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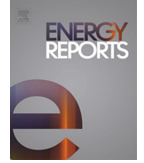
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Development of low-speed wind energy harvesting device

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Abstract

Since the energy demand increases, the sources of fluid energy such as wind energy and marine energy have attracted widespread attention, especially vortex-induced vibrations (VIV) excited by wind energy. This paper proposes a wind energy harvesting device-based VIV concept. The proposed device converts the mechanical energy of the oscillator into electrical energy. Different design shapes, that motivates disturbance in airflow, were proposed and tested. The proposed designs were numerically and experimentally tested to gauge their performance and efficiency in generating power. The detailed design and analysis for VIV including computational fluid dynamics (CFD) simulation were carried out. The CFD simulations were concentrated on the elastic rod (mast), which represents the critical component of the proposed model. Wind tunnel was used to conduct the experimental work. Piezoelectric sensors were utilized to measure and monitor extracted power. The best location of the piezoelectric sensors on the mast was investigated and located. The results of the simulations are reported in this paper. For each simulated case, lift coefficient, velocity, pressure, and vorticity contours are presented. It was also concluded that adding complexity to the geometry of the cylindrical proposed design would increase the lift force, and therefore, increasing the power. Promising numerical and experimental results were obtained, and power generation was maximized.

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Keywords: Wind energy; Vortex induced vibrations; Power generation; Energy harvesting device

1. Introduction

In today's world, with ever-increasing emissions of polluting substances into the atmosphere, it is critical to put a stop to this detrimental trend. Most countries, who are on the verge of a huge environmental crisis, are in critical need of the assistance of cutting-edge clean energy technology to bring this serious problem under control. Solar energy, wind energy, ocean energy, and other large-scale green energy assets are all accessible as viable alternatives to exploitation of fossil fuels and other resources that raise a country's carbon footprint. The goal of this research is to look at one of the most recent methods of energy harvesting: wind power. One of the lists of brand-new methods to produce renewable energy, particularly wind power, nowadays, which includes various types of vertical

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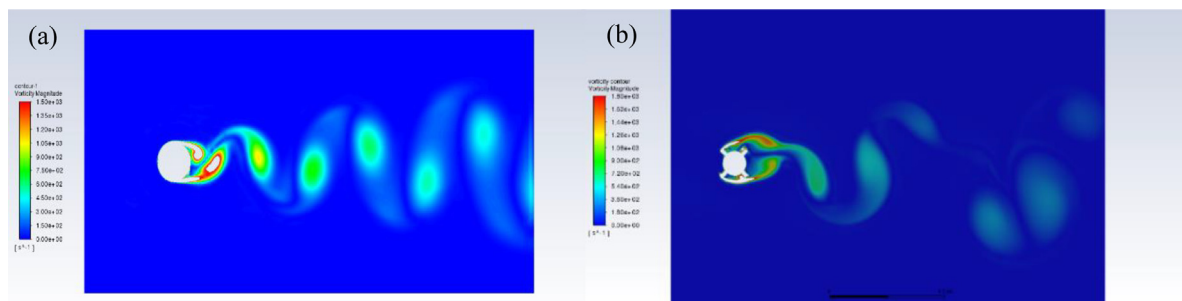


Fig. 1. Vorticity contours at $v = 10$ m/s for both (a) simple cylinder (b) complex and modified cylinder.

and horizontal wind turbines, is of particular interest to scientists: Energy harvesting using Vortex-Induced Vibration (VIV) [1]. The concept behind the described energy harvesting method derives from a well-known fluid mechanics phenomenon called Vortex Shedding, which occurs when fluid flow passes around a blunt body and vortices begin to shed in an oscillatory fashion downstream. A basic illustration of the vortex shedding phenomena is shown in Fig. 1, where the creation of vortices following the item in the flow and on the lateral sides of the object is clearly seen. This oscillating tendency results in an oscillatory lift force, which is the force exerted on that body in the lateral direction, and this force is a significant source of energy that may be gathered. As a result, scientists and engineers apply various ways to deliver this oscillatory force to a component as a means of converting it to electrical energy.

