A state-of-art review on Bladeless Wind Turbine

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Abstract. As a result of continuous depletion of non-renewable energy sources, new methods of harvesting energy are being developed. A unique way of harvesting wind energy, namely Bladeless Wind Turbine (BWT) is discussed in this paper. It differs from conventional turbine by harvesting energy through Vortex Induced Vibration (VIV) which is safe and quiet in operation. It has no bearings, gears or any rotating device hence it has low maintenance cost and high life. The scope of BWT as the renewable energy source varies from offshore to wind farms considering the availability of high intensity winds. BWT is a trio of diverse engineering branches: Electrical Engineering, Fluid Dynamics and Mechanics of Solids that often makes it nonlinear as well as complex. This article includes a basis for vortex-induced vibrations, dynamic modelling, components of BWT and energy harvesting unit. Optimum shape to harvest the energy is outlined in combination with mathematical model of the turbine. Various modes to harness vibrational energy, including different orientations and surface extensions, to widen the operating range and increase performance are covered in the review. This paper is a complete outline of BWT which shows the advancement of technology from VIV to commercially available products.

Keywords: Bladeless Wind Turbine, Vortex Induced Vibration, Bluff body, Strouhal number, Linear alternator.

1. Introduction
Renewable energy is flourishing with new inventions with cost effective products and establishing the assurance of clean energy for the future. However, not every resource of energy is a perk of nature. Hydro-electric and biomass power plant create trade-offs, while considering the effect on wildlife, climate change and other issues. Use of solar energy systems prevents production of greenhouse gases, but it utilizes some of toxic materials in exchange of storing energy which affects the environment. The Government of India has set a spotlight on renewable energy sources to meet 175 GW by 2022 which includes 60 GW of wind and 100 GW solar energy [1]. Power from wind energy can be generated by two methods: (1) Rotational wind harvesting and (2) Oscillation wind harvesting. Rotational wind harvesting is a traditional method in which large spinners include turbine blades which rotate and generate electricity. Increase in number of turbines increases the wake formation which leads to large space requirement and high cost [2]. Oscillation wind harvesting is a less common method to generate electricity among these two. When a gust of wind flows over a body, the motion of the wind gets disturbed and starts creating turbulence behind the body. Shedding of vortices from body generates uneven pressure which makes the body to vibrate under the effect of varying aerodynamic forces [3]. Once natural frequency of body matches with the shedding frequency, the body will resonate. This resonating body is called BWT. Vibrations induced in the turbine leads to the linear motion of the turbine. This linear motion generates energy with the help of electro-mechanical devices and stores it in a battery which can be used later on as per the requirement. BWT has been a subject of significant and world-wide research. But it still is a nascent technology. This paper reviews
the principles behind BWT and VIV with different components of BWT and energy harvesting. The challenges of BWTs are debated at the end.

2. Vortex induced vibration

When air flows around a body it can induce oscillatory motion by vortex shedding. The vibration induced in body by the vortices is called VIV. There are two important factors in VIV that will be zenith in this section, vortex shedding frequency \((f_s)\) and vortex wake formation. Karman [4] was first to come up with the idea of wake formation behind the bluff body. He showed that the ideal arrangement of infinite double row of vortices for an inviscid flow is stable for any displacement. Bearman [5] describes bluff body as the one which when placed in a fluid stream generates separated flow over a substantial proportion of its surface. Gerrard [6] explains the mechanics of vortex formation region, he proposes that the mutual interaction between two free shear layers is a key factor in the vortex-street formation. He postulates three conditions (as shown in Figure 1) for the fluid particles of opposite shear layer drawn across the wake: 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 controls the shedding frequency, the strength of the vortices shed and the base pressure.

![Gerrard's vortex-formation model](image)

The flow around cylinder/bluff body depends on surface roughness, Reynolds number \((Re)\), perturbation of flow and body geometry. The surface roughness and perturbation of flow are uncertain so the influence of Reynolds number and body geometry are taken into consideration in this section. The effect of body geometry becomes important because of separation of free streamlines at different angles from the body. The bluffer the cross section of the body, more will be the drag and lower will be the shedding frequency. Su et al. [7] have performed numerical simulation on square cross-section. When the cross-section of body is asymmetric then vibration of body is known as galloping. Parkinson et al. [8–10] were among the few early investigators to emphasize that the combined effect of VIV and galloping can cause large fluctuations at much earlier speeds than VIV. Roshko [11] studied the different body configuration and deduced the relation between shedding frequency and wake width, known as Universal Strouhal number \((St)\). Universal Strouhal number has a fixed value of 0.2. Rayleigh [12] studied the vibrations in string and defined a non-dimensional physical quantity known as the Strouhal number \((St)\), which is more specific and often used for referring VIV.

\[
S_t = \frac{f_s D}{U} \quad \text{(1)}
\]

\[
S_t = \frac{f_s d'}{U} \quad \text{(2)}
\]

As the separation on the continuous surface has no fixed points it will be highly dependent on Reynolds number. Most of the earlier studies have been done at low Reynolds number. Creeping flow \((Re<1)\) like Oseen’s Navier-Stokes equation and Stokes’s law are described in Milne-Thompson [13]. Roshko [14] plotted a curve showing variation of Strouhal number at low Reynolds number. Later on,
the discontinuity in Roshko’s curve is solved by Williamson [15]. Siqueria [16] did the simulation at low Reynolds number and obtained the similar results as obtained by Williamson. Belvins [17] deduced that the composition of vortex in a flow pattern changes with change in Reynolds number. Sparkya [18] discussed the flow around the cylinder at high Reynolds (500 – 6x10⁴).

Many experimental and numerical analysis have been carried out to understand the nature of flow with variation of Reynolds and Strouhal number which is shown in the table 1.

