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Design and analysis of MADEW turbine rotor

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ABSTRACT

This article presents the adoption of the structure of mahogany seed and designing a Horizontal Axis Wind Turbine (HAWT) which is found to be more efficient than the existing wind turbines. The aim was to validate the experimental values of mahogany airfoil design using wind tunnel experiment and compare the numerical analysis result with CFD software. Mahogany seeds consist of different airfoil design in its cross section at different points along length. They have a complex structure. The rough surface texture generates turbulence in turn shows better performance. The design and analysis of a turbine based on the concept 'Mahogany Airfoil Design for Wind Energy' abbreviated and named as MADEW-Turbine is done here. The proposed HAWT is complex in shape and increases the expense of manufacturing, but it is evident that it can work in low wind speed areas and produces higher amounts of power than the existing systems.

KEY WORDS: Airfoil design, MADEW, HAWT, CFD.

1. INTRODUCTION

Horizontal Axis Wind Turbines (HAWT)'s are used in high altitude wind areas. The efficiency of wind turbines are measured based on Betz's law. According to Betz's law, no turbine can extract more than 16/27 (59.3%) of the kinetic energy in wind. The factor 16/27 (0.593) is known as Betz's coefficient or Betz's limit.

The geometry of the mahogany seeds let it to auto rotate a fraction of a few second after its fall. These seeds have low terminal velocities which provide sufficient time for wind to carry them far away from the tree, before they reach the ground. Figure 1 and 2 show the shape of the seed, it can be seen that it mimics an airfoil. The wing has a non-uniform geometry. The leading edge is thicker at the root. The irregularities on the seed provide structural strength and also the surface roughness. Surface roughness creates turbulence that improves autorotation performance.

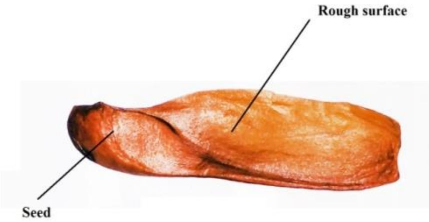

Figure.1. Mahogany seed

Figure.2. Selected seed cross sections

2. EXPERIMENTAL SETUP

The experiment is conducted to find the best Mahogany seed among the available seeds. We arbitrarily selected 15 matured mahogany seeds. From the rough estimation it is found that not all the seeds show autorotation. The trial phase was to select seeds with auto-rotation characteristics. In the trial phase we obtained 10 seeds which show autorotation (fig.3). The 10 seeds are taken for the next phase for further selection with respect to time. The process adopted is similar to interferometry.

A room without air flow is created and bright light is provided (Fig.4). A height of 2.0 m is marked on a white screen from the floor and a provision to drop the seeds from a height 2 m is made. The test is to drop the seeds from a height of 2.5 m and to measure the time taken to travel from 2.0 m to 0 m marked on the screen. It is assumed that the terminal velocity is attained at 2.0 m when a seed is dropped from a height of 2.5 m. The distance travelled by a seed in this test is 2 m with its terminal velocity and is captured using a 16.2 Mega Pixel, 24 fps camera in slow motion mode. A 500 W incandescent lamp is used for lighting purpose (extremely bright). From the measurements, the seed.1 takes the highest time and it is chosen for the design purpose.

Methodology: Methodologies of the work include design, analysis, testing and observations and calculations and are explained below.

Design: The measurements from the rotation test are taken for the design process. The mahogany seed cross sections are similar to airfoils. Initially the cross sections are identified at equal distances. They are measured for linear values using a vernier caliper which has a least count of 0.02 mm. The measurements are taken for 0.02 mm accuracy. The 4 cross sections taken for study are given below.

As shown in the figure 5 the NACA cross sections similar to Mahogany cross sections are identified. The NACA (National Advisory Committee for Aeronautics) numbers used are from 4-digit series. For example, the NACA 9330 airfoil has a maximum camber of 9% located 30% (0.3 chords) from the leading edge with a maximum thickness of 30% of the chord. Four-digit series airfoils by default have maximum thickness at 30% of the chord (0.3 chords) from the leading edge. Design process is done using CATIA V5 R20 – Part modeling – The material chosen for

design is Glass Reinforced Plastic (GRP). GRP is used for manufacturing wind turbine most commonly which is also adopted here.
Each part created on CATIA V5 R20 has a chord length of 200 mm and a width of 200 mm. 4 cross sections from Mahogany seed were named Mahogany-1, Mahogany-2, Mahogany-3 and Mahogany-4 which are similar to NACA 9330, NACA5730, NACA3414 and NACA 3508 respectively. Rotor is also designed using CATIA V5 R20. It is done in 'Part Design'. Three rotors are produced with following criteria.

