Numerical investigation of stand-still characteristics of a bio-inspired vertical axis wind turbine rotor

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Abstract. This paper reports the preliminary findings of a numerical study of a 500 W bio-inspired Vertical Axis Wind Turbine (VAWT) rotor for an urban environment. The rotor shapes are inspired by seed pods of two trees found commonly in India viz. *Mimosa* and *Bauhinia Variegata*. 15 samples of seed pods were collected from each of these trees and their diameter-to-height ratio (d/h) & helix pitch-to-height ratio (p/h) were measured. Baseline rotor shapes were based on these measurements. Subsequently, d/h and p/h ratios were varied and a 3D parametric CFD analysis was carried out using an open-source CFD solver, OpenFOAM. 3D CAD models of the rotors were created using SOLIDWORKS. Grids were generated by blockMesh and snappyHexMesh tools of OpenFOAM. Numerical simulations revealed that for a d/h of 0.27 and p/h of 0.7, the single bladed helical shaped rotor produced a stand-still aerodynamic torque of about 0.26 Nm at a wind speed of 2 m/s. This was higher than the typical cogg ing torque of a 500 W permanent magnet generator. Hence, the bio-inspired single bladed helical shaped rotor with d/h of 0.27 and p/h of 0.7 would exhibit early start-up at wind speeds as low as 2 m/s and would be suitable for optimally operating in an urban environment.

1. Introduction
Harnessing energy from the wind flow in an urban environment have always posed engineering challenges. Wind patterns in urban environments typically exhibit vortices. Hence, vertical – axis wind turbines, which have omni-directional operating capability, are a natural choice. They were first introduced by the Finnish engineer S.J. Savonius in 1922 [1]. Paraschivoiu [2] reported the experimental data of a Savonius vertical axis wind turbine, carried out at Sandia National Laboratories. L. Battisti et al. [3] compared the variations of the Darrieus rotor in terms of performance and load. It was recommended that a helical blade structure should be adopted as it reduced the cyclic oscillations and vibrations caused due to aerodynamic loads. Marco Raciti Castelli et al. [4] compared the annual energy output of a drag type versus a lift type VAWT when integrated with a building and concluded that the drag type turbine exhibited self-starting characteristics and a high power output even at wind speeds below 8m/s. Alaimo et al. [5] compared static and dynamic performance of a helical and a straight bladed lift type VAWT using CFD. They reported that helical VAWT had a higher average torque coefficient even at low wind speeds and a higher number of operational hours compared to a straight bladed VAWT.
With the growing demand for energy in urban sites, creative solutions for harnessing energy from wind in these disturbed environments to supply power to buildings on a more personal scale are being explored. Small scale turbines, mainly VAWTs are being incorporated with the structure of the building. They have gained a lot of popularity due to their self-starting characteristics, ability to produce energy in turbulent conditions, easy maintenance and aesthetic appeal. Stankoiv et al. [6], provides various examples of cases where a VAWT have been incorporated with buildings. The first conceptual bespoke type VAWT was incorporated into an aerodynamically shaped building by Project ZED (Towards Zero Emission Urban Development). The proposed energy tower Burj-al-Taqa in Dubai had a bespoke VAWT incorporated into it. A real life example of a VAWT incorporated into a building exists in Technisches Rathus, Munich in Germany. Introduced by Gorlov, the helical vertical axis wind turbines are believed to have better performance characteristics due to the twisted blade structure. They are self-starting at low wind speeds and the helical aerodynamic design results in a smooth and quiet operation.

Our survey of the commercial and experimental helical drag type wind turbine designs revealed that they generally modified versions of Savonius rotors with two helical blades. In light of these literatures studied thus far, a bio-inspired single bladed helical drag type VAWT rotor design was conceptualized and numerical parametric analysis was carried out to arrive at a geometry which would have a start-up wind speed of 2 m/s.

2. Methodology
The designs for the VAWT rotors were inspired from helical shapes found in nature. There are various naturally occurring seed pods having helical structures for better dispersal of seeds. Of these different seed pods, it was observed that the pods of Bauhinia Variegata (figure 1a) and Mimosa (figure 1b) species rotated naturally in the presence of gentle breeze. Bauhinia Variegata L. belongs to the family of Leguminosae [7]. Being native to India, this tree is found across all parts of the country. Commonly called Mimosa, the scientific name of this particular tree is Leucaena Leucocephala. It belongs to the Fabaceae family of the Mimosoidae tribe and is a wild species of legume [8]. Although native to southern Mexico, it has become widely distributed in India. In both types, the seeds are contained within two valves made up of multiple layers. When the humidity level in the air drops, the seed dries up, each layer shrink in opposite directions leading to presence of mechanical stresses in the valve [9]. The seed pod splits in half forming a helical structure.