\textbf{Table 1.} Reynolds and Strouhal number on circular cylinder [19]

| Reynolds number regime | Flow regime | Flow form | Flow characteristic | Strouhal number (St) | Drag coefficient (C_D) | Separation angle (Ө_s) |
|------------------------|-------------|-----------|---------------------|----------------------|------------------------|------------------------|
| Re →0                  | Creeping flow | Stable, no wake | -                  | 60                  | -                      | -                      |
| 3-4 < Re < 30-40       | Vortex pairs in wake | Steady, symmetric separation | -                  | 1.5 < C_D < 4.52 | 130° < Ө_s < 180° |
| 30-4 < Re < 80-90      | Onset of karman street | Laminar, unstable wake | -                  | 1.17 < C_D < 1.59 | 115° < Ө_s < 130° |
| 80-90 < Re < 150-300   | Pure karman street | Karman street | 0.14 < St < 0.21  | -                    | -                      |
| 150-300 < Re < 1-1.3x10⁵ | Sub-critical regime | Laminar, with Vortex instability | St = 0.21 | C_D = 1.2 | Ө_s = 80° |
| 1-1.3x10⁵ < Re < 3.5x10⁶ | Critical regime | Laminar separation, Turbulent reattachment Turbulent separation Turbulent wake | No preferred frequency | 0.2 < C_D < 1.2 | 80° < Ө_s < 140° |
| 3.5x10⁶ < Re           | Super-critical regime | - | 0.25 < St < 0.30 | C_D = 0.6 | Ө_s = 115° |

It is clear that the vortex separation starts from 30 < Re < 80 and so as vortex induced vibration, though its effect is negligible until Re > 300. It is found that cylinder wakes exhibit three dimensional flow structures above a Reynolds number of 189 approximately [20].

Anagnostopoulos et al. [21] performed experiments on a rigid cylinder with low mass damping and observed 0.55D of maximum response at low Reynolds number. Khalak et al. [22] showed that response of flexible cylinder is affected by reduced velocity. Govardhan and Williamson [23] and Klamo et al. [24] showed that the Reynolds number has significant influence on the maximum amplitude of a rigid cylinder, with low damping as shown in Figure 2. Similar kind of study has been done by Raghvan and Bermitsas [25] and Ding et al. [26] at high Reynolds number.
The size of wake behind the body and distribution of vortices are more important when we talk about BWTs, because to generate substantial amount of power we require number of BWTs in a particular array so that the wake of one turbine do not hinder the upstream flow for others. Considerable and significant studies exist on multi-cylinder array for cross-flow in a heat exchanger. In-line arrangement of two cylinders is the simplest form of multi-cylinder arrangement. Two more parameters are involved when we talk about multi-cylinder arrangement, first is attack angle and second is the ratio of centre spacing to diameter. Attack angle is the angle between the flow direction and centre line of the cylinders. Kim et al. [27] found that when two cylinders are in tandem arrangement, the first cylinder behaves similar to an isolated cylinder, when the spacing between them is more than 2.7D. King and Johns [28] observed synchronization of down-stream and up-stream cylinders for L/D = 3.5-7. Assi [29] published several papers on tandem arrangement of two cylinders for different spacing ratio and attack angles. He calculated lift and drag forces on downstream cylinder at centre spacing 4D and Re = 10^4 as shown in Figure 3.
Alam et al. [30] studied mutual interaction between two cylinders, and analyzed many aerodynamic characteristics at $Re = 6.5 \times 10^4$. They experimentally obtained the graph of Strouhal number and spacing ratio as shown in Figure 4.

![Figure 4. Strouhal number Vs spacing ratio [30].](image)

Arionfard and Nishi [31] performed an experiment on mechanically coupled double cylinder with different spacing ratio and obtained the highest power for cylinder separated at spacing ratio of 0.9 and center of gravity ratio of zero. Haider and Sohn [32] calculated the aerodynamic forces and amplitude of two cylinders in tandem arrangement. He also showed that they have a minimum value when spacing distance is 3.5D. Ding et al. [33] performed CFD on tandem arrangement and obtained the same result as obtained by Haider and Sohn. Bearman and Wadcock [34] analyzed the behaviour of two cylinders arranged side-by-side separated at 1.85D as shown in Figure 5.

![Figure 5. Side-by-side arrangement of two cylinders [34].](image)

Zodrakovich [35] studied the region of interference between two cylinders and drew the maps of interference regimes for different spacing and attack angles (0-90°). Sayyadi and Motekallem [36] conducted numerical simulations on three cylinders arranged in triangular arrangement.

### 3. Components of BWT

The main components of BWT are: mast, central base, suspension and tuning system, power converting device/alternator, and power storage device. Figure 6 shows the schematic diagram of the BWT.
3.1 Mast:

It is a cylindrical or conical straw like structure directly exposed to the upstream wind. Vortex shedding occurs in the wake of the mast. Function of the mast can be co-related with the blades of wind turbine. In conventional turbine, the energy flow is, Wind energy → Rotation of blades → Gear train → Generator. Likewise in BWT, it is, Wind energy → Oscillation of mast → Alternator. Material and shape of the mast are two important parameters. The material should be light in weight and stiff. For such combination, a use of composite material is advised. The shape of mast must be symmetric in all the directions because wind direction is not constant throughout the day.

The shape of mast have to be cylindrical so that amplitude of vibration is not affected by the wind direction. Moreover, a variation can be made by giving taper to the cylinder and it can be linear as well as non-linear. Taper ratio is defined as the ratio of the length of cylinder to the difference of maximum and minimum diameter of the cylinder. Gaster [37] performed water tunnel experiments on the tapered cylinder with taper ratio of 36:1 and 18:1 and showed that the shedding frequency of tapered cylinder is slightly lower than the circular cylinder. Piccirillo and Van Atta [38] studied four tapered cylinders varying from 50:1 to 100:1. They performed experiments at low Reynolds number, greater than 100, and found that wake behind the tapered cylinder is made up of discrete shedding of vortices, at constant frequency. Papangelou [39] obtained a mathematical model by performing several experiments in wind-tunnel, the solution describes different features and flow over tapered cylinder at low Reynolds number. Jespersen and Levit [40] performed numerical simulation over a tapered cylinder considering unsteady 3D flow at low Reynolds number. Hisao and Pan [41] performed experimental investigation on wake behind the tapered cylinder. Techet et al. [42] performed series of tests to understand vortex flow pattern (like 2S, 2P) behind the tapered cylinder. They observed hybrid mode of shedding between Reynolds number ranging from 400 and 1500. Hover et al. [43] measured forces on the circular and tapered cylinder. Balasubramanian et al. [44] experimentally investigated the dynamics of pivoted tapered cylinder. Valles et al. [45] solved unsteady 3D Navier-Stoke’s equation at low Reynolds number to explore the vortex formation behind the tapered cylinder. Narshimamurthy et al. [46] observed discrete cellular vortex shedding by doing numerical simulation over a tapered cylinder. Visscher et al. [47] studied time-based 3D flow with the help of Stereo PIV (Particle Image Velocimetry). Zeinoddini et al. [48] studied the vibration of tapered cylinder for ocean applications. Sayed-Aghazadeh et al. [49] compared a straight cylinder with linear and non-linear tapered cylinder, and provided a detailed description about vortex shedding, reduced damping, etc.