- 0 angle of attack,0 roll angle
- 15 angle of attack,0 roll angle
- 15 angle of attack,19.4 roll angle

Figure.3. Selected seed

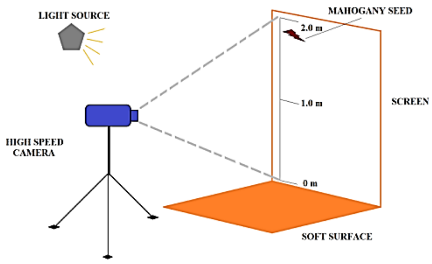

Figure.4. Experimental setup

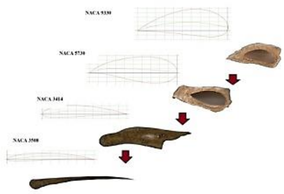

Figure.5. Mahogany seed cross sections and Airfoils

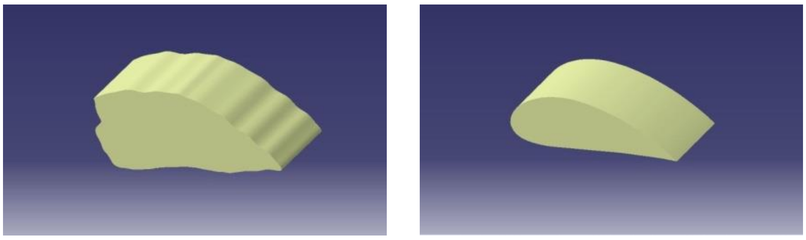

Figure.6. Mahogany – 1 and NACA 9330

Analysis: Analysis is carried out in ANSYS FLUENT 15.0 First phase analysis consists of comparison between NACA airfoils and Mahogany cross sections for drag and lift. ANSYS Fluent analysis is an iterative process and is based on 3- stage Runge-Kutta iteration equation.
Conditions used for the analysis are the same for each cross section
Model – k-epsilon
Materials
Fluid – Air – density 1.225 kg/m^3
Solid – Glass Reinforced Plastic – GRP –density 1740 kg/m^3
Temperature – 288.16 K
Viscosity – 1.7894e – 05 kg/m-s
Inlet velocity – 10 m/s
Reference – Absolute
Outlet pressure – 0 Pascal
Solution methods
Scheme – SIMPLE (Semi Implicit Method for Pressure Linked Equations)
Gradient – Least square cell based
Pressure – 2^{nd} orders
Momentum – 2^{nd} order upwind
Turbulent Kinetic Energy - 2^{nd} order upwind
Analysis results are shown below- the first row shows the drag and second row shows the lift in Mahogany and NACA airfoils.

