A state-of-the-art Review on vortex induced vibrations phenomenonBladeless Wind Turbine Technology

ABSTRACT

Vortex bladeless wind turbine (VBWT) is a new wind power extraction technology that is dependent on the Aero-elasticity phenomenon that is calledvortex induced vibrations – VIV – which is derived from the study of flow induced vibrations, it is the phenomenon that arises from the interaction of inertial, structural and aerodynamic forces over a bluff body.it has been found that when Air – ideal gas - flows around a body an induced oscillatory motion can be established by vortex shedding. By leveraging the induced oscillatory motion resulting from VIV, Vortex Bladeless aims to generate power in a novel way. The absence of traditional blades sets this technology apart from conventional wind turbinesand introduces different dynamics in the extraction of wind energy.VBWT devices are particularly advantageous in low to moderate wind situations, where traditional turbines may prove inefficient or unfeasible. Moreover, their reduced noise levels and compact size render them suitable for urban or ecologically sensitive regions.The selection of this new technology to be investigated and studied will play an important role in wind energy field of study opening a new chapter in the development of this kind of renewable energy, leading to generate power with a lesser cost than that produced by the conventional wind turbines by 40 %.Nonetheless, the efficacy of VBWT may be constrained in high-wind conditions where conventional turbines thrive, and their performance is significantly influenced by certain design and resonance attributes.

KEYWORDS:VBWT, VIV, Straul number, bluff body, vortex shedding, CFD.

1. INTRODUCTION

The acknowledgment of the significance of unconventional renewable energy sources has markedly increased in recent years. Wind energy is a sustainable and renewable resource that plays a crucial role in addressing global emissions reduction requirements and enhancing global energy consumption. In 2014, China attained the highest installed capacity of wind power, but Denmark excelled in per capita wind energy production. [1].Its environmentally sustainable characteristics, capacity for job development, and beneficial ecological effects render it an essential element of national initiatives for attaining energy sustainability. The current advancements in the industry, such as bladeless wind turbines (BWT), signify a substantial progression. This technology presents various potential advantages, including low wind speed performance, simplicity and ease of maintenance, reduced visual impact, diminished noise pollution, and independence from wind direction. Data training concluded in October 2023[1].The research presented here examines the current state of wind technology, evaluates the role of wind electric generation actuators, and explores the development of a multi-energy wind power framework and an innovative bladeless turbine design.

2. REVIEW ON VORTEX INDUCED VIBRATIONS PHENOMENON AND VBWT

Wind energy conversion has gained popularity and competitiveness in recent years. Wind turbines can be categorized into two types based on their structural characteristics: conventional wind turbines and bladeless wind turbines. Conventional wind turbines are designed using circular methodologies, such as horizontal axis wind turbines (HAWT). The generators are frequently linked directly to the drive shaft. Nevertheless, the efficacy of conventional wind turbines is diminished when wind energy is transformed into electrical energy via gearboxes and various transmissions, like to a vehicle.

Betz's law delineates the properties of rotating airfoil wind turbines. The power output of a wind turbine reaches its optimum when the wind velocity is reduced to one-third of its original speed. Consequently, the theoretical efficiency is 59% of the wind energy that may be harnessed, but the actual efficiency ranges from 20% to 40%, with an average value of approximately 35% of the generated power being turned into electrical energy[2]. Besides, the running cost is also high due to the wear of the gears. Such a small problem can cause the whole mechanical failure. Traditional wind turbines suffer a lot from mechanical wear, fatigue, and other problems. Conversely, considerable attention has been directed into bladeless wind turbines due to its notably simplified mechanical design, which lacks moving blades on the drive shaft or exhibits a comparatively reduced rotational force on the drive shaft [31-33].Vortex-induced vibrations have been regarded as the pluming phenomenon of classical resonance caused by the flow across bluff bodies with a sharp edge, such as columns, cylinders, and spheres [3].The vortex-induced vibrations electric generator enhances the flow speed to increase the energy of the flow and lengthens the vortex street.

