Whether the Darrieus Rotor with Straight-Blades or Curved-blades is the Best, in Terms of Aerodynamic Efficiency

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Abstract An essential part of any wind turbine system is the rotor because it is the component that is in direct contact with wind and converts its kinetic energy into mechanical power. Then, it can either use this mechanical power directly to run some machinery, or you can use it to run an electricity generator and get electricity. One such turbine which is ideal for small-scale applications is the Darrieus wind turbine. This turbine has two blade configurations, straight or curved. This study aims to figure out the influences of these two blade configurations on the aerodynamic performance of the wind turbine. The engineering geometric shape of a parabolic Darrieus rotor was selected with certain dimensions, in this study it called P-D, and then a straight blade Darrieus rotor was extracted from it, in this study it called S-D1, similar to that of a parabolic in terms of rotor diameter and rotor height values, number of blades, blade section length and its type. Thus, a geometric similarity was obtained between the two rotors in terms of height to diameter ratio value and solidity value. Another rotor called S-D2 was also extracted and it is similar to P-D in terms of blade length, which means that the parabolic blade is straightened. There is also a similarity in solidity, and therefore it can be said that the masses of the rotors P-D and S-D2 are equal. This is the methodology that was followed to make the comparison in terms of aerodynamic. This analysis is done by developing a computer program that is based on mathematical model called multi-stream tube which modified to apply on both configurations of Darrieus turbine. The straight-bladed configuration is the best, according to this study.

1. Introduction
Regardless of what the type of turbine is, the rotor or "blade assembly" is thought to be an essential component since it is responsible for extracting kinetic energy from the wind and turning it into useful shaft power. Therefore, it is imperative that the rotor is of high aerodynamic performance to make an efficient wind turbine. Consequently, all the attention befalls on the design of the rotor, and its geometrical parameters. There are several geometrical parameters, each with its own relative influence on the aerodynamic performance. One key indicator of performance is Cp or "power coefficient" as a function of tip speed ratio $\lambda_0$. Cp and $\lambda_0$ are both non-dimensional quantities and have the following defining functions:

$$C_p = \frac{P}{0.5 \rho V^3 A} \quad \text{.................................................................(1)}$$
\[ \lambda_0 = \frac{\omega R}{V} \]  \hspace{10em} (2)

Where: \( P \) is rotor shaft power (W), \( \rho \) is air density (kg/m³), \( V \) is wind speed (m/s), \( A \) is rotor swept area (m²), \( \omega \) is the rotational speed of the rotor (rad/s), and \( R \) is rotor radius (m).

2. Rotor geometrical parameters

As see in Fig. 1, the rotor is made up of a number of blades, “N”, all of which have a cross-section of an airfoil with constant chord length “C”. Regardless of the configuration of the blades, the rotor has a height of “2H” and diameter “2R”. Comes to thought, in the first step of the aerodynamic design process, the choice between the two configurations of the blades straight or curved. Another point to consider is that Darrieus wind rotors also vary from one another depending on the values of \( N, C, R, \) and \( H \). All these factors combine to have an effect on rotor performance. The variables \( N, C, R, \) and \( H \) are usually grouped into two non-dimensional groups, which are \( (H/R) \) and \( (NC/R) \). As can be seen from the expressions, the first group is the rotor height to diameter ratio, and the second one is known as rotor solidity, which is defined as the ratio of total blade platform area to the rotor swept area. In comparison to the straight-bladed rotor (solidity = 0.5NC/R), the solidity of a curved bladed rotor is better approximated by the function, which includes both \( (NC/R) \) and \( (H/R) \) \([5]\). In addition, blade aerodynamic efficiency, structural considerations, and manufacturing costs are some of the metrics considered when choosing a particular blade shape.