On comparing linear tapered cylinder with uniform cylinder, wider lock in ranges (range of wind velocity in which power output is obtained) were observed in case of smaller taper ratio. In case of
larger taper ratio, its properties such as amplitude and lock in range are almost equal to the uniform cylinder. If the reduced velocity is not in the lock in range, the oscillations will not take place. Taper ratio can be positive or negative, positive refers to the larger diameter at bottom and negative refers to smaller diameter at bottom. Hybrid vortex shedding has been observed in a case of tapered cylinder. Hybrid shedding consists of 2S (2 single vortices per cycle of oscillation) shedding from larger diameter part and 2P (2 pair of vortices per cycle of oscillation) shedding from smaller diameter part of the cylinder [49]. As the reduced velocity (ratio of original velocity to the product of natural frequency of body in water and average diameter) changes, beginning from lower reduced velocities at smaller diameter to higher reduced velocities at larger diameter, the point of splitting of 2S and 2P shedding shifts its position along the length of the cylinder. The location of splitting shifts below the mid-point over the span of cylinder. 2P shedding can be observed over the entire length of the cylinder for a higher reduced velocity. With the increase in reduced velocity, the effect of 2S shedding goes on decreasing. In Figure 7, dashed line shows the splitting point of the 2S and 2P shedding over increasing reduced velocity [49]. The point remains same for both positive and negative tapered cylinders at which 2S and 2P shedding splits. This implies that the effect of cross flow wind on a tapered cylinder is independent of boundary conditions and it is an intrinsic feature of the tapered cylinder.

![Mast](image)

**Figure 7.** Flow Visualization over linearly tapered cylinder (a) positive taper (b) negative taper [49].

Wan et al. [50] studied the synergic effect of VIV and galloping for the cylindrical and rectangular body. To maximize the amplitude, they came up with a newly designed cylinder with bulb cross section. A series of experimental investigations were performed on a D-shaped section at different angles and for different wind speeds to optimize the bulb shape.
3.2 Central Base:
Central base is made up of a strong material like iron which provides foundation for the whole structure. Central rod attached to the base supports the cantilever motion of the mast. Different electro-mechanical devices can also be mounted on it. The rod is under fatigue loading so it must be flexible enough to bend otherwise the cantilever motion of mast will experience resistance. Hence, carbon fibre rod is more suitable for this application.

3.3 Suspension and Tuning system:
Spring and dampers can be used in the system for smooth functioning and tuning of the mast. Electromagnetic devices like permanent magnets and coils can also be used for the same. Designing the turbine for a particular frequency is difficult because of varying wind velocity throughout the day, that is why BWT must be incorporated with the tuning units. Two pairs of permanent magnets have been added for tuning purpose, one attached to the oscillating mast while other to the fixed rod as shown in Figure 9.

\[
 f(x) = \frac{1}{2\pi} \sqrt{\frac{k + k'(x)}{m} - \left(\frac{c}{2m}\right)^2} 
\]

Where, \( k + k'(x) \) is stiffness of the system and \( k'(x) \) is due to magnetic repulsion, and \( f(x) \) is the natural frequency of the system.

Vortex Bladeless, a Spanish company created a new wind power generation device, namely Vortex Tacoma. The maximum power output of Vortex Tacoma is 100W. It uses electro-mechanical device for both energy generation and tuning as shown Figure 10 [51]. It is clear that lock-in range of device
is increased with incorporating tuning system; which ensures the continuous output for large range of wind velocity.

![Figure 10. Arrangement of alternator and tuning system (a) stator (b) permanent magnets and (c) structure [51].](image)

### 3.4 Power converting unit/ Alternator:
Piezoelectric or electromagnetic devices are coupled with oscillatory motion of the mast or cantilever action of rod to convert kinetic energy into electrical energy. Electromagnetic devices are more preferred than piezoelectric because of higher energy loss in piezo. One important thing is that the orientation or function of these devices must not depend on wind direction. Likewise, an alternator having ring shaped magnet on the mast works as a rotor and the stator on rod is independent of wind direction [51]. Other than piezo and electromagnetism, electrostatic devices like variable capacitor can also be used.

### 3.5 Power storage device:
Power obtained from conversion is minimal. The maximum wind speed near the onshore is about 5-10 m/s. Wind with such a speed will impart fluctuating lift forces (which is quite less) on the mast. After overcoming the resistance of structure, very less force is spared. That’s why it cannot be used directly and need to be stored in a battery or similar storage devices so that in substantial amount of time we can have required power.

### 4. Dynamic modelling
Dynamic modelling of the mast is identical to the modelling of cylindrical bluff body and can be done by using a numerical method or by doing a FEM analysis in software like Ansys [52]. In the last few decades, many researchers have developed dynamic models of bluff body using free and forced vibration model, reducing damping model and nonlinear exciter. Formulation of theoretical model on the behaviour of VIV has not yet been successful because the interaction of fluid and structure includes a large number of extremely complex nonlinear parameters, including vortex intensity, nonlinear turbulence characteristics, fluid viscosity, and so on. Early work in dynamic modelling of circular cylinder includes the work of Bishop and Hassan [53], Koopman [54], Feng [55], Skop and Griffin [56]. Bishop and Hassan [53] concluded that a ‘non-linear self-excited fluid oscillator’ might be applied to calculate the forces acting on a cylinder. They made a series of response diagrams by varying various parameters. Koopman [54] extended the work of dynamic modelling by determining the region of synchronization for the oscillating cylinder. Representation of fluctuating lift force using nonlinear oscillator model was also performed. In such a model, oscillations of cylinder have been studied with respect to reduced damping. Reduced damping is the ratio of structural damping to ratio...
of fluid mass to structure-mass. Alternatively, a more suitable semi-empirical model was proposed by Hartlen and Currie [57], who were the first to successfully interpret the inherent VIV phenomena such as grip range, self-excitability, and self-limiting characteristics through the introduction of a trail oscillator model. Iwans and Blevins [58] observed the effect of reduced damping on the structural response of elastically supported rigid cylinder, and showed that the response and synchronization will increase with decrease in damping. Parkinson [59] used mass, spring and damper system driven by fluid force and obtained the equation for transverse vibration. Sparkya [18] derived an empirical relation of limiting amplitude as a function of reduced damping. Skop and Griffin [56] analyzed the asymptotic behavior of the structural response close to Zero structural damping. Stuabli [60] experimentally showed the hysteresis effect caused due to non-linear relation between response and fluid force, using forced-displacement excitation model. Albarede and Monkewitz [61] presented a model predicting structural response with non-linear oscillator equation. Meneghini et al. [62] derived the structural equation for forced vibration in marine risers. From free and forced vibration model, forced model is the preferred one as it has more flexibility with experimental setup, i.e condition for vibration can be controlled. Morse and Williamson [63] showed the close correspondence between free and forced model using energy portraits (graph of energy transferred to the body and energy dissipated by damping) and also stated that the model might exhibit hysteric transition. Efstathios [64] derived a criteria of limiting amplitude for freely vibrating elastic cylinder corresponding to the zero structural damping. Bunzel and Franzni [65] studied a multi-degree of freedom for vortex induced vibration and concluded that two-degree of freedom model for vortex induced vibration and concluded that two-degree of freedom energy capturing device was more significant and efficient than single degree of freedom. From Bishop and Hassan [53] to till today these models have been repeatedly changed and improved by many researchers [66–69] and the elucidating in structural response has constantly been increased.