The other conventional method to convert the mechanical power as the result of oscillations is employing the electromagnetic field to convert the mechanical movement to electric power. This strategy was adapted by [2] to convert the vortex-induced vibrations to electrical power. They also considered a magnetic system to regulate the natural frequency of the system in a way that the oscillation would be enhanced. In addition, a structure without a shaft and gear had been proposed this study. Coupled with using a magnetic field to change the natural frequency of the vortex generator as means to enhance the power generation, broadening the range of that the Reynolds numbers in which VIV occurs are a great strategy. To this aim, Huynh et al. [3] employed springs with nonlinear behavior to expand this range in both numerical and experimental FSI studies. Furthermore, ordinary springs are evaluated in this study, and the results of this study revealed that nonlinear ones could immensely elevate the power generation efficiency. A numerical study on the influences of the vortex generator geometry on the VIV phenomenon and power generation was performed Chizfahm et al. [4]. Two types of conical and cylindrical vortex generators are considered in this study. The results of this study revealed that at low Re numbers, the cylindrical vortex generator is the more efficient one; however, at high Re numbers using the conical one leads to better efficiency, and the authors recommend using flexible base structures to acquire better utilization of the available mechanical power. In another study by Dai et al. [5] the effect of the geometry and orientation of the vortex generator on the power generation was assessed. In this study, all possible orientations of a cylindrical vortex generator connected to a mast are scrutinized experimentally, authors focused on the region of synchronization and the attainable power for each case. Abdelkefi in [6] investigated the impacts of the vortex generator shape and analyzed different cross-sections triangular, squared shape, and a vortex generator with D cross-section. They examined the range in which VIV occurs as well as the performance of power generation. They concluded that Triangular vortex generators with an angle of 30 degrees have the best performance in terms of delivering power. A study in which various vortex generators with various cross-sections are assessed to utilize the galloping phenomenon in VIV was conducted by Yanga et al. [7]. A piezoelectric component is used to convert the energy. Among the squared-shape, triangular, D-cross-section, and rectangular experimentally tested vortex generators, the squared ones have the best performance in employing the galloping phenomenon. Energy harvesting from the galloping phenomenon for different shapes of cross-sections was explored by Abdelkefi in [8]. Some other studies focused on the wake-galloping phenomenon. The energy harvesting using piezoelectric components because of mentioned phenomenon, was analyzed by Hubbs and Hu in [9] and the result of that study notes that linear arrangement of cylindrical deformable vortex generators can have far-reaching implications on increasing the power generation.

2. Fluid flow governing equations

The conservation of mass and momentum equations are the most fundamental equations in every fluid flow domain. However, according to the turbulent nature of wind flow in this study, the momentum equation should be written in a way that the effect of turbulent stresses is considered:

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

Conservation of momentum (Cauchy-equation)

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \tau \quad (2)$$

In which ρ is the density, t is time, \mathbf{u} is the velocity field, p is the pressure, and τ is the turbulent stress tensor, and would be calculated based on the selected model in the CFD software. Solving these equations, the Lift coefficient is attainable, which is necessary for power generation calculations:

$$C_L = F_L / \frac{1}{2} \rho U^2 A \quad (3)$$

where: F_L is lift force, A is reference area, and U is freestream velocity. Also, Strouhal number (St), which is mandatory for finding vortex shedding frequency, can be calculated from the equation below:

$$St = fL/U \quad (4)$$

where: St is Strouhal number, f is Vortex shedding frequency, and L is characteristic length:

2.1. Pre-processing fluid properties and flow parameters

Due to the turbulent nature of the wind flow in this study, mesh generation, especially the size of the first layer grid, is of substantial importance. To calculate the height of the first layer, first, the Reynolds number should be calculated:

$$Re = VD/\nu \quad (5)$$

where V is free stream velocity [m/s], D is diameter [m] and ν is kinematic viscosity [m²/s]. And then, the skin friction coefficient C_f :

$$C_f = [2 \log_{10}(Re) - 0.65]^{-2.3} \quad (6)$$

Therefore, wall shear stress can be obtained:

$$\tau_w = C_f \cdot \frac{1}{2} \rho_{air} V^2 \quad (7)$$

And, the non-dimensional friction velocity can be calculated by:

$$u_\tau = \sqrt{\tau_w / \rho_{air}} \quad (8)$$

Now, based on the non-dimensional height y^+ , the first inflation layer height can be obtained:

$$y_p = \frac{y^+ \mu}{\rho u_\tau} = \frac{y^+ \nu}{u_\tau} \text{ and } y_H = 2y_p \quad (9)$$

Therefore, based on the information above and flow parameters, the first layer height can be calculated as reported in [Table 1](#).

2.2. Setting-up CFD analysis parameters

Reference values used in the simulation analysis are reported in [Table 2](#). Fluent, which is a computational fluid dynamics software was used for meshing and CFD analysis.

Table 1. Results of fluid calculation for generation of girds' first layer.

#	D [mm]	ν (m ² /s)	V (m/s)	Re	y^+	y_H [mm]
1			10	25 618	1	1.483
2	40		15	38 427	1	1.038
3		0.00001561	20	51 235	1	0.8046
1			10	117 870 000	30	5.057
2	180		15	176 810 000	30	5.031
3			20	235 750 000	30	4.973

Table 2. Reference values.

Criterion	Unit	Value	Criterion	Unit	Value
Area	m ²	0.04 * 0.1	Temperature	K	298
Density	kg/m ³	1.184	Velocity	m/s	10
Length	m	0.04	Viscosity	kg/(m s)	0.00001561
Pressure	kPa	0	Ratio of specific heat		1.4

3. Results and discussion

3.1. CFD and simulation results

The results of CFD simulations for two different geometries (simple cylinder and complex cylinder) at wind speed 10 m/s are presented. Fig. 1. shows the vorticity contours for simple cylinder and complex cylinder respectively. It can be noticed that the complex cylindrical shape produced more flow disturbance and intensive vortices. This will largely contribute and motivate the mast to vibrates and hence produce more energy.

