Effect of solidity on the dynamic behaviour of the Darrieus turbine with leading-edge protuberance

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Abstract
The dynamic behaviour of the straight–type Darrieus turbine with leading-edge protuberance (LEP) was analysed under various solidity ratios at several tip speed ratios through experiments. The Darrieus turbine is a type of Vertical Axis Wind Turbine (VAWT) which uses wind energy to generate electricity. This type of turbine was subjected to vortex-induced and buffeting types of vibrations. These vibrations were more sensitive to the number of blades and tip speed ratios. Based on the experimental measurements, the results revealed that, at a low tip speed ratio, the four-bladed turbine exhibits lesser vortex-induced vibrations than those of the three and five-bladed turbines. However, at a high tip speed ratio, the three-bladed configuration operates well against the vortex-induced vibrations. In the case of buffeting, a three-bladed turbine diminishes the dynamic oscillations at both low and high tip speed ratios, whereas the four and five-bladed turbines induce dynamic oscillations at slightly higher amplitudes. However, the amplitude of buffeting is smaller than those of vortex-induced vibrations.

Keywords: Dynamic response; Darrieus turbine; LEP; Vortex-Induced Vibrations; Buffeting

1. Introduction
The use of renewable energy sources has increased dramatically in the recent decade. With the increasing concern about the consequences of fossil fuels on global warming, there is a renewed interest in wind energy as a sustainable, pollution-free source and helps in generating electricity by utilizing kinetic energy. With the advancement in technology, several wind turbines have been designed and developed. The Vertical Axis Wind Turbine (VAWT) is a type of turbine where the rotor shaft is transverse to the wind, are gaining attention because their design is simple, they use wind from all directions, and are ideal for micro-generation. Moreover, their manufacturing and maintenance costs are relatively low, they operate at low wind speeds, and in high turbulence with skewed wind conditions, and do not require any yaw device [1]. These factors have led to increased interest in studying VAWTs despite their low efficiencies. Darrieus turbines are the most common lift-type VAWTs and are efficient even at high tip speed ratios. Straight-
bladed (H - type) Darrieus turbines are well known for their low cost and a high average of output torque. Generally, a three-bladed turbine is used in which each blade is located at 0°, 120°, 240° azimuth angles.

The VAWTs can exhibit different types of vibrations. Vortex Induced Vibration (VIV) occurs in the across-wind direction (X) when the frequency of vortex shedding due to flow separation matches the natural frequency of the structure. This 'lock-in' phenomenon results in high amplitude vibrations of the turbine. Buffeting is a type of vibration induced due to the gustiness of the wind, and that takes place along the wind direction (Y). As the VAWTs are usually placed on the roofs of building, they are especially susceptible to these vibrations. Insight studies are required to diminish these vibrational behaviours and to broaden the scope of application to all suitable places.

The leading-edge protuberance (LEP) on the turbine blades can effectively reduce dynamic oscillations for a wide range of wind speeds. Especially, the high LEP is more advantageous in terms of vibrational control [2]. The dynamic responses of the turbine are more susceptible to the solidity and tip speed ratio of the turbine. The effect of the number of blades on the dynamic behaviour of the Darrieus turbine geared transmission system was studied [3]. The results revealed that with the increase in the number of blades from two to three and three to four, the amplitude of vibration significantly decreases. With the increase in blade number, the oscillations of the dynamic vibrations gradually decrease. The vibrational amplitude is sensitive to the variation of the tip speed ratios. The dynamic oscillations drastically change with the tip speed ratios. They concluded that the three-bladed design configuration is the optimum choice for greater dynamic behaviour considering both aerodynamic efficiency and dynamic vibration. The excitation mechanism was deeply analysed for three types of aeroelastic/aerodynamic phenomena [4]. The results conveyed that the VIV dominates at lower wind speeds, while buffeting dominates at higher wind speeds. Buffeting amplitudes are substantially smaller than VIV amplitudes. As a result, to increase the performance and lifespan of the turbine, it is required to examine the VAWTs under all of these circumstances.

We have studied the dynamic behaviour of the VAWT having LEP, at different solidity and tip speed ratios, through experiments. Specifically, we have studied a Darrieus H-type turbine and investigated the vibrations in a non-stationary regime for three, four, and five-bladed configurations at two tip speed ratios.