2.1 BLADELESS WIND TURBINE (BWT)

The exploration of innovative approaches like bladeless wind turbines contributes to the diversity of renewable energy solutions, helping to meet the growing demand for clean and sustainable energy worldwide.bladeless wind turbines (BWT) being a "trio" involving diverse engineering branches which include Fluid Dynamics, Mechanics of Solids, and Electrical Engineering [4]. The collaboration of these three engineering branches - Fluid Dynamics, Mechanics of Solids, and Electrical Engineering - represents a holistic approach to the design, analysis, and implementation of bladeless wind turbines.It underscores the multidisciplinary nature of engineering solutions that aim to harness wind energy in innovative and sustainable ways.Additionally, their performance may vary depending on specific environmental conditions. This new approach depends on the Vortex-Induced Vibrations (VIV) and Structure and Design parameters.

2.2 Vortex-Induced Vibrations (VIV)

Vortex bladeless wind turbine (VBWT) is a wind power extraction technology that is dependent on the Aero-elasticity phenomenon, [5] specifically vortex-induced vibrations (VIV). The Aero-elasticity of structures, in the context of wind energy, refers to the interaction of aerodynamic forces with the elastic properties of the structure itself. Aero-elasticity refers to the coupling between aerodynamic forces and the elastic response of a structure. In the case of wind turbines, this involves the interaction between the wind flow and the mechanical structure of the turbine. [1]

Vortex-Induced Vibrations (VIV) are a specific type of oscillatory motion induced by the shedding of vortices in the wake of a bluff body (such as the Vortex Bladeless wind turbine).Blevins (2001) states that VIV is a type of aero elastic motion induced by the vortex shedding from a bluff body. The passage by Blevins offers a comprehensive explanation of how the interaction between fluid flow and a bluff body, such as a cylinder, leads to the formation of a vortex street and induces vibrations in the structure. The following words by Blevins provide a clear description “as a fluid particle flows toward the leading edge of a cylinder, the pressure in the fluid particle rises from the free stream pressure to the stagnation pressure. The high fluid pressure near the leading edge impels flow about the cylinder as boundary layers develop about both sides. However, the high pressure is not sufficient to force the flow about the back of the cylinder at high Reynolds numbers[6]. At the broadest part of the cylinder, the boundary layers detach from each side of the cylinder surface, creating two shear layers that extend downstream in the flow and delineate the wake. Since the innermost portion of the shear layers, which is in contact with the cylinder, moves much more slowly than the outermost portion of the shear layers, which is in contact with the free flow, the shear layers roll into the near wake, where they fold on each other and coalesce into discrete swirling vortices. A regular pattern of vortices, called a vortex street, trails aft in the wake” [7].

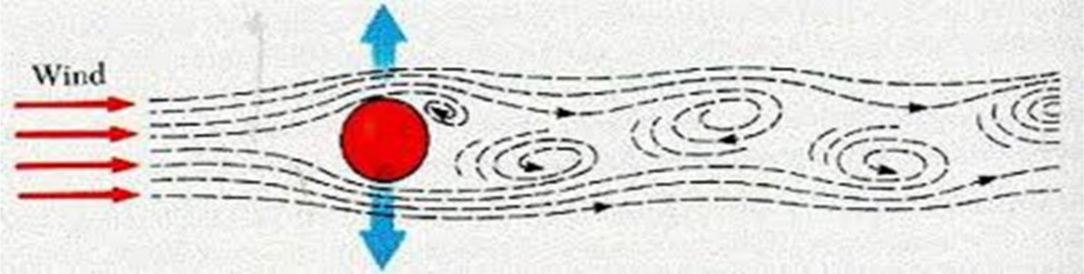


Figure1:Vortex Induced VibrationAlnounou et al. 2023[1]

Karman (1911) Highlighting the significance of Karman vortex street fundamental concept who was first to come up with the idea of wake formation behind the bluff body. The phenomenon of vortex shedding and vortex-induced vibrations (VIV) in the context of fluid dynamics is particularly when air flows around a body it can induce oscillatory motion. There are two important factors in VIV[7]. The formation and behavior of the vortex wake are equally important in VIV. The wake refers to the region of disturbed flow downstream of a bluff body, where vortices are shed. The characteristics of the wake, including its size, shape, and stability, play a significant role in determining the nature of vortex-induced vibrations. Researchers and engineers often study the vortex wake to gain insights into the dynamics of VIV. The vortex shedding frequency is a critical factor in VIV. It represents the rate at which vortices are shed from a bluff body as a fluid (such as air or water) flows past it. This frequency is influenced by the body's shape, fluid velocity, and other parameters. That why Understanding and controlling the vortex shedding frequency is crucial in analyzing and predicting VIV.[7] Bearman (1984) defined a bluff body as an object or shape which when placed in a fluid stream (such as air or water) generates separated flow over a substantial proportion of its surface. [8] Gerrard (1966) explains the mechanics of vortex formation in the wake of a bluff body, often characterized by the formation of a vortex street, can be explained through the concept of free shear layers and their mutual interaction. [9]