![Figure 1. The original design of Darrieus with parabolic shape and the upgraded design is straight blades](image_url)

3. Mathematical modelling of Darrieus rotor

There are many mathematical models in the literature which may be employed for the analysis of Darrieus rotors. One such mathematical model is called blade-element-momentum methods, which has been proposed and developed by several authors \([6]\) \([7]\) \([8]\) \([9]\). The model recreates the rotor by replacing it with double actuator discs, which are then enclosed in single or multiple stream tubes. It then does its job of figuring out air velocity distribution by equating the axial component of the aerodynamic forces acting on the rotor with the time rate change of axial momentum of the disc(s). The velocity distribution is important for finding out the rotor’s power. Another type of mathematical model which has been previously used is the vortex model, proposed by Larsen \([10]\). This model recreates the rotor by replacing it with a system of bound and trailing vortices, a method similar to the vortex-lattice method used for analysing the design and performance of aeroplane wings and propellers. Hirch and Mandal introduced what is called the cascade model \([11]\), which closely replicates a technique of cascade flow analysis, which is usually used in the field of turbomachinery. The model put forward by Paraschivoiu is the most reliable one for the determination of local aerodynamic blade forces because it is accurate. However, for the determination of overall rotor performance, we have chosen the multi-
stream tube model proposed by Strickland. The justification for using this model over any other comes from the fact that this study is primarily concerned with finding out the overall performance of the two configurations of rotors. In this research, Strickland’s model (Multi streamtube model) used to make a computer program by Microsoft Visual Software that took rotor geometrical variables as the independent variable and gave out the variation of $C_p$ with $\lambda_0$. Then, the published wind tunnel experimental results were used to validate it. The validation is shown in figure 2, as expected, there was little to no discrepancy between the experimental results and the data given by the program over most of the $\lambda_0$ range [12].

4. Rotor configurations studies
To achieve the goal of this research, 15 configurations has been verified, Divided into 7 types Parabolic-Darrieus (PD) and 8 types H-Darrieus (SD). The values that chosen for the rotor’s geometrical variables were carefully considered using the help of previous studies. It was evident in those previous studies that a value of 0.2 for (NC/R) is best for optimal rotor performance for both types of rotors, curved or straight [12]. The following relations are those which all curved bladed configurations strictly follow:

\[
\frac{r}{R} = \sin\left(\frac{\pi z}{2H}\right) \tag{3}
\]

\[
\beta = \tan^{-1}\left\{\frac{2H/R}{\cos(\pi z/2H)}\right\} \tag{4}
\]

Where $r$, $z$ and $\beta$ are as shown in figure 2. However, for H-Darrieus ($r/R$) = 1 and $\beta$ = 90°

Firstly, 3 geometric shapes were taken, analysed and compared with each other. they called P-D, S-D1, and S-D2 which shown in Table 1 and Fig. 3. The P-D and S-D1 configurations were chosen to compare the performance of curved versus straight-bladed rotors while keeping the (H/R) and (NC/R) ratios constant. This means that both of the configurations have the same solidity value. The rotor S-D2 is called the "equivalent rotor" of P-D because both of them have the same blade length. This is done to compare the actual performance of the different rotor configurations whilst keeping the mass and solidity to be constant throughout the configurations. To reduce the cyclical variations of aerodynamic forces in the rotor blades to a minimum, N (number of blades) chosen to be equal to 3 due to its advantage in terms of reducing the problem of starting. It is evident from the literature that lightly loaded three-bladed rotors are able to self-start when steady wind conditions are provided. In comparison to three-bladed rotors, the two-bladed rotors have a self-starting that is heavily dependent on the initial orientation.
[13][14]. The cross-sectional shape of the blades of the three rotors was NACA0012 airfoil. This airfoil type was chosen because the aerodynamic lift and drag coefficients ($C_l$ & $C_d$) data for a range of angles of attack ($\alpha$) from zero to 360 was readily available [15] [16] [17].

Successively, as will be explained in the results section later, each geometric shape of the Parabolic Darrieus type - and its equivalent of the H- Darrieus type were selected to be under comparison at one time by constant the mass of the rotor and at other times by constant the height to diameter ratio ($H/R$) of the rotor. For further clarification, when looking at Table 1 it can easily be seen that PD1 equivalent to SD1, PD2 equivalent to SD2 and so in the same pattern for the rest of the shapes in the Table 1.