Mahogany - 1 NACA 9330

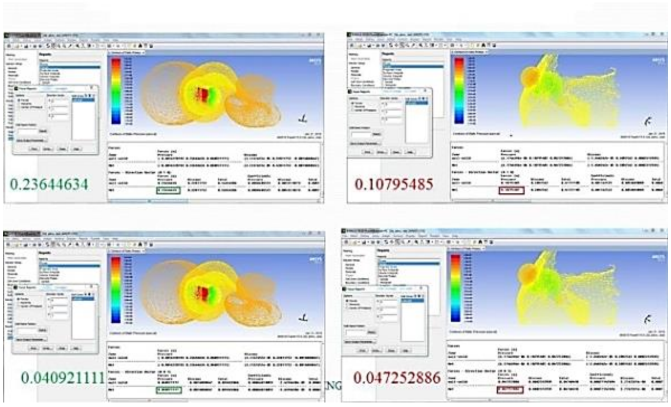

Figure.7.Mahogany-1 and NACA 9330 Analysis

Mahogany - 2 NACA 5730

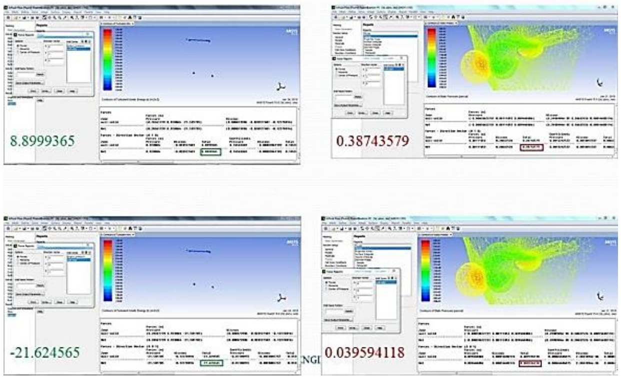

Figure.8.Mahogany-2 and NACA 5730 Analysis

Mahogany - 3 NACA 3414

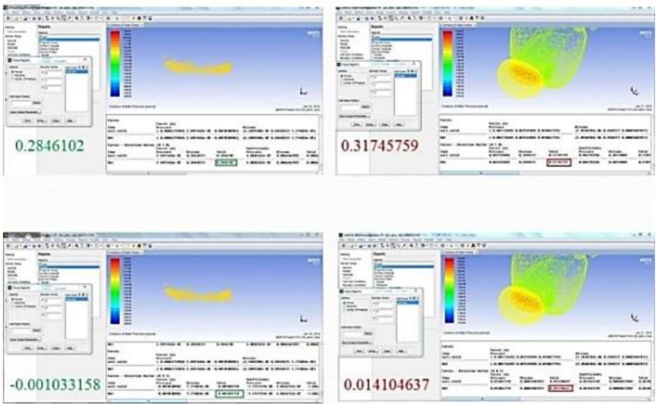

Figure.9.Mahogany-3 and NACA 3414 Analysis

Mahogany - 4 NACA 3508

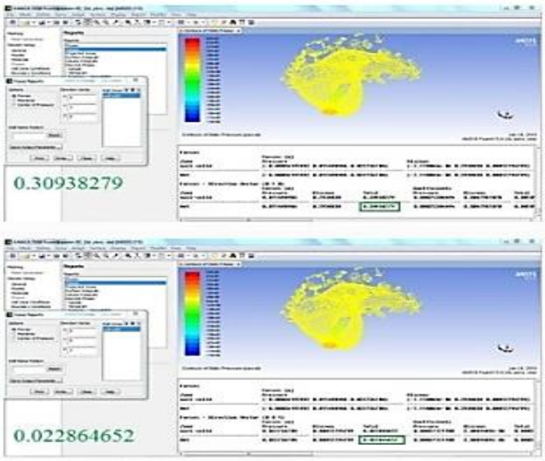

Figure.10.Mahogany-4 and NACA 3508 (identical)

Second phase analysis consists of comparison of drag, lift and turbulence between rotors with:

- 0 degree roll angle, 0 degree angle of attack
- 0 degree roll angle, 15 degree angle of attack
- 19.4 degree roll angle, 15 degree angle of attack

Conditions used for the analysis are the same for each cross section
Model – k-epsilon
Materials

- Fluid – Air – density 1.225 kg/m^3
- Solid – Glass Reinforced Plastic – GRP –density 1740 kg/m^3

Temperature – 288.16 K
Viscosity – 1.7894e – 05 kg/m-s
Inlet velocity – 4m/s
Reference – Absolute
Outlet pressure – 0 Pascal
Solution methods
Scheme – SIMPLE (Semi Implicit Method for Pressure Linked Equations)
Gradient – Least square cell based
Pressure – 2nd orders
Momentum – 2nd order upwind
Turbulent Kinetic Energy - 2nd order upwind