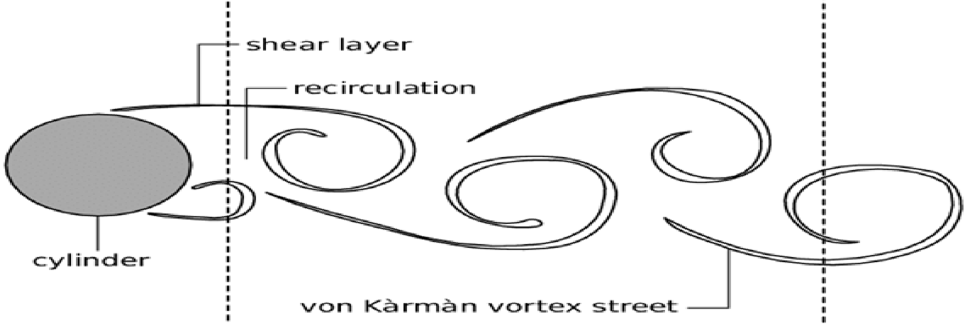


Figure 2: Configuration of the cylinder wakeGerrard (1966) [9]

A shear layer is a region in a fluid flow where there is a significant velocity gradient across the layer. In the context of a bluff body, a free shear layer is formed as the fluid flows past the body, and the boundary layer separates from the surface as shown in figure 2. This separation creates a layer of fluid with differing velocities on either side of the shear layer.[9]The reciprocal interaction between two free shear layers is a crucial element in the development of a vortex street. The separated flow areas (shear layers) adjacent to the bluff body fluctuate or interact with one another as they progress downstream.This interaction leads to the shedding of vortices alternately from each side, creating the characteristic pattern known as a vortex street.Theodore von Kármán's work on vortex shedding and the formation of the vortex street is foundational in fluid dynamics. The regular pattern of vortices in the wake of a bluff body is often referred to as a Von Kármán vortex street [7].

The alternating shedding of vortices forms a Karman vortex street. These vortices are shed in a regular and rhythmic pattern, creating a wake behind the bluff body. The shedding frequency is influenced by various factors, including the fluid velocity, the body's shape, and the properties of the fluid[7].

Figure3:von - Karman vortex street (Von Kármán 1911)[7]

Gerrard (1966) postulates three conditions for the fluid particles of opposite shear layer drawn across the wake as shown in Figure 4: a) they can be entrained into the growing vortex thus reducing its strength, b) they can find their way into the shear layer with vorticity of opposite sign to theirs, and c) they can be fed back into the near-wake region. The quantity of fluid that follows these routes across the wake does indeed play a crucial role in determining the shedding frequency; strength of vortices shed, and base pressure. [9] The shedding frequency is governed by the rate at which vortices are formed and shed in the wake. The more fluid that is drawn across the wake, the higher the shedding frequency tends to be. A greater volume of fluid results in more interactions and vorticity production, leading to an elevated shedding frequency[9]. The quantity of fluid that follows these routes influences the strength of the vortices shed. As more fluids participate in the mixing and shearing processes, the resulting vortices tend to be stronger. This is due to the greater magnitude of velocity differences and vorticity generated by a larger amount of fluid flow [9].**As wellthe**volume of fluidand its associated flow properties affect the base pressure. The mixing and vorticity in the shear layer impact the pressure distribution at the base of an object. When more fluid is involved in the fluid routes across the wake, it alters the pressure distribution and can influence the base pressure.[6]

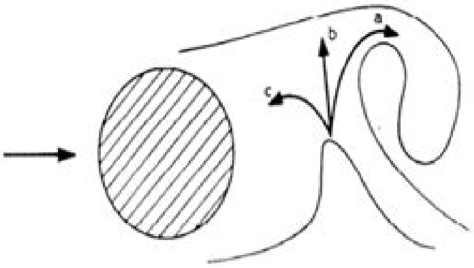


Figure 4: Vortex formation model by (Gerard 1966)[9]

Rayleigh (1869) defined the relation between the shedding frequency and wake width, known as The Universal Strouhal number (St). It is a dimensionless quantity that relates the shedding frequency of vortices behind a bluff body to the characteristic flow speed and the width of the wake. The Strouhal number is often used in fluid dynamics to describe the oscillatory behavior of bodies in a fluid stream, particularly in the context of vortex shedding [10].