Nomenclature

| Symbol | Description |
|--------|-------------|
| VAWT   | Vertical Axis Wind Turbine |
| LEP    | Leading Edge Protuberance |
| NREL   | National Renewable Energy Laboratory |
| S      | Length of the blade |
| N      | Number of blades |
| D      | Diameter of the turbine |
| R      | Radius of the turbine |
| c      | Chord length |
| $U_\infty$ | Wind Speed |
| $\lambda$ | Tip speed Ratio |
| $\sigma$ | Solidity ratio |
| $\omega$ | Angular velocity of the blade |

2. Methodology

The design of the turbine is intended to have low vibrational characteristics by the presence of LEP. The LEP is incorporated from the humpback whales, a bio-inspired design is thought to offer the potential to improve the blade stability of wind turbines. The high LEP is preferable in terms of dynamic oscillations [2]. The three-bladed, four-bladed, and five-bladed turbine configurations with high LEP are modelled and machined. The optimum configuration is selected based on the dynamic stability. The front view of the modelled three-bladed turbine is depicted in Fig. 1. The top view of the modelled three-bladed turbine is
shown in Fig. 2. In the aspect of maximum power, the NREL’s S1046 symmetrical airfoil has been selected for the profile of the blades.

2.1 Experimental Setup
The VAWT with different configurations are mounted in front of an axial wind blower tunnel. A Triaxial accelerometer and RPM sensor are mounted to the central shaft to measure the acceleration in three orthogonal directions and speed of the turbine for different solidity and tip speed ratios. The displacement data is obtained by integrating the acceleration data and filtered to observe the low-frequency oscillations. The data for three-bladed, four-bladed, and five-bladed turbine is plotted to compare the performance.

Tip Speed Ratio ($\lambda$) is the ratio of the tip speed of the blade to the wind speed

$$\lambda = \frac{\omega R}{U_\infty}$$  \hspace{1cm} (1)

Solidity Ratio ($\sigma$) is the ratio of the overall area of the blades to the swept area of the turbine

$$\sigma = \frac{Nc}{D}$$  \hspace{1cm} (2)

For a given chord length and rotor diameter of a turbine, the solidity ratio is directly related to the number of blades. The solidity ratio corresponding to $N = 3, 4, \text{ and } 5$ are 0.47, 0.68, and 0.72 respectively. These characteristics are required to comprehend the Darrieus turbine's functioning and are beneficial in enhancing the turbine's performance.
3. Results and Discussion

High solidity turbine produces more power as the effective area for the turbine to utilize the wind increases. However, the aerodynamic efficiency decreases with increase in solidity due to the interference between the blades and vibrations. Hence, the solidity of the turbine contributes a crucial role in terms of its operating conditions and fatigue oscillations. This section primarily focuses on the dynamic responses of the turbine under various solidity ratios. As discussed earlier, for a given chord length and a radius of the Darrieus rotor, the solidity ratio directly relates to the number of blades of the turbine. The representation in terms of the number of blades is more intuitive and recognizable. So, we will be using solidity and the number of blades interchangeably. The dynamic behaviour is sensitive to the tip speed ratio. Depending upon the tip speed ratio, any type of vibration in an excitation mechanism can dominate. Hence, the effect of the tip speed ratio should be analysed to select the optimum conditions of the turbine.

3.1 Effect of Solidity on Tip Speed of the turbine

The efficiency and speed of the turbine are affected by the number of blades. The increased number of blades should result in increased torque as more area of rotor strikes the wind. However, the increase in torque gets smaller and smaller due to increase in inertia and blade interference. Thus, the increase in turbine efficiency decreases with increase in number of blades. The speed and torque of the turbine doesn’t only depend upon the inertia but also on the properties of blade and the angle of attack. Fig. 3 shows the variation of tip speed to wind speed for different turbine configurations. The tip speed of the turbine increases with an increase in the number of blades from three to five-bladed configuration with high LEP. For a given wind speed, a five-bladed turbine rotates faster. Also, the increase in solidity reduces the self-starting torque of the turbine.
3.2 Vortex-Induced Vibrations (VIV)