Table 1. Parabolic & straight blade - Darrieus rotor configurations

| Symbol | H (m) | R (m) | C (m) | N | (H/R) | (NC/R) |
|--------|-------|-------|-------|---|--------|--------|
| PD1    | 1.16  | 1.16  | 0.03  | 3 | 1      | 0.078  |
| PD2    | 1.16  | 1.16  | 0.06  | 3 | 1      | 0.155  |
| PD3    | 1.16  | 1.16  | 0.09  | 3 | 1      | 0.233  |
| SD1    | 1.16  | 1.16  | 0.03  | 3 | 1      | 0.078  |
| SD2    | 1.16  | 1.16  | 0.06  | 3 | 1      | 0.155  |
| SD3    | 1.16  | 1.16  | 0.09  | 3 | 1      | 0.233  |
| PD4    | 0.812 | 1.16  | 0.07  | 3 | 0.7    | 0.181  |
| PD5    | 1.276 | 1.16  | 0.07  | 3 | 1.1    | 0.181  |
| PD6    | 1.74  | 1.16  | 0.07  | 3 | 1.5    | 0.181  |
| SD4    | 0.812 | 1.16  | 0.07  | 3 | 0.7    | 0.181  |
| SD5    | 1.276 | 1.16  | 0.07  | 3 | 1.1    | 0.181  |
| SD6    | 1.74  | 1.16  | 0.07  | 3 | 1.5    | 0.181  |
| P-D    | 1.044 | 1.16  | 0.07  | 3 | 0.9    | 0.181  |
| S-D1   | 1.63  | 1.16  | 0.07  | 3 | 1.4    | 0.181  |
| S-D2   | 0.812 | 1.16  | 0.07  | 3 | 0.7    | 0.181  |

Where:
PD & P-D is Parabolic Darrieus
SD & S-D is H Darrieus

Figure 3. Rotor S-D1 and S-D2 extracted from rotor P-D for comparison

5. Results and discussion
As we have mentioned already, the decision as to which rotor configuration (straight vs curved bladed) is best suited can be made entirely on their aerodynamic performance. This study not looking at structural considerations because they don’t matter much in the case of small-scale standalone Darrieus
wind rotor systems. The literature seems to indicate that the lower the value of (H/R), the higher the chance of the rotor self-starting [18] [19].

5.1. Influence of (NC/R) for curved and straight-bladed rotors

Fig. 4 shows Cp($\lambda_0$) curves of pairs of rotors, with each pair containing both straight and curved-bladed rotor configurations (PD1, PD2, PD3, SD1, SD2 and SD3). Although have set the value of (NC/R) differently for each rotor pair, all of the rotors have (H/R) ratio equal to one. The ratio (NC/R) has a positive correlation with the value of maximum power coefficient ($C_{pm}$), but after a certain point, the correlation becomes negative. The fact that the value of $C_{pm}$ starts having a negative correlation with the value of (NC/R) at a certain $\lambda_0$ is indicative of the fact that there is a decrease in rotational speed ($\omega$), which ultimately aids higher gear-up ratios. The Cp($\lambda_0$) becomes "peakier" when the term (NC/R) increase, thereby narrowing the ($\lambda_0$) range over which optimal rotor performance can be expected. Fig. 4 indicates that similar trends are followed by the influence of (NC/R) on the straight-bladed rotors. In comparison with curved-blade rotors, the values of $C_{pm}$ are significantly higher for straight-bladed rotors.

![Figure 4. Influence of (NC/R) on Cp($\lambda_0$) for pairs of curved and straight-blade configurations H/R = 1](image)