The Strouhal number (St) is defined by the formula:

$$St=\frac{f\cdot D}{U} \quad (1)$$

where:

f is the shedding frequency of vortices,

D is the characteristic dimension (often the diameter of the bluff body), U is the characteristic flow speed.

The Universal Strouhal number ($St_{\text{universal}}$) is a specific case where, after extensive studies on various bluff bodies and flow conditions, researchers observed that the Strouhal number tends to have a relatively constant value of approximately 0.2 for a broad range of configurations.[10]

Milne-Thompson (1996) mentioned that Reynolds is crucial in predicting and analyzing fluid flow behaviors, especially around continuous surfaces where flow separation occurs and has no fixed points.The behavior of free shear layers is significantly influenced by the Reynolds number. At low Reynolds numbers, shear layers are more stable and laminar. As the Reynolds number increases, shear layers become more unstable and transition to turbulent, affecting vortex formation and shedding.[11]On the behalf of Understanding vortex shedding influence on different flow regimes - from creeping flow to turbulent flow - Roshko's (1954) work likely contributed valuable insights into the understanding of vortex shedding behaviors, especially in the low Reynolds number range. Roshko’s curve shows the variation of Strouhal number at low Reynolds numbers, it is significant in understanding the behavior of vortex shedding behind bluff bodies in fluid flows. These findings are important for predicting and analyzing flow patterns, optimizing designs of structures exposed to fluid flows, and improving the efficiency of devices that harness energy from vortex shedding, such as vortex bladeless wind turbines **(VBWT)** [12].

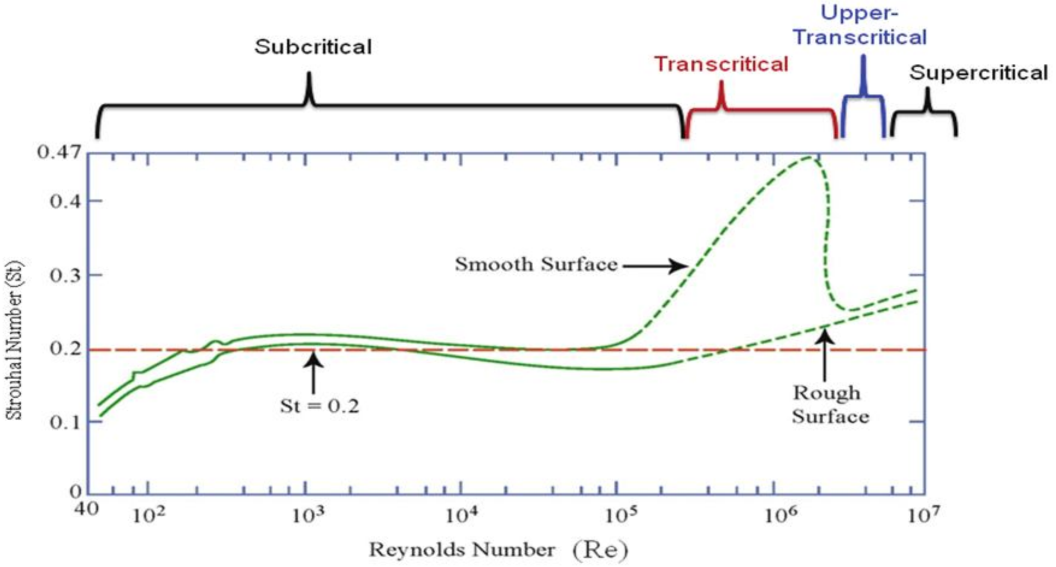
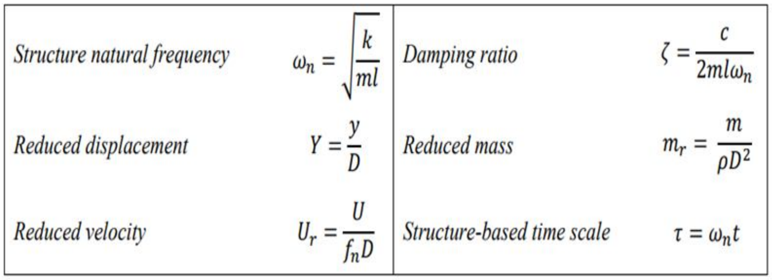