![Figure 1. Seed pod specimens of (a) Bauhinia Variegata and (b) Mimosa.](image)

15 samples of each of these seed pods were collected and their geometric features, i.e. ratio of diameter-to-height (d/h) and pitch-to-height (p/h) were measured. It was observed that for Bauhinia Variegata, the average d/h was 0.08 and p/h was 0.35. For Mimosa, the average d/h was observed to be 0.09 and p/h was 1.21. Using the average d/h and p/h ratios of both seeds, two baseline rotors were conceptualized. Frontal area of the wind turbine was computed using the equation (1) given below

\[ P = \frac{1}{2} \rho A v^3 C_p \eta \]  

(1)

Here, \( C_p \) is the coefficient of performance of the turbine and \( \eta \) is the electromechanical efficiency. The
electromechanical efficiency is generally taken as 80%. $C_p$ for a drag type VAWT ranged between 0.1 and 0.15 [6]. The design velocity was taken to be 6 m/s [6]. The rotor’s frontal area was calculated for a power rating of 500 W permanent magnetic generator (PMG) using equation (1). For VAWT, the frontal area, $A$ is the product of rotor diameter ($d$) and height ($h$).

For the turbine to be self-starting, the stand-still aerodynamic torque of the rotor must exceed the cogging torque of the generator. Hence, the present study focused on assessing the self-starting capability of a spectrum of bio-inspired single bladed helix rotors. Stand-still aerodynamic torque for wind speed of 2 m/s was numerically estimated and compared with the cogging torque which is about 0.2 Nm for a typical 500 W PMG [10].

In the first phase of numerical analysis, p/h ratios for both the bio-inspired baseline rotors were kept same and d/h ratios were varied as a multiple of the average baseline values. Details of the dimensions of the candidate rotors are given in Table 1 and the 3D CAD models are shown in figure 2.

| Table 1. Dimensions of the Rotor Designs |
|------------------------------------------|
| Bauhinia Variegata (p/h = 0.35)          |
| d/h                                      |
| 0.04                                     |
| 0.08                                     |
| 0.25                                     |
| 0.5                                      |
| d (m)                                    |
| 1.1224                                   |
| 1.587                                    |
| 2.806                                    |
| 3.986                                    |
| h (m)                                    |
| 28.059                                   |
| 19.841                                   |
| 11.224                                   |
| 7.936                                    |

| Mimosa (p/h = 1.21)                      |
| d/h                                      |
| 0.045                                    |
| 0.09                                     |
| 0.27                                     |
| 0.54                                     |
| d (m)                                    |
| 1.1904                                   |
| 1.6835                                   |
| 2.916                                    |
| 4.124                                    |
| h (m)                                    |
| 26.455                                   |
| 18.706                                   |
| 10.8                                     |
| 7.637                                    |

Figure 2. 3D CAD Models of the rotors with different d/h based on (a) Bauhinia Variegata and (b) Mimosa seed pods.

Geometries, shown in figure 2, were modeled using SOLIDWORKS and exported to OpenFOAM as an STL file. The flow domain has an overall dimension of 40 m X 20 m X 40 m. The blockMesh tool was used to define the domain and create a hexahedral mesh within it. The snappyHexMesh tool along with the surfaceFeatureExtract tool was used to subtract the 3D CAD model of the rotor from the domain, smoothen geometry and refine the mesh around it. A typical mesh contained 2,85,707 hexahedral cells, 402 prisms and 12,826 polyhedral cells with a mesh level refinement of 3 around the rotor. The total number of points in the typical mesh was 3,19,567. The simpleFoam solver contained in OpenFOAM was used to simulate the wind flow around the static rotor and obtain the stand still aerodynamic torque. SIMPLE algorithm is used for velocity – pressure coupling. Standard RANS k-ε turbulence model was used. The wall functions of the generic of the k-ε turbulence model are as shown below.
\[ y^+ = \frac{c_y^{1/4} \sqrt{\kappa} y}{v} \]

\[ \nu_t = \nu \left( \frac{\kappa y^+}{\ln(\kappa y^+)} - 1 \right) \]

\[ \tau_w = \rho(v + \nu_t) \left( \frac{u - u_w}{y} \right) \]

(2)

Here, \( c_y = 0.09 \), \( E = 9.8 \), \( \kappa = 0.41 \) are model coefficients, \( \tau_w \) is the viscous stress, \( k \) is the turbulent kinetic energy, \( u \) is the streamline velocity, \( y \) is the distance of the first cell from the wall, \( u_w \) is the velocity boundary condition at the wall, \( \rho \) is the density and \( \nu \) is the kinematic viscosity.