The vortex-induced vibrations occur in the across-wind direction (X). For $\lambda = 0.04$, the vortex shedding is dominant for a three-bladed configuration and vibrates with larger amplitudes, as shown in Fig. 4. When the number of blades is increased to four, the amplitude of vibration significantly decreases. With a further increase from four to five blades, the central shaft displacement slightly decreases. With the increase in $\lambda$ from 0.04 to 0.15, the vibration amplitude declines for the three-bladed turbine and witnesses a decreased pattern, as depicted in Fig. 5. Whereas, for four and five-bladed turbines, there is a slight increase in the dynamic oscillations initially followed by a gradual decrease. The three-bladed turbine exhibits lower mechanical vibrations than the other configurations. We can conclude that, at a low tip speed ratio, the turbine exhibits a larger vibration due to vortex shedding, and four and five-bladed configurations give lower mechanical vibrations. At a high tip speed ratio, the vortex shedding is suppressed, and a three-bladed turbine performs well.

3.3 Buffeting

Buffeting occurs in the along-wind direction (Y). For $\lambda = 0.04$, the vibration due to buffeting is less and operates under safe conditions for a three-bladed turbine, as shown in Fig. 6. We can observe that the buffeting is quite dominant in four blades, and the vibration amplitude slightly decreases as we move to five blades. However, the buffeting amplitudes are smaller than those of vortex-induced vibrations. For $\lambda = 0.15$, the three-bladed turbine performs well by suppressing the vibration due to buffeting and exhibits lower amplitudes. For four and five-bladed turbines, the buffeting amplitude slightly increases with the increase in tip speed ratio, as demonstrated in Fig. 7. It can be understood that using three blades at a high tip speed ratio result in a better dynamic vibration due to buffeting.

Figure 3: Tip speed vs Wind speed for $N = 3$, 4 and 5
Figure 4: Displacement across - wind direction at $\lambda = 0.04$

Figure 5: Displacement across - wind direction at $\lambda = 0.15$
Figure 6: Displacement along - wind direction at $\lambda = 0.04$

Figure 7: Displacement along – wind direction at $\lambda = 0.15$
3.4 Effect of Solidity on Peak-to-Peak Amplitude Across and Along Wind Direction

At a lower tip speed ratio, the four-bladed turbine exhibits a lesser maximum amplitude of VIV. However, the amplitude increases gradually with an increase in tip speed ratio. At a higher tip speed ratio, the three-bladed turbine gives a lesser maximum amplitude, indicating that the dynamic oscillations of VIV are declining as the tip speed ratio increases, as shown in Fig. 8. The three-bladed turbine exhibits a lesser maximum amplitude of buffeting at a low tip speed ratio. With the increase in tip speed ratio, the increase in maximum amplitude is lesser for three blades which is not the case with four and five blades. At higher tip speed ratios, the three-bladed turbine operates well against buffeting, as depicted in Fig. 9.

![Figure 8: Peak-to-Peak amplitude across wind direction](image)

![Figure 9: Peak-to-Peak amplitude along wind direction](image)
4. Conclusion
Based on the experimental measurements, the effect of solidity on the dynamic behaviour of the Darrieus turbine with leading-edge protuberance was analysed. The results revealed that the VAWTs with different blade configurations exhibit periodic oscillations and are susceptible to two types of vibrations. At a low tip speed ratio, the three-bladed turbine exhibits larger amplitudes due to vortex-induced vibrations. However, the vortex shedding diminishes as the tip speed increases. The amplitude of vortex-induced vibration is lesser for four and five-bladed turbines but increases with tip speed ratio. The turbines oscillate owing to buffeting at amplitudes less than vortex-induced vibrations when the tip speed ratio is high. At a low and high tip speed ratio, the three-bladed turbine gives lower buffeting oscillations. Thus, it can be concluded that the three-bladed configuration of VAWTs with LEP generates the highest performance in terms of dynamic behaviour at high tip speed ratios and four-bladed configuration at low tip speed ratios. The study was primarily focused on the time domain of the vibrations. The vibrational characteristics in the frequency domain may be different and changes the entire conclusion upside down. Hence, it is essential to study the vibrations in both the domains to come to single conclusion. The frequency aspect of the vibrations of these configurations are under research.

5. References

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