*Figure 5:**Relationship between Strouhal number and Reynolds number for circular cylinders. Roshko (1554) [12]***

Sarpkaya asserts that the body's motion becomes the predominant factor during the lock-in phase. The flow "adapts" to this motion by modifying its attributes (virtual mass, frequency, and vortex shedding) to synchronize with the body's oscillations. This arrangement enables the system to function at a uniform frequency, enhancing the body's movement. 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.[13]It was observed that vortex separation begins in the Reynolds number range of 30 < Re < 80, with vortex-induced vibrations occurring, though their effect remains negligible until Re> 300. Additionally, cylinder wakes exhibit three-dimensional flow structures at Reynolds numbers greater than approximately 189 [14].

In the study of flow-induced vibrations **(FIV)**, it is common practice to convert the governing equations into their dimensionless form to generalize the results. By doing so, the behavior of the system can be described using dimensionless parameters that apply across a range of scales, geometries, and fluid conditions. This process also allows for easier comparison between different experiments and simulations.Consequently, a set of dimensionless parameters are defined.

Fig .6: dimensionless parameters of FIV(Boretto 2019)[4]



Structure natural frequency	$\omega_n = \sqrt{\frac{k}{ml}}$	Damping ratio	$\zeta = \frac{c}{2ml\omega_n}$
Reduced displacement	$Y = \frac{y}{D}$	Reduced mass	$m_r = \frac{m}{\rho D^2}$
Reduced velocity	$U_r = \frac{U}{f_n D}$	Structure-based time scale	$\tau = \omega_n t$

Experimental observation related to a rigid cylinder, particularly with low mass damping and observing that the maximum response occurred at a specific location (0.55D) for low Reynolds numbers. Anagnostopoulos et al. (1992) states that Mass damping, particularly in the context of structures like cylinders or beams, refers to the structure's inherent ability to absorb and dissipate vibrational energy. When a system has low mass damping, it means that the structure offers little resistance to vibrational motion, allowing the vibrations to persist over time [15].Khalak et al. (1997) demonstrates that the Reduced velocity (Ur) is a critical dimensionless parameter in fluid-structure interaction, especially for flexible structures like cylinders in crossflow [16].

It is defined as the product of the flow velocity (*U*), a characteristic length (such as the diameter of the cylinder *D*), and the kinematic viscosity of the fluid (*v*):

$$\boldsymbol{Ur = \frac{UD}{v}} \qquad \textbf{(2)}$$

The reduced velocity has a significant impact on the vibration modes of a flexible cylinder in fluid flow, and it plays a key role in the phenomenon known as lock-in or synchronization. This lock-in phenomenon occurs when the frequency of vortex shedding from the flow coincides with the natural frequency of the structure, causing the vibrations to become amplified. Changes in reduced velocity can lead to different dynamic responses, including instabilities and vibrations.[16]

Indeed, the Reynolds number plays a crucial role in determining the fluid flow characteristics around a rigid cylinder, especially in the context of vibrations and dynamic responses. And a crucial role on the maximum amplitude of a rigid cylinder, with low damping. [14-16].In the case of bladeless turbines, the intentional use of vortices for energy generation is a fascinating approach. Technology seeks to capture and convert the energy inherent in vortex-induced vibrations into usable electricity. By doing so, bladeless turbines aim to provide an alternative to traditional wind turbines with rotating blades.

