Simulation

Table 4. Comparison between [20] model and current model outputs

[20] Model	Current Model
Cylinder diameter 0.09 m	Cylinder diameter 0.09 m
Turbine Length 1 m	Turbine Length 1 m
Mast length 800 mm	Mast length 446 mm
Turbine mass 7.63 kg Velocity = 5 m/s	Turbine mass 4.8 kg Velocity = 10 m/s
Drag Coeff =1	Drag Coeff =0.684
Max. Drag force = 1.38 N	Max. Drag force = 0.125 N
Max. Lift force = 0.482 N	Max. Lift force = 0.626 N
Shedding freq. 69.81 Hz	Shedding freq. 29.45 Hz
Max. power =1.5e-3 watt	Max. power = 8.7e-5 watt





8. Environmental Impact, Urban installation Art and Economical Impact

In the context of achieving a sustainable and ecologically conscious future, innovation and development of renewable energy technologies are essential. This project focuses on creating a bladeless wind turbine for cities to meet the urgent demand for clean energy both domestically and globally. In recent decades, traditional wind turbines have been increasingly popular, but Vortex bladeless wind turbines have also shown their benefits and distinctiveness in urban settings. To maximize wind energy output in urban environments with limited space and a landscape dominated by buildings, a Vortex Bladeless Wind Turbine (VBWT) is developed. Regarding a lack of accessible space and the growing number of high-rise structures, urban wind energy offers an affordable choice [22]. Because of the compact size and low noise levels of VBWTs, it has been integrated into urban areas and has demonstrated their appropriateness for decentralized energy generation [23]. Low wind speeds in metropolitan regions and fluctuating urban wind conditions make traditional wind turbines useless. In contrast to traditional wind turbines (HAWT and VAWT), VBWT can alternatively be categorized as small urban wind turbines (SUWT), which ensures minimal environmental impact and hence promotes societal acceptance [12].

Table 5. Comparison between bladeless wind turbines and blade wind turbines [24]

Feature	Bladeless wind turbine	Blades wind turbines
Blades	Not needed	Needed
Wind velocity	It operates low wind Velocity	It operates at high wind Velocity
Noise	Don't make noise	Make noise
Maintenance cost	Low cost	High cost
Movable rotating parts	It does not contain rotating parts	Rotating parts contain
Payoff	Relatively low payoff	Higher payoff
Size	Compact size	Large size
Its impact on wildlife	It does not affect wildlife Affect wildlife	Affect wildlife

9. Conclusion

The investigation of novel methods such as bladeless wind turbines enhances the variety of renewable energy options, aiding in the fulfillment of the increasing global demand for clean and sustainable energy. Vortex Bladeless wind turbines possess a minimal carbon footprint, operate silently, and feature a low center of gravity that facilitates compactness. VBWT's multidisciplinary and interdisciplinary approach in engineering science in the context of wind energy reflects a philosophical view. This approach introduces engineering as a cognitive science that functions well for both humans and nature, foreshadows the harmony and alternatives that science can produce, giving engineers a fresh perspective on how to interact with Nature toward engineering-friendly science and sustainability. VBWT is a promising technology for harvesting wind energy in urban cities. The comparison performed in this study highlights the importance of investigation about some design parameters such as mast length and diameter, mast shape and other design parameters and optimize the VBWT design for optimum power outputs.

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