Aerodynamic moments were calculated using the static pressure distribution and viscous stress over the rotor surface.

First phase of these numerical studies revealed that the bio-inspired rotors based on the Bauhinia Variegata were inadequate to produce stand-still aerodynamic torques to counter the cogging torque of a typical 500 W PMG. However, stand-still aerodynamic torque for the bio-inspired seed pods based on Mimosa and with \( d/h \) of 0.27 were higher than the cogging torque of a typical 500 W PMG.

In the second phase of analysis, for the \( d/h \) ratio of 0.27, \( p/h \) ratio was varied. For different \( p/h \) values, designs were carried out. Geometries are given in Table 2 & 3D CAD models are shown in figure 3.

| Table 2. Dimensions of Rotor Designs (2) |
|----------------------------------------|
| p/h | 0.175 | 0.35 | 0.7 | 1.21 | 2.4 |
| p (m) | 1.89 | 3.78 | 7.56 | 13.068 | 25.92 |
| h (m) | 10.8 | 10.8 | 10.8 | 10.8 | 10.8 |

3. Results

3.1 Assessment of \( d/h \)

Streamline plots of the flow, across the candidate bio-inspired rotors with inflow air velocity of 2 m/s are shown in figure 4. Streamlines are defined by

\[ \frac{dx_s}{ds} \times \vec{u}(\vec{x}_s) = 0 \]

(3)

Here \( \times \) denotes the vector cross product and \( \vec{x}_s(s) \) is the parametric representation of one streamline at a moment in time. If the components of the velocity are written as \( \vec{u} = (u, v, w) \) and those of the streamline as \( \vec{x}_s = (x_s, y_s, z_s) \), then the 3D streamlines are represented as shown below

\[ \frac{dx_s}{u} = \frac{dy_s}{v} = \frac{dz_s}{w} \]

(4)

From the study of these streamline plots, two observations were made. Firstly, as the \( d/h \) ratio increased, secondary vortices started appearing in the vicinity of the rotor. These vortices aided in the momentum transfer from the air to the helical blade, causing it to rotate. Secondly, for the smaller \( d/h \) ratios, diameter of the rotor became small, resulting in a slender rotor. A slender rotor was found to be ineffective to capture the kinetic energy of the frontal wind.
For all the candidate bio-inspired rotors, plots of stand-still aerodynamic torque vis-à-vis cogging torque of a 500 W PMG, which is typically 0.2 Nm, are shown in figure 5. Of all the candidate rotors, Mimosa seed pod based rotors, with d/h of 0.27 exhibited capability of generating stand-still torque higher than 0.2 Nm in wind speed of 2 m/s. Hence, in phase II of our study, we chose d/h as 0.27.

3.2 Assessment of p/h
Streamline plots of the flow across the candidate bio-inspired rotors with inflow air velocity of 2 m/s are shown in figure 6. From the streamline plots, it was observed that as the p/h ratio increases, secondary vortices appeared around the rotor. They helped in the momentum transfer from air to the rotor. For rotors with smaller p/h ratios, the number of revolutions is high. Due to this, the incoming air just flew past through the rotor without imparting turning moment to the rotor. For all the candidate bio-inspired rotors considered in phase II of the numerical study, plots of stand-still aerodynamic torque vis-à-vis cogging torque of a 500 W PMG, which is typically 0.2 Nm, are shown in figure 7. For a wind speed of 2 m/s, stand still aerodynamic torque of the rotor having a p/h ratio of 0.7 and above exceeded 0.2 Nm.
4. Conclusion
Present study was an attempt to recreate nature’s helical structures as single bladed helical drag type VAWT rotor. Two baseline rotors were conceptualized based on seed pods shapes of *Mimosa* and *Bauhinia Variegata*. Two geometric parameters of the bio-inspired rotors viz. d/h and p/h were varied and the stand-still aerodynamic torques were numerically estimated for a frontal wind speed of 2 m/s. From these studies, we observed that a bio-inspired single bladed helical drag type VAWT with d/h ratio of 0.27 and p/h ratio of 0.7 exhibited start up tendency at wind speed as low as 2 m/s. Hence, a bio-inspired rotor with these geometric characteristics should be considered as a candidate rotor for an urban environment.

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