2.3 BWT MAIN COMPONENTS

Basically, bladeless technology consists ofa vertical cylinder called Mast attached to an elastic rod to harness wind energy.Mast -Vertical Cylinder - designed to oscillate (move back and forth)due to vortexsheddingphenomenon when exposed to wind. Instead of capturing kinetic energy through rotating blades, like traditional turbines, this occurs when air flows around the cylinder, creating alternating low-pressure vortices that cause the cylinder to vibrate, secondly, Elastic Rod holds the cylinder in place is flexible, allowing it to oscillate with the wind's energy. The elasticity of the rod helps enhance the oscillations and matches the wind speed with the natural frequency of the system,Achieving lock-in phase generation. And an Alternator System where the mechanical energy generated by the cylinder’s oscillations is then converted into electrical energy by an

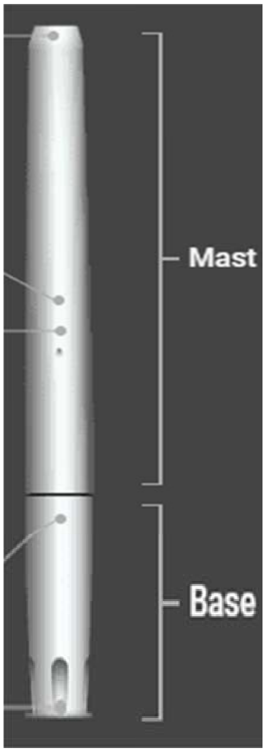


Figure 7: BWT main componentsprinciple (Vortex Bladeless S.L., 2018)[18]

alternator. In many designs, this is done using a linear alternator, which directly transforms the back-and-forth motion into electrical current[17].

(Vortex Bladeless S.L., 2018)Both**passive** and **active** tuning mechanisms are introduced to extend the operational wind speed range of a Vortex Bladeless Turbine.

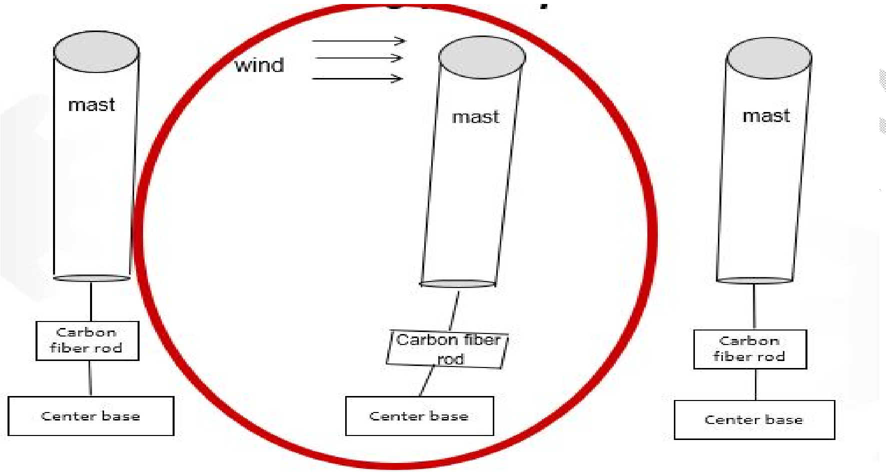


Figure8: SchematicdiagramofBWT Working principle (Vortex Bladeless S.L., 2018)[18]

The mast must possess a cylindrical shape to ensure that the amplitude of vibration is unaffected by wind direction.Vortex Bladeless, a Spanish firm, has developed a novel wind energy producing apparatus called Vortex Tacoma. The Vortex Tacoma has a maximum power output of 100 watts. It employs an electro-mechanical mechanism for energy generation and tuning, as seen in Figure 9[18].The incorporation of a tuning system evidently enhances the lock-in range of the device, ensuring a consistent output throughout a broad spectrum of wind velocities.

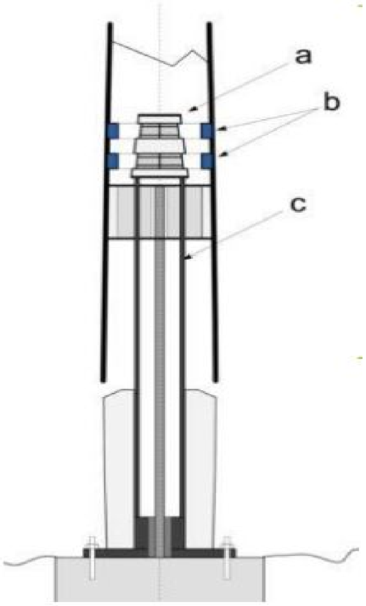


Figure 9: Arrangementofalternatorandtuningsystem(a)stator(b)permanentmagnetsand(c) structure(Vortex Bladeless S.L., 2018)[18]