The accurate modeling of BWT can be done by considering a fluid flow over a body with the help of Navier-Stokes equation in the presence of a moving body [70]. During the dynamic modeling, basically two things are calculated namely lift force and tip deflection at different wind speeds. Lift force depends on the cross-sectional area of the body. Larger cross-sectional area gives better lift force, results at higher wind speed. In case of BWT, synchronization occurs at lock in range which is the ideal condition. In the case of tapered mast, for shorter diameter area, better lift force is experienced in pre-synchronization phase i.e. at less velocity than lock in velocity. For larger diameter area, better lift force is obtained at post-synchronization phase i.e. at larger velocity than lock in velocity [52]. In the case of cylindrical mast, the cross-sectional area is same throughout the length of the cylinder. Hence, the lift force on cylindrical mast remains constant throughout the length [71]. So, during pre-synchronized phase, right circular cylinder will give better power output and during post-synchronized phase tapered or conical mast will give better power output. Lift force at distance ‘x’ from the fixed point on the mast can be calculated from the equation:

\[ C_l(x, t) = \frac{Q(x, t) - 2\alpha \dot{Y}(x, t)}{D_{in}} \]  

where,

- \( C_l \) = Lift co-efficient,
- \( Q \) = Exciting component of fluctuating lift co-efficient,
- \( \dot{Y} \) = Transverse velocity of slice of BWT,
- \( \omega_s \) = Vortex shedding frequency,
- \( \alpha \) = Empirical constant.

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

\[ \ddot{Q}(x, t) - \alpha G(C_{lo} - 4Q^2)(x, t)\dot{Q}(x, t) + \alpha^2 Q(x, t) = \alpha F \frac{\dot{Y}(x, t)}{D} \]  

where, \( C_{lo}, G, F \) are empirical parameters [57].
For a stationary cylinder, the right-hand side of the Eq. 5 is 0. Therefore, the fluctuating lift coefficient has the amplitude equal to $C_{LO}$ and for cylindrical section, $C_{LO} << 1$ [72]. Since the structure of the BWT is different for each and every case as per the requirement, the equations for the calculation of momentum and motion can be derived individually.

![Diagram](image)

**Figure 11.** (a) Schematic model of BWT (b) Free body diagram of BWT [52].

5. Energy Harvesting

Energy harvesting with the help of VIV can be possible with the help of electromagnetic devices, piezoelectric material or electro-static devices. For that two ways are most preferred: (i) by using linear alternator and (ii) with the help of piezoelectric material. For generating electricity using these two applications, a cylinder or any shaped body is considered as a bluff body which is free to oscillate in any direction. Body makes vibration with the help of stream of air or water depending on the condition where the body is placed. The transverse displacement of the body varies almost equivalent to the sinusoidal curve with time [73]. Also, the amplitude of the displacement can be characterized into three categories i.e. initial, upper and lower branch [74]. For generating electricity with the help of linear alternator, combination of coil and magnet is used. There are two types of linear alternators: axial type and transverse type. Axial type linear alternator has permanent magnetic rings which are attached on the rod which oscillate during the machine working time. The magnetic poles (N pole or S pole) of the ring are radial and on each side of the oscillating rod, the magnetic poles alternate from ring to ring. Two magnetic rings are at each end of the oscillating rod, and the permanent magnet ring, plunger, stator core and air gap between the oscillating rod and stator core form a magnetic ring [75]. In transverse type, either a coil or magnet is used as a stator and the other can be attached to the oscillating body. As discussed earlier in chapter 3.3, Vortex Tacoma makes the use of linear alternator for energy conversion. Oscillation of Vortex Tacoma is very close to cantilever action.

Maximum power output can be obtained when the body moves away from the mean position and when the body returns to the mean position from the extreme position. The length of the coil does not affect the power output with the help of linear alternator but the increasing length gives significant output continuously even at low displacement [76]. Increased length covers more area of the body, results in covering more area over the magnet, gives continuously significant power output. During VIV the upper body has higher displacement in comparison with the lower body or the pivoted part. Increased length covers the upper part of the body which can have a smaller displacement at low velocity compared to lower part. This ultimately gives continuous power output.
The use of piezoelectric materials to convert mechanical energy into electrical energy is commonly referred to as piezoelectric energy harvesting. A piezoelectric collector must be connected to the main structure in order to transfer the vibration energy effectively from the main body to the collector. There are many ways to establish this mechanical interface, but the best choice usually depends on the design constraints and the characteristics of the overall system [78]. A significant amount of research is going on to incorporate the non-linearities into a harvester design in order to expand its lock-in range and improve its performance in unsteady vibrational environments [79–85].

An experiment was conducted to harvest the energy from BWT by using piezoelectric material in which the relation between motion of the bluff body (cylinder) and the harvested power is modelled by using Gauss law [86,87]. The relation between the vortex shedding and the fluctuating lift co-efficient is modelled by Skop and Griffin equation [50].

\[
\begin{align*}
C_J \ddot{Y} + \frac{V}{R} \theta &= 0 \\
\dot{C}_L + \omega_C^2 C_L - [C_L^0 - C_L^0 - \left( \frac{C_L^0}{\omega_C} \right) \times (\omega_C G \dot{C}_L - \omega_C^2 H C_L)] &= \omega_F \left( \frac{\dot{Y}}{D} \right)
\end{align*}
\]

Y Transverse Displacement
D Diameter of the cylinder
\(\omega_F\) Shedding Frequency
U Velocity
\(C_L\) Fluctuating lift co-efficient
R Load Resistance
\(C_p\) Capacitance

The four co-efficient \(C_{LO}, H, F, G\) can be identified from experiment.