5.2. Influence of (H/R) for straight and curved bladed rotors

Whilst keeping the value of (NC/R) constant and equal to 0.18, Fig. 5 represents the Cp($\lambda_0$) curves for pairs of straight-bladed and curved bladed rotors with varying values of (H/R). The results are surprising. It is evident from the data that the ratio of height to diameter bears no influence on the Cp($\lambda_0$) curve when dealing with the straight-bladed rotor (H- Darrieus). One reason for this is that radial distance, r, and the angle $\beta$ are constant over the entire rotor blade. Therefore, for a given azimuth angle ($\theta$), the flow conditions are invariant to the height. When speaking in practical terms, the effect of blade-tip power losses will be obvious on the Cp($\lambda_0$) curve. When dealing with the curved bladed rotor, the value of $r$ and $\beta$ are not constant and vary across the blade length (H). Consequently, the height of the rotor is going to influence the Cp($\lambda_0$) curve. The manifestation of this influence can be figured out from the decrease in Cp as (H/R) increases over the low to medium ($\lambda_0$) range. it can be seen in the figure that this decrease in Cp is to be expected for other values of (NC/R) as well and that it is related to an increase in $\beta$ resulting from an increase in the ratio (H/R). Concerning the Darrieus Parabolic curves in Fig. 5, in the medium and high range of $\lambda_0$ values, an increase in (H/R) leads to a slight decrease in Cp values.
5.3. Comparison between curved and straight-bladed rotors

Two particular rotor geometrical configurations were chosen for this comparison. These are solidity (NC/R) and height to diameter ratio (H/R), and rotor mass.

5.3.1. Comparison where (H/R) and (NC/R) are kept constant

The rotor configurations called P-D and S-D1 used in this comparison. Noticed that the aerodynamic performance of curved rotor, P-D, had beaten the straight-bladed rotor, S-D1, on the basis of the Cp(λ₀) merely. These results were seen for the low and high (λ₀) values. However, the discrepancy was noticed over the middle range of (λ₀), where Cp is substantially higher for rotor S-D1. Relation (1) clearly states that the shaft power, P, is directly proportional to both Cp and A, which means we may have to look at the ACp(λ₀) values since the straight-bladed rotor has a larger swept area, A. Since A was used to define Cp, it might not sound reasonable to include its effects, but bear in mind that the rotor P-D and S-D1 are not geometrically symmetrical. They are made of different geometrical parameters. Therefore, the inclusion of swept area, A is imperative. As it is evident from Fig. 6 that the straight-bladed rotor is more promising than the curved bladed rotor over the entirety of the Cp(λ₀) curve.

Figure 5. Influence of H/R on Cp(λ₀) curve for pairs of curved and straight-blade configurations at NC/R = 0.18.

Figure 6. Comparing the performance of two-straight blades rotors with the curved-blades rotor
5.3.2. Comparison given identical rotor mass and (NC/R)

We have used rotor configurations named P-D and S-D2 for this comparison. We obtained the rotor S-D2 by straightening out the blades of the rotor P-D. Doing so increased the swept area greatly while keeping the increase in (H/R) a minimum. As seen before that for a constant (NC/R), the value of the variable (H/R) bears no effect on the Cp(λ₀) curve for a straight-bladed rotor. When this previous sentence is kept in consideration, it is not hard to grasp that you will observe from Fig. 6 the coincidence of Cp (λ₀) curves for S-D1 and S-D2 rotors. Therefore, the aforementioned results of the comparison of Cp (λ₀) curves for P-D and S-D1 also go with P-D and S-D2 Cp(λ₀) curve comparison. However, the considerable difference in the swept area of rotors P-D, S-D1, and S-D2, Fig. 7, will tell us that the “equivalent” straight bladed rotor offers sizable advancement in aerodynamic performance in comparison with the curved bladed rotor.

6. Conclusion

Staying within the confines of the accuracy of the mathematical method which we employed for analysis, the results of our study have the following conclusions:

- For any rotor configuration, decreasing solidity will decrease the mass of the rotor, and it will run faster, which is ideal for electricity generation.
- The power coefficient curve as a function of (λ₀), or Cp (λ₀) curve, is invariant to the rotor height to diameter ratio for the straight-bladed rotor. However, for the curved bladed configuration, the ratio (H/R) has a sizable effect on the Cp curve over the low to medium (λ₀) range.
- When solidity (NC/R) and height to diameter ratio (H/R) are kept constant, the straight bladed rotor configuration has much more promising results.
- When rotor mass and solidity are kept constant, the straight bladed rotor configuration wins again.

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