2.4 ENERGY GENERATION

Energy harvesting by Vortex-Induced Vibration (VIV) can be achieved via electromagnetic devices, piezoelectric materials, or electrostatic

devices. Two methods are predominantly favored: (i) employing a linear alternator and (ii) utilizing piezoelectric materials. To generate energy utilizing these two applications, a cylinder or any shaped object is regarded as a bluff body that is free to oscillation. In any orientation. The body produces vibrations by the flow of air or water, contingent upon the state in which the body is positioned. The transverse displacement of the body is nearly identical. to the sinusoidal waveform over time[19].The amplitude of the displacement in vortex-induced vibrations (VIV) can be categorized into three phases: the initial branch, the upper branch, and the lower branch [20]. For generating electricity using a linear alternator, a combination of a coil and a magnet is employed. As the bluff body oscillates, the magnet moves relative to the coil, inducing an electromagnetic field and generating electrical current through Faraday's law of electromagnetic induction. Linear alternators are classified into two categories: axial type and transverse type. The axial type of linear alternator features permanent magnetic rings affixed to a rod that oscillates during operation. Themagnetic poles (North pole or South pole)
The magnetic poles of the ring are radial, alternating on each side of the oscillating rod.
ring to ring. Two magnetic rings are positioned at each end of the oscillating rod, while the permanent magnet ring, plunger, stator core, and air gap between the oscillating rod and stator core constitute a magnetic assembly[21]. In a transverse configuration, either a coil or a magnet function as the stator, while the other component may be affixed to the oscillating body. Vortex Tacoma employs a linear alternator for energy conversion. The oscillation of Vortex Tacoma closely resembles cantilever action [17]. The application of piezoelectric materials for the conversion of mechanical energy into electrical energy is prevalent. pertains to piezoelectric energy harvesting. A piezoelectric collector must be affixed to the primary structure to efficiently transfer vibrational energy from the main body to the collector. There Numerous methods exist to construct this mechanical interaction, although the optimal selection typically hinges on the design. limitations and the attributes of the comprehensive system [22]. The primary drawback

of utilizing a piezoelectric energy harvester is its low energy conversion efficiency, indicating significant energy losses associated with piezoelectric materials. The harvester produces energy via mechanical strain, necessitating that the body remains in a state of continual fatigue, hence requiring flexibility [23].

2.5 DYNAMIC MODELING

The dynamic modeling of the mast is analogous to that of a cylindrical bluff body and can be executed using a numerical approach or by finite element method (FEM) analysis in software like ANSYS[24]. In recent decades, numerous researchers have formulated dynamic models of bluff bodies utilizing free and forced vibration models, reduced damping models, and nonlinear exciters. Development of a theoretical model regarding

The behavior of VIV has not yet been achieved due to the interplay between fluid and structure

comprises numerous highly intricate nonlinear properties, such as vortex intensity, nonlinear turbulence characteristics, fluid velocity characteristics, fluid viscosity, etc. The forced vibration model is preferred over the free vibration model due to its greater flexibility in experimental design, allowing for regulated vibration conditions. Morse and Williamson demonstrated the strong correlation between free and forced models utilizing an energy picture[25]. Bunzel and Franzni investigated a multi-degree of freedom system for vortex-induced vibration and determined that a two-degree of freedom energy-capturing device was more substantial and efficient than a single degree of freedom system [26].

Th precise modeling of BWT can be achieved by analyzing fluid flow over a body utilizing the Navier-Stokes equation in the context of a moving body [27]. During dynamic modeling, the lift force is analyzed at various wind speeds. The lift force is contingent upon the cross-sectional area of the object. A larger cross-sectional area generates greater lift force, particularly at elevated wind speeds. In the case of BWT, synchronization transpires inside the lock-in range, which represents the optimal state.