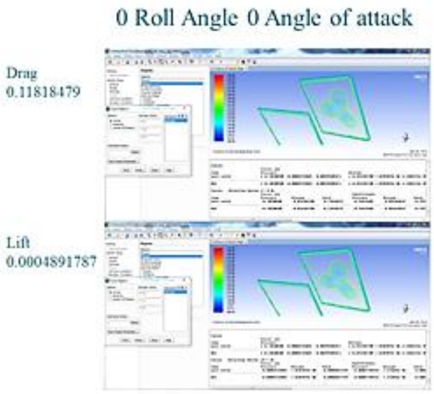

Figure.11.0 degree Roll angle and 0 degree Angle of attack

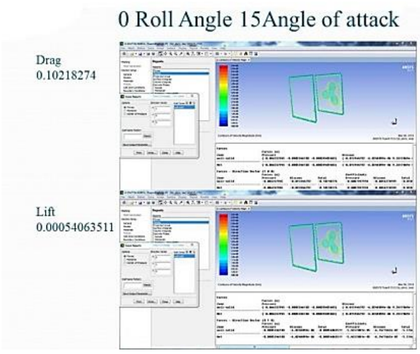

Figure.12.0 degree Roll angle and 15 degree Angle of attack

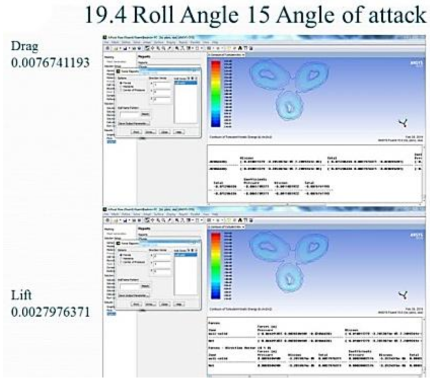

Fig.13.19.4 degree Roll angle and 15 degree Angle of attack

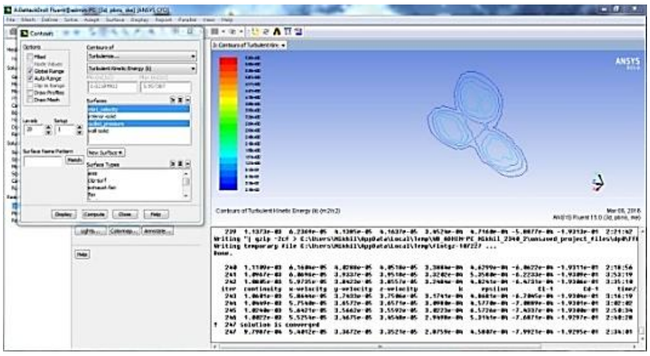

Figure.14. Turbulence in 0 degree Roll angle 0 degree Angle of attack

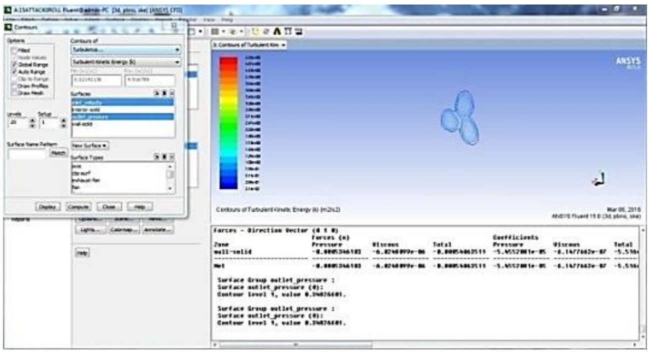

Figure.15. Turbulence in 0 degree Roll angle15 degree Angle of attack

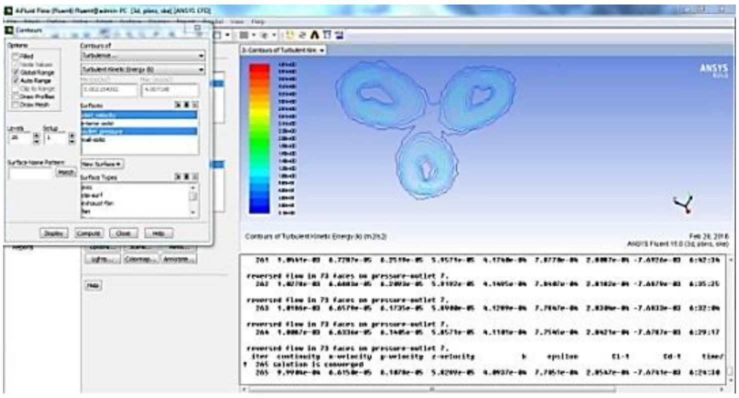

Figure.16. Turbulence in 19.4 degree Roll angle 15 degree Angle of attack

Table.1.Rotor analysis results

Type	Drag	Lift
0 Roll Angle; 0 Angle of attack	0.1181	0.0004
0 Roll Angle; 15 Angle of attack	0.1021	0.0005
19.4 Roll Angle; 15 Angle of attack	0.0076	0.0028

Subsonic wind tunnel testing: Subsonic wind tunnels are low-speed wind tunnels used for operations at very low Mach number, with speeds in the test section up to 480 km/h (~ 134 m/s, M = 0.4). They may be of open-return type (also known as the Eiffel type), or closed-return flow (also known as the Prandtl type) with air moved by a propulsion system usually consisting of large axial fans that increase the dynamic pressure to overcome the viscous losses. Small scale MADEW rotor (1:500) is tested on a subsonic wind tunnel as shown in the figure 17.