Nayfeh and his colleagues [88–92] used modern nonlinear dynamics methods to determine the parameters of phenomenological models that can be used to represent the lift coefficient on a stationary cylinder. The conclusion was, as the load resistance increases the synchronization region shifts to the higher velocity part. Also, the load resistance affects the natural frequency of the oscillator. Linear parameters of the load resistance affect synchronization and electro-mechanical damping. Non-linear parameters of the load resistance affect hardening and hysteresis of the oscillator which eventually affect the power output [77]. Truitt and Mahmood [93] studied the dynamics of piezoelectric energy harvesters with the help of aero-elastic behavior of a bluff body and fluid-based...
theories. They compared PZT (Lead Zirconate Titanate) piezoelectric energy harvesters and PVDF (Polyvinylidene fluoride) based piezoelectric energy harvesters and showed that PVDF will give better result in certain fluid medium while in most of cases, PZT proved to be more effective than PVDF. Gang et. al. [94] conducted an experiment with a piezoelectric wind harvester in which three rods are attached at a circumferential angle of 45 degrees and 60 degrees with three different cross-sections, namely circular, triangular and square. The results concluded that the rods attached at 60 degrees provide better performance than rods attached at 45 degrees.

The main disadvantage of using piezoelectric energy harvester is its energy conversion efficiency, which is very less that suggests more losses with piezo. Also, the harvester generates energy through mechanical strain that means the body is continuously under fatigue so it has to be flexible and durable [95]. Due to rare property of piezo materials, they are high costly too which makes it ambiguous choice for using in BWT. Piezoelectric energy harvesting coupled with the non-linear permanent magnets improves performance as well as reduces the natural frequency of the structure. Zhang et al. [96] introduced a pair of mutually exclusive permanent magnets to energy capturing device by using cantilever structure. Experimental results showed that capturing efficiency enhanced by 29% and lock-in range was broadened by 138%.

6. Orientation and extensions in Bluff Body

The orientation of a bluff body plays an important role in the oscillation when energy is harvested from VIV. Song et al. [97] experimentally proved that the lighter mass and larger diameter body can be more efficient in case of generating power. An experimental study was conducted in which 4 different orientations of the bluff body were taken into consideration, i.e. bottom (case 1), top (case 2), horizontal (case 3), and vertical (case 4) as shown in Figure 13.

![Figure 13. Orientation of bluff body [98.]](image)

All the four bodies were made from foam material, light in weight. The surrounding condition for all the 4 bodies were kept similar. Piezoelectric material was attached at the bottom of the body for the harvesting the energy [98]. Mathematical calculations have been done considering the wake oscillator model [99]. The case 4 configuration has been previously studied under the negligible effect of gravity and aerodynamic forces [100–102]. The experiment states that the orientation in the case 4 proves to be more effective for the higher wind speed of around 3-8 m/s. For a lower wind speed of around 1-3 m/s, orientation of case 2 is more effective. Orientation of case 1 has more effect of gravitation as compared to case 2 because the beam and the body of case 1 are completely under the tension all the time which makes it difficult to oscillate. The orientation in case 3 has more effective mass and this leads to lower natural frequency and higher damping constant, as a result, orientation of case 3 has lowest power output. Orientation of case 4 has least effective mass, higher natural frequency and lowest damping constant among the other cases because of its geometry, which yields highest output and has a wider range of wind speed [98], which can be seen in Figure 14.
Figure 14. Voltage Time relation for all four cases [98].

Table 2. Natural Frequency and Damping Ratio for all four configuration [98]

| Case | Natural Frequency (Hz) | Damping Ratio |
|------|------------------------|---------------|
| 1    | 6.8                    | 0.0139        |
| 2    | 6.6                    | 0.0135        |
| 3    | 6.4                    | 0.0152        |
| 4    | 12.2                   | 0.0109        |

The efficiency of BWT is more if it works in the lock-in zone. The current research in BWTs is mainly focused on increasing the band-width of lock-in range using various extensions in the design of a oscillating bluff body. Zhang et al. [103] suggested the model of adding a cylindrical body to a cantilever beam, so it can harvest the piezo energy, which is presented in Figure 15. The increased range of lock-in frequency was obtained in this model as compared to original model (Single cylinder). The lock-in range and power output are heavily dependent on the distance between two cylinders (L) as the flow pattern between the cylinder changes by changing the distance, which changes Strouhal number (St) and lift coefficient (C_l). The average power for a different distance ‘L’ with varying wind speed is shown in Figure 16. It is clearly seen that for corresponding wind range (highlighted in blue) there is an increment in average power with decrease in distance.

Figure 15. Piezo energy harvester [103].

Figure 16. Experimental result of piezo energy harvester [103].
Song et al. [104] analyzed the effect on split-cylinder shown in Figure 17. The experiment showed that the splitter gradually increases the band-width of harvester, and peak voltage decreases when aspect ratio is 0.5. Experimental studies showed the ideal splitter of length as 0.65D.

Figure 17. Cylinder with end splitter [104].

7. Conclusion
Energy harvesting using various techniques of flow-induced vibrations has gained importance since the last few decades. As far as wind energy is concerned, the most efficient technology based on flow-induced vibration is BWT. It occupies less space and requires very less maintenance which is advantageous for harvesting wind energy. The construction is simple and can be changed easily as per the need of the location to get maximum output. The phenomenon of VIV proves useful in harvesting wind energy. By changing the shape of the turbine, hybrid vortex shedding can be done to get maximum output. D shape section proves to be the most promising design; however, it is advised to use tapered shape cylinder along with some tuning system in order to have wide range of frequency. Use of linear alternator is the most effective and efficient way in harvesting energy by using BWT. This technology promises clean energy for the future with the ability of reaching from onshore to commercial buildings. In order to increase the scope of this technology, the advancement in different area is required.

- Other than flow-induced vibration power generation is a linear technology. One of the methods that can be implemented is to introduce linear technology like linear alternator with BWT or advancing non-linear methods by adopting multi-degree system or nonlinear stimulation.
- Hybridization of power generation that means the arrangement must be made so that power generation is not only dependent on one technology like Electro Magnetic Induction (EMI), instead, other technology must be incorporated in the system along with EMI like piezoelectric rod to generate electricity from piezo effect during cantilever action of rod.
- Artificial neural network can be used to get more accurate and rapid response during its working.
- Different materials with required strength and stiffness can be searched in order to make the system light in weight, and different configurations can be tried to reduce the natural frequency.