In the case of a cylindrical mast, the cross-sectional area remains constant along the whole length of the cylinder. Consequently, the lift force on the cylindrical pole remains uniform along its length [28]. During the pre-synchronized phase, a right circular cylinder will yield superior power production, however in the post-synchronized phase, a tapered or conical mast will provide enhanced power output. Lift force at distance ‘x’ from the fixed point on the mast can be calculated from the equation:

$$C_L\,(x, t) = Q\,(x, t) - \frac{2\alpha}{D\omega s}\,\dot{Y}(x, t) \qquad (3)$$

where,

C_L= Lift co-efficient,

Q = Exciting component of fluctuating lift co-efficient

$\dot{Y}$= Transverse velocity of slice of BWT

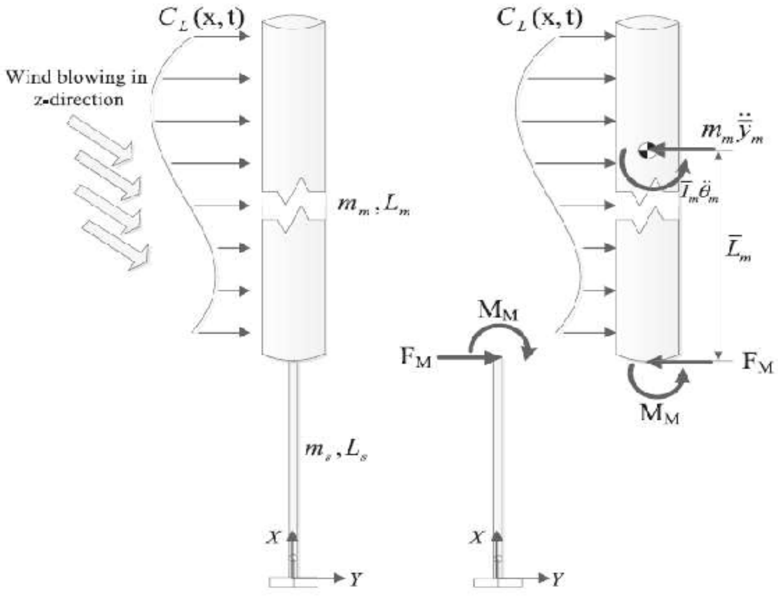
ωs = Vortex shedding frequency

α = Empirical constant

The excitation component of the fluctuating lift co-efficient Q(x,t) is used to satisfy the Van der pol equation

$$\ddot{Q}(x, t) - \omega s G\,(C_{LO}^2 - 4\,Q^2(x, t))\,\dot{Q}(x, t) + \omega s^2\,Q\,(x, t) = \omega s F\,\frac{\dot{Y}(x,t)}{D} \quad (4)$$

where, C_{LO}, G, F are empirical parameters [29]For a stationary cylinder, the right-hand side of the Eq. 4 is 0, Consequently, the variable lift coefficient possesses an amplitude equivalent to C_{LO}, and for the cylindrical section$C_{LO}<<1$[30]. The structure of the BWT varies for each situation according to specific requirements, necessitating the derivation of equations for momentum and motion calculations.



(a) *(b)*

Figure10:(a) Schematic model of BWT (b) Free body diagram (chizfahm et al. 2008)[24]

3. CONCLUSIONS

Energy harvesting through various techniques of flow-induced vibrations has gained significant importance over the past few decades. In the realm of wind energy, one of the most efficient technologies based on flow-induced vibrations is the Bladeless Wind Turbine (BWT). BWTs offer several advantages: they occupy less space, require minimal maintenance, and provide a simple yet adaptable construction. This flexibility allows for easy modification based on the specific needs of the installation site to achieve maximum energy output. The use of vortex-induced vibrations (VIV) in BWTs proves particularly beneficial for harnessing wind energy efficiently.It is essential to consider the environmental parameters of installation sites, as operational conditions may not always be suitable for turbine functionality. For instance, a turbine will create electricity solely when it resonates inside the lock-in range.Most of the designs prioritize enhancing the lift coefficient, which constitutes 50% of the total force, while largely disregarding the drag component in most instances,The structure must be designed to optimize the utilization of most of the fluid energy.

LIST OF ABBREVIATIONS

CFD:	Computational fluid dynamics
FEM:	finite element method
VIV:	vortex-induced vibrations
FIV:	Flow-induced vibrations
BWT:	Bladeless Wind Turbine
VBWT:	vortex bladeless wind turbines
ωs:	Vortex shedding frequency
HAWT:	Horizontal Axis Wind Turbine
M_r:	Reduced mass
U_r:	Reduced velocity
C_l:	Lift co-efficient

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