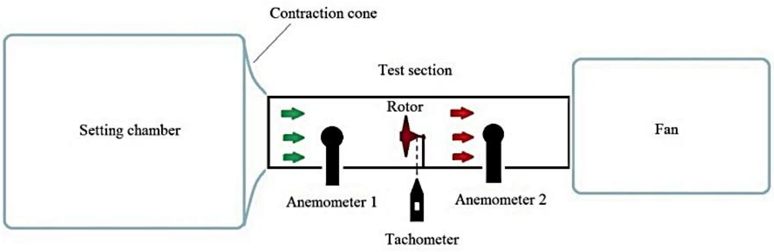

Figure.17. Wind tunnel testing

Observations and calculations: Betz's law indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. According to Betz's law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind.

Let us make the reasonable assumption that the average wind speed through the rotor area is the average of the undisturbed wind speed before the wind turbine, v_1, and the wind speed after the passage through the rotor plane, v_2, i.e. $(v_1 + v_2)/2$.

The mass of the air streaming through the rotor during one second is;

$$m = \rho A\left(\frac{v_{1+}v_2}{2}\right) \qquad (1)$$

Where, 'm' is the mass per second, $'\rho'$ is the density of air, 'A' is the swept rotor area and $[(v_1 + v_2)/2]$ is the average wind speed through the rotor area. The power extracted from the wind by the rotor is equal to the mass times the drop in the wind speed squared

(According to Newton's second law):

$$P = m\frac{(v_1^2 - v_2^2)}{2} \qquad (2)$$

Substituting 'm' into this expression from the first equation we get the following expression for the power extracted from the wind:

$$P = \frac{\rho}{4}(v_1^2 - v_2^2)(v_1 + v_2)A \qquad (3)$$

Now, let us compare our result with the total power in the undisturbed wind streaming through exactly the same area A, with no rotor blocking the wind. We call this power P_O;

$$P_0 = \left(\frac{\rho}{2}\right) v_1^3 A \qquad (4)$$

The ratio between the power we extract from the wind and the power in the undisturbed wind is then:

Power coefficient (C_P),

$$C_P = \frac{P}{P_0} = \frac{1}{2}\left(1 - \left(\frac{v_2}{v_1}\right)^2\right)\left(1 + \left(\frac{v_2}{v_1}\right)\right) \qquad (5)$$

Equation (5) is the base of calculations in this project. C_P values are calculated for checking the efficiency of the MADEW turbine at different configurations. We can see that the function reaches its maximum for $v_2/v_1 = 1/3$, and that the maximum value for the power extracted from the wind is 0.59 or 16/27 of the total power in the wind.

3. RESULTS AND DISCUSSION

Based on Betz law, the Coefficient of performance of the MADEW turbine with 19.4 degree roll angle and 0, 5 and 10 degrees angle of attack are calculated. These values are tabulated below.

Table.2. Calculated C_P values

Angle of attack (degree)	0	0	0	5	5	5	10	10	10	15	15	15
V1 (m/s)	2.5	3.5	4.0	2.5	3.5	4.0	2.5	3.5	4.0	2.5	3.5	4.0
V2 (m/s)	2.4	3.2	3.6	2.2	3.0	3.3	2.1	2.8	3.0	1.9	2.6	2.9
Speed (rpm)	4	7	12	108	149	173	147	200	230	170	238	298
Cp	0.154	0.157	0.181	0.212	0.246	0.291	0.324	0.359	0.383	0.372	0.391	0.409

It is found to be the best performance of MADEW turbine rotor is at 15 degree angle of attack and 19.4 degree roll angle. The C_P of modern wind turbines is 0.4- 0.45 and they are mostly used in medium and high wind speed areas. Here the maximum C_P is 0.409 and surprisingly at a wind speed of 4 m/s. Also the speed of rotation is 298 rpm at 4 m/s. At 0 angle of attack the performance is negligible.

4. CONCLUSION

From the results, rough surface of air foils increases the turbulence and thus performance. The resulting turbulence of the structure is acceptable and the probability of failure is less at low wind speeds.

(1) Wind turbine rotors perform better when a coning angle is provided. It is not an existing method of providing a coning angle/roll angle in a wind turbine. Roll angle is usually provided in helicopters for auto rotative purpose. Here roll angle is adopted from the characteristics of Mahogany seed and it is found to be useful in better performance of MADEW turbine rotor.
(2) The design adopted from nature for wind turbine rotor is found to be usable in low wind speed areas. According to test results it is clear that MADEW turbine rotor works efficiently at wind speeds less than 10m/s and failure can be expected above the same.
Our work is solely mechanical and auxiliary components such as generator, gear box, tower, etc. are not considered and the further work can be done by studying a complete wind turbine.

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