Before we make it as common as solar panels there are certain challenges which need to be overcome:

- Lack of maturity; this technique is still in its developing stage and there is a long way to go. Intelligence of combining electromagnetism with fluid dynamics in this fashion is very complex and hard. Moreover, the energy cannot be used directly, some kind of storing device is required.
- Power generation; converting wind energy into electrical energy by using translation motion is inefficient as compared to rotational energy conversion in conventional turbines. Also, the
piezoelectric way of generating electricity is the least efficient as compared to static and electromagnetic induction.  
- In all the designs, focus is made on improving lift coefficient i.e. lift force which is 50% of total force while other component i.e. drag is ignored in most of the designs. Somehow the structure must be made in such a way that it utilizes most of the fluid energy.  
- One must take care of environmental conditions of instalment sites as operating conditions will not always be adequate for functioning the turbines. For example, turbine will only generate energy when it resonates within lock-in range.  
- Cost of light weight material and strong electro-mechanical coupling with permanent magnets will be more when it comes to install a number of turbines to get substantial power output.

References

[1] Gupta A Tentative State-wise break-up of Renewable Power target to be achieved by the year 2022 so that cumulative achievement is 175,000 MW. Delhi: MNRE MNRE
[2] Chaudhari C C, Shiriram M A, Unhale S G and Nirmal R S 2017 Fabrication of vortex bladeless windmill power generation model Int. J. Sci. Technol. Eng. 3 52–6
[3] Wang J, Geng L, Ding L, Zhu H and Yurchenko D 2020 The state-of-the-art review on energy harvesting from flow-induced vibrations Appl. Energy 267 114902
[4] Von Kármán T 1911 Über den Mechanismus des Widerstandes, den ein bewegter Körper in einer Flüssigkeit erfährt Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Math. Klasse 1911 509–17
[5] Bearman P W 1984 Vortex shedding from oscillating bluff bodies AnRFM 16 195–222
[6] Gerrard J H 1966 The mechanics of the vortex formation region of vortices behind bluff bodies J. Fluid Mech. 25 143
[7] Su Z, Liu Y, Zhang H and Zhang D 2007 Numerical simulation of vortex-induced vibration of a square cylinder J. Mech. Sci. Technol. 21 1415
[8] Parkinson G V and Smith J D 1964 The square prism as an aerelastic non-linear oscillator J. Mech. Appl. Math. 17 225–39
[9] Parkinson G V and Brooks N P H 1961 On the aerelastic instability of bluff cylinders
[10] Parkinson G V and Wawzonek M A 1981 Some considerations of combined effects of galloping and vortex resonance J. Wind Eng. Ind. Aerodyn. 8 135–43
[11] Roshko A 1954 On the drag and shedding frequency of two-dimensional bluff bodies Natl. Advis. Comm. Aeronaut.
[12] Rayleigh J W . 1896 The Theory of sound, vol. I and II
[13] Milne-Thomson L M 1996 Theoretical hydrodynamics (Courier Corporation)
[14] Roshko A 1954 On the development of turbulent wakes from vortex streets Natl. Advis. Comm. Aeronaut. Report 119 25
[15] Williamson C H K 1991 2-D and 3-D aspects of the wake of a cylinder, and their relation to wake computations Lect. Appl. Math., Am. Math. Soc. 28 719
[16] Siqueira C R 1999 Simulação numérica do escoamento ao redor de cilindros: aplicação a problemas bi e tridimensionais DSc Thesis, Univ. Sao Paulo
[17] BLEVINS R D 2001 Flow-Induced Vibrations 2nd Edition
[18] Sarpkaya T 2004 A critical review of the intrinsic nature of vortex-induced vibrations J. Fluids Struct. 19 389–447
[19] Schlichting H and Gersten K 2016 Boundary-layer theory (Springer)
[20] Williamson C H 1989 Oblique and parallel modes of vortex shedding in the wake of a circular cylinder at low Reynolds numbers (California Inst of Tech Pasadena Graduate Aeronautical Labs)
[21] Anagnostopoulos P and Bearman P W 1992 Response characteristics of a vortex-excited cylinder at low Reynolds numbers J. Fluids Struct. 6 39–50
[22] Khalak A and Williamson C H K 1997 Fluid forces and dynamics of a hydroelastic structure with very low mass and damping J. Fluids Struct. 11 973–82
[23] Govardhan R N and Williamson C H K 2006 Defining the modified Griffin plot in vortex-induced vibration: revealing the effect of Reynolds number using controlled damping J. Fluid Mech. 561 147
[24] Klamo J T, Leonard A and Roshko A 2005 On the maximum amplitude for a freely vibrating cylinder in cross-flow J. Fluids Struct. 21 429–34
[25] Raghavan K and Berntsen M M 2011 Experimental investigation of Reynolds number effect on vortex induced vibration of rigid circular cylinder on elastic supports Ocean Eng. 38 719–31
[26] Ding Z J, Balasubramanian S, Lokken R T and Yung T 2004 Lift and damping characteristics of bare and straked cylinders at riser scale Reynolds numbers Offshore Technology Conference (Offshore Technology Conference)
[27] Kim S, Alam M M, Sakamoto H and Zhou Y 2009 Flow-induced vibrations of two circular cylinders in tandem arrangement. Part I: Characteristics of vibration J. Wind Eng. Ind. Aerodyn. 97 304–11
[28] King R and Johns D J 1976 Wake interaction experiments with two flexible circular cylinders in flowing water J. Sound Vib. 45 259–83

[29] Assi G R . 2009 Mechanisms for Flow-Induced Vibration of Interfering Bluff Bodies
[30] Alam M M, Moriya M, Takai K and Sakamoto H 2003 Fluctuating fluid forces acting on two circular cylinders in a tandem arrangement at a subcritical Reynolds number J. Wind Eng. Ind. Aerodyn. 91 139–54

[31] Arionfard H and Nishi Y 2019 Experimental investigation on the performance of a double-cylinder flow-induced vibration (FIV) energy converter Renew. Energy 134 267–75

[32] Haider B A and Sohn C H 2018 Effect of spacing on a pair of naturally oscillating circular cylinders in tandem arrangements employing IB-LB methods: Crossflow-induced vibrations Int. J. Mech. Sci. 142 74–85

[33] Ding L, Bemitsas M M and Kim E S 2013 2-D URANS vs. experiments of flow induced motions of two circular cylinders in tandem with passive turbulence control for 30,000< Re< 105,000 Ocean Eng. 72 429–40