3.2. Results discussion

The impact of wind freestream velocity on lift coefficient, regardless of shape, is the most important point that can be gleaned from the results reported here. The simulation's purpose was to determine the lift force as a way of calculating the power that proposed designs could deliver. As these graphs show, raising the velocity first does not result in a linear rise in the lift coefficient. The lift coefficient increases in proportion to the increase in wind velocity. Another thing worth mentioning is that as wind velocity rises, the frequency of lift coefficient rises as well, which is a crucial contributing factor in piezoelectric power generation. Although the nature of this physical problem is transient, the lift coefficient oscillations behave in a steady manner after a certain amount of time. The results show that raising the velocity delays the beginning of stable behavior. The main purpose, however, was to assess the impact of modifying the geometry on this event. According to the lift coefficient graphs, adding complexity to the geometry dramatically increases the lift force exerted on the vortex generator object. For example, at $v = 20$ m/s, the lift force given to the complicated cylinder vortex generator is more than three times that of a simple cylinder. In addition, for the last three cases which exact sizes are used for the simulation, due to the larger area exposed to the wind flow, the larger oscillatory lift force is exerted in the vortex generator, and the main purpose for doing the simulation for this part was to assess the designed system in the real-world scale. The vorticity distribution in the case of the complex cylinder is different, and the size of the vortices is much larger, and the power of the vortices is not focused on the core of the vortex, as can be seen in the presented results (Fig. 1), demonstrating that the angular velocity of fluid elements is much higher and distributed more evenly in a single vortex.

Maximum attainable power from each example, three geometrical shapes (simple cylinder, complex cylinder, and modified cylindrical shape) at three different wind speeds ($v = 5, 10, 15$ m/s) and three locations for piezoelectric sensor (top, middle and bottom). The power that can be extracted at several locations of the piezoelectric is depicted in Fig. 2. The combination of these factors geometrical shape, velocity and piezoelectric position formed the cases from 1st to 9th and the 10th case represents real model with real dimension (6 m height). It was found that at wind speed 15 m/s for complex cylindrical geometry and piezoelectric positioned at the bottom of the mast produced maximum power.

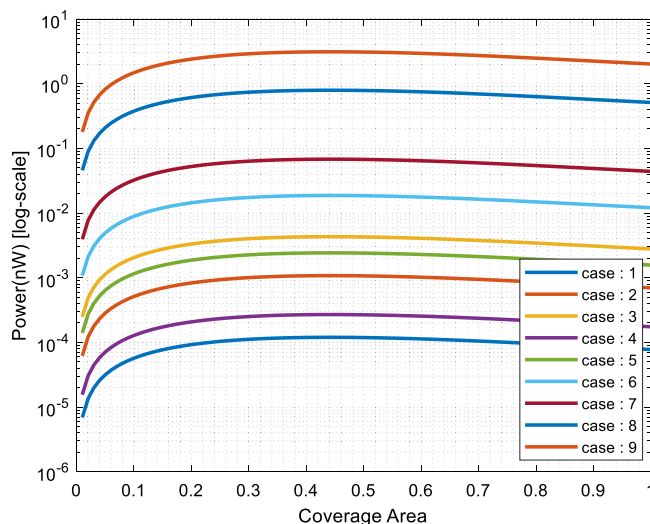


Fig. 2. Output power at different locations of the piezoelectric component located near the vortex generator.

The preceding results show that both wind velocity and complex geometry contributed to the rise in lift coefficient making it promising in generating power.

4. Conclusion

The effect of changing vortex generator shape on VIV energy harvesting was investigated numerically and experimentally. A simple cylinder, a complex cylinder, and a real-world size complex cylinder vortex generator have been considered in this study ANSYS Fluent software, which utilizes the Finite Volume Method (FVM), has been used to perform CFD simulation. Velocity, pressure, and vorticity contours were generated and interpreted. More importantly, the transient behavior of the lift coefficient over time is presented for each case. The results of the numerical study demonstrate that increasing the inlet velocity increases the maximum magnitude of the lift coefficient, its frequency, and the needed time to reach the pseudo-steady situation in this problem which has a transient nature. In addition, adding complexity to the cylinder geometry enhances the maximum lift force applied to the vortex generators substantially and can boost the efficiency of VIV energy harvesting. As a result, every factor that contributes to increasing the lift force increases the generated power. The numerical results' trends are in good agreement with the experimental tests. The optimum piezoelectric component location that maximized energy generation was experimentally determined. Based on the acquired results, the order of the generated power by the proposed designs ranges from 0.01 to 100 nW.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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