[34] Bearman P W and Wadcock A J 1973 The interaction between a pair of circular cylinders normal to a stream J. Fluid Mech. 61 499–511

[35] Zdravkovich M M 1988 Review of interference-induced oscillations in flow past two parallel circular cylinders in various arrangements J. Wind Eng. Ind. Aerodyn. 28 183–99

[36] Sayaadi H and Motekallem A 2016 Numerical Simulation of Vortex Induced Vibration of Three Cylinders in Regular Triangle Arrangement at High Reynolds Number Int. J. Coast. Offshore Eng. 4 1–10

[37] Gaster M 1969 Vortex shedding from slender cones at low Reynolds numbers J. Fluid Mech. 38 565–76

[38] Piccirllo P S and Van Atta C W 1993 An experimental study of vortex shedding behind linearly tapered cylinders at low Reynolds number J. Fluid Mech. 246 163–95

[39] Papangelo A 1992 Vortex shedding from slender cones at low Reynolds numbers J. Fluid Mech. 242 299–321

[40] Jespersen D and Levit C 1991 Numerical simulation of flow past a tapered cylinder 29th Aerospace Sciences Meeting p 751

[41] Hsiao FB, Pan JY C C 1992 The study of vortex shedding frequencies behind tapered circular cylinders. Symp. flow-induced Vib. noise, ASME, 6

[42] Techet AH, Hover FS T M 1998 Vortical patterns behind a tapered cylinder oscillating transversely to a uniform flow J. Fluid Mech. 79–96

[43] Hover FS, Techet AH T M 1998 Forces on oscillating uniform and tapered cylinders in cross-flow. J. Fluid Mech. 97–114

[44] Balasubramanian S, Haan Jr F L, Szewczyk A A and Skop R A 2001 An experimental investigation of the vortex-excited vibrations of pivoted tapered circular cylinders in uniform and shear flow J. Wind Eng. Ind. Aerodyn. 89 757–74

[45] Valles B, Andersson H I and Jønsson C B 2002 Oblique vortex shedding behind tapered cylinders J. Fluids Struct. 16 453–63

[46] Narasimhamurthy V D, Andersson H I and Pettersen B 2009 Cellular vortex shedding behind a tapered circular cylinder Phys. Fluids 21 44106

[47] Visscher J, Pettersen B and Andersson H I 2011 Experimental study on the wake behind tapered circular cylinders J. Fluids Struct. 27 1228–37

[48] Zeinoddini M, Tanimi V and Seif M S 2013 Stream-wise and cross-flow vortex induced vibrations of single tapered circular cylinders: an experimental study Appl. Ocean Res. 42 124–35

[49] Seyed-Aghazadeh B, Carlson D W and Modarres-Sadeghi Y 2015 The influence of taper ratio on vortex-induced vibration of tapered cylinders in the crossflow direction J. Fluids Struct. 53 84–95

[50] Sun W, Jo S and Seok J 2019 Development of the optimal bluff body for wind energy harvesting using the synergetic effect of coupled vortex induced vibration and galloping phenomena Int. J. Mech. Sci. 156 435–45

[51] Villarreal D J Y and SL V B 2018 IVT resonant wind generators vol 2 1–6

[52] Chizfahm A, Yazdi E A and Eghtesad M 2018 Dynamic modeling of vortex induced vibration wind turbines Renew. Energy 121 632–43

[53] Bishop R E D and Hassan A Y 1964 The lift and drag forces on a circular cylinder oscillating in a flowing fluid Proc. R. Soc. London. Ser. A. Math. Phys. Sci. 277 51–75

[54] Koopmann G H 1967 The vortex wakes of vibrating cylinders at low Reynolds numbers J. Fluid Mech. 28 501–12

[55] Feng C . 1968 The measurement of vortex-induced effects in a flow past stationary and oscillating circular and D-section cylinders

[56] Skop R A and Griffin O M 1973 A model for the vortex-excited resonant response of bluff cylinders J. Sound Vib. 27 225–33

[57] Hartlen R T and Currie I G 1970 Lift-oscillator model of vortex-induced vibration J. Eng. Mech. Div. 96 577–91

[58] IWAN, W. D. & BLEVINS R. D 1974 A model for vortex induced oscillation of structures J. Appl. Mech. 581 – 586

[59] Parkinson G V 1974 Mathematical models of flow-induced vibrations of bluff bodies Flow-induced Struct. Vib. 75-15253 04-39) Berlin, Springer-Verlag, 1974, 81–127

[60] Staubli T 1983 Calculation of the vibration of an elastically mounted cylinder using experimental data from forced vibration J. Fluids Eng. 225–229

[61] Albarède P and Monkewitz P A 1992 A model for the formation of oblique shedding and “chevron” patterns in cylinder wakes Phys. Fluids A Fluid Dyn. 4 744–56

[62] Meneghini J R, Saltara F, Fregonesi R A and Yamamoto C T 2005 Vortex-induced vibration on flexible cylinders WIT Trans. State-of-the-art Sci. Eng. 18

[63] Morse T L and Williamson C H K 2009 Prediction of vortex-induced vibration response by employing controlled motion J. Fluid Mech. 634 5
[64] Efstathios Konstantinidis limiting amplitude in vortex-induced vibration of elastically mounted circular cylinders 10th Int. Conf. Flow-Induced Vib. (& Flow-Induced Noise)

[65] Bunzel L O and Franzini G R 2017 Numerical studies on piezoelectric energy harvesting from vortex-induced vibrations considering cross-wise and in-line oscillations Proceedings of the 9th European Nonlinear Dynamics Conference—ENOC2017, Budapest, Hungary pp 25–30

[66] Violette R, De Langre E and Szydłowski J 2007 Computation of vortex-induced vibrations of long structures using a wake oscillator model: comparison with DNS and experiments Comput. Struct. 85 1134–41

[67] Wang L, Jiang T L, Dai H L and Ni Q 2018 Three-dimensional vortex-induced vibrations of supported pipes conveying fluid based on wake oscillator models J. Sound Vib. 422 590–612

[68] Gao Y, Zong Z, Zou L and Takagi S 2018 Vortex-induced vibrations and waves of a long circular cylinder predicted using a wake oscillator model Ocean Eng. 156 294–305

[69] Gao Y, Zou L, Zong Z, Takagi S and Kang Y 2019 Numerical prediction of vortex-induced vibrations of a long flexible cylinder in uniform and linear shear flows using a wake oscillator model Ocean Eng. 171 157–71

[70] Skop R A and Balasubramanian S 1997 A new twist on an old model for vortex-excited vibrations J. Fluids Struct. 11 395–412

[71] Robin W 2015 The Power of the Vortex: An Interview with David Suriol of Vortex Bladeless Renew. Energy Mag.

[72] A. Proto, V.W. Goldschmidt G H T 1968 Hydroelastic forces on bluff cylinders J. Basic Eng.

[73] Zhao J, Nemes A, Jacono D L and Sheridan J 2012 Comparison of fluid forces and wake modes between free vibration and tracking motion of a circular cylinder 18th Australasian Fluid Mechanics Conference, Australasian Fluid Mechanics Society

[74] Khalak A and Williamson C H K 1999 Motions, forces and mode transitions in vortex-induced vibrations at low mass-damping J. Fluids Struct. 13 813–52

[75] Chen C 2011 Permanent magnet linear alternator magnetic field analysis Am. Soc. Eng. Educ. Ac 1731 2011

[76] Soti A K, Thompson M C, Sheridan J and Bhardwaj R 2016 Electrical Power Generation from Vortex-Induced Vibrations of a Circular Cylinder Energy 4 5

[77] Abdelfeki A, Hajj M R and Nayfeh A H 2012 Phenomena and modeling of piezoelectric energy harvesting from freely oscillating cylinders Nonlinear Dyn. 70 1377–88

[78] Safaei M, Sodano H A and Anton S R 2019 A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later (2008–2018) Smart Mater. Struct. 28 113001

[79] Barton D A W, Burrow S G and Clare L R 2009 Energy harvesting from vibrations with a nonlinear oscillator International Design Engineering Technical Conferences and Computers and Information in Engineering Conference vol 48982 pp 427–36

[80] Erturk A, Hoffmann J and Inman D J 2009 A piezomagnetoelastic structure for broadband vibration energy harvesting Appl. Phys. Lett. 94 254102

[81] Cottone F, Vocca H and Gammaioni L 2009 Nonlinear energy harvesting Phys. Rev. Lett. 102 80601

[82] Mann B P and Owens B A 2010 Investigations of a nonlinear energy harvester with a bistable potential well J. Sound Vib. 329 1215–26

[83] Masana R and Daqaq M F 2011 Electromechanical modeling and nonlinear analysis of axially loaded energy harvesters J. Vib. Acoust. 133

[84] Quinn D D, Vakakis A F and Bergman L A 2007 Vibration-based energy harvesting with essential nonlinearities International Design Engineering Technical Conferences and Computers and Information in Engineering Conference vol 48027 pp 779–86

[85] Stanton S C, McGehee C C and Mann B P 2010 Nonlinear dynamics for broadband energy harvesting: Investigation of a bistable piezoelectric inertial generator Phys. D Nonlinear Phenom. 239 640–53

[86] Erturk A, Vieira W G R, De Marqui Jr C and Inman D J 2010 On the energy harvesting potential of piezoelectric systems Appl. Phys. Lett. 96 184103

[87] Abdelkefi A, Nayfeh A H and Hajj M R 2012 Modeling and analysis of piezoelectric energy harvesters Nonlinear Dyn. 67 925–39.

[88] Nayfeh A H, Owis F and Hajj M R 2003 A model for the coupled lift and drag on a circular cylinder International Design Engineering Technical Conferences and Computers and Information in Engineering Conference vol 37033 pp 1289–96

[89] Marzouk O, Nayfeh A H, Akhtar I and Arafat H N 2007 Modeling steady-state and transient forces on a cylinder J. Vib. Control 13 1065–91.

[90] Akhtar I, Nayfeh A H and Ribbens C J 2009 On the stability and extension of reduced-order Galerkin models in incompressible flows Theor. Comput. Fluid Dyn. 23 213–37.

[91] Akhtar I, Marzouk O A and Nayfeh A H 2009 A van der Pol–Duffing oscillator model of hydrodynamic forces on canonical structures J. Comput. Nonlinear Dyn. 4.

[92] Marzouk O A and Nayfeh A H 2010 Characterization of the flow over a cylinder moving harmonically in the cross-flow direction Int. J. Non. Linear. Mech. 45 821–33.

[93] Truitt A and Mahnoodi S N 2013 A review on active wind energy harvesting designs Int. J. Precis. Eng. Manuf. 14 1667–75.

[94] Hu G, Tse K T, Wei M, Naseer R, Abdelkefi A and Kwok K C S 2018 Experimental investigation on the efficiency of circular cylinder-based wind energy harvester with different rod-shaped attachments Appl. Energy 226 682–9.
[95] Kim H S, Kim J-H and Kim J 2011 A review of piezoelectric energy harvesting based on vibration Int. J. Precis. Eng. Manuf. 12 1129–41.
[96] Zhang L B, Abdelkefi A, Dai H L, Naseer R and Wang L 2017 Design and experimental analysis of broadband energy harvesting from vortex-induced vibrations J. Sound Vib. 408 210–9.
[97] Song R, Shan X, Lv F and Xie T 2015 A study of vortex-induced energy harvesting from water using PZT piezoelectric cantilever with cylindrical extension Ceram. Int. 41 S768–73.
[98] Dai H L, Abdelkefi A, Yang Y and Wang L 2016 Orientation of bluff body for designing efficient energy harvesters from vortex-induced vibrations Appl. Phys. Lett. 108 53902.
[99] Dai H L, Abdelkefi A and Wang L 2014 Theoretical modeling and nonlinear analysis of piezoelectric energy harvesting from vortex-induced vibrations J. Intell. Mater. Syst. Struct. 25 1861–74.
[100] Yang Y, Zhao L and Tang L 2013 Comparative study of tip cross-sections for efficient galloping energy harvesting Appl. Phys. Lett. 102 64105.
[101] Akaydin H D, Elvin N and Andreopoulos Y 2012 The performance of a self-excited fluidic energy harvester Smart Mater. Struct. 21 25007.
[102] Dai H L, Abdelkefi A and Wang L 2014 Piezoelectric energy harvesting from concurrent vortex-induced vibrations and base excitations Nonlinear Dyn. 77 967–81.
[103] Zhang L B, Dai H L, Abdelkefi A and Wang L 2017 Improving the performance of aeroelastic energy harvesters by an interference cylinder Appl. Phys. Lett. 111 73904.
[104] Song J, Hu G, Tse K T, Li S W and Kwok K C S 2017 Performance of a circular cylinder piezoelectric wind energy harvester fitted with a splitter plate Appl. Phys. Lett. 111 223903.