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Performance Analysis of a 3D Printed PLA Micro Wind Turbine

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A B S T R A C T

This project of a wind turbine aims at designing, analysis, and the fabrication of a mini wind turbine using 3D printing technology. This shall be an educative and a practical approach for renewable energy production. The fundamental parts of this turbine include a rotor blade, hub, tail, and the motor mount all designed using the CAD software with lightweight yet hard PLA material. The design consists of a 3-blade horizontal-axis rotor with blades having airfoil shapes optimized for energy harvesting. The generator utilizes a small DC motor or alternator in which the mechanical energy coming from the rotor is changed to electrical energy that powers the illumination of LEDs or charges a rechargeable battery. The turbine features a lightweight tower and yaw mechanism to align itself fully with the wind direction. Power generation capacity is estimated with the aid of equations on wind power considering the swept area, wind speed, and the coefficient of power.

Keywords: 3-D printing, Poly lactic acid (PLA), coefficient of power, swept area, Yaw Mechanism.

Introduction

Introduction Additive manufacturing is a sunrise industry and 3D printing technologies are an innovation driver in most scientific disciplines. The bandwidth of applications reaches from precision engineering, for instance human prothesis and robotics to large constructions, such as entire residential buildings. In addition, the research on 3D printing methods is often based on open access principles, i.e. the free sharing of ideas and blueprints. In aerodynamics, lightweight applications include the wings of small air vehicles and the rotor blades of wind turbines. In general, aerodynamic bodies are exposed to a complex combination of steady and unsteady loads. Rotor blades, in particular, need to resist fluctuating bending forces, countless load cycles due to the blade rotation and the intermittent effects of inflow turbulence, wind shear and (local) stall.

To reduce the manufacturing cost of the wind turbine by making it with PLA polymer instead of metals. To enhance the design customization by using AM instead of traditional methods which allowed to make optimized blade designs like Aero foil design. To reduce the rotational inertia and increase the tendency of the blades to rotate fast by using light weight PLA material. To maintain environmental sustainability by using biodegradable PLA material which is less harmful to environment.

Aerodynamic considerations

The blade design, see Fig.1, NACA 9417 aero foil is preconditioned by the wind tunnel facility and the available 3D printer. The rated inflow velocity is u = 7.5 ms-1 and the rotor radius is restricted by the maximum printing volume, R = 1 m. For security purposes, the rotational speed is limited to nmax ≈ 800 min-1 leading to a design tip speed ratio (TSR) of λd = 4 at a Reynolds number of Re ≈ 1·105. Furthermore, the blade design is based on one identical airfoil from root to tip.

Fig.1: NACA 9417 aero foil design

An aerodynamic blade design is crucial in improving the efficiency and performance of rotating machinery such as turbines, compressors, fans, and aircraft propellers. The primary purpose of using an aerodynamic blade is to reduce air resistance (drag) while maximizing lift or thrust, depending on the application. By carefully shaping the blade to allow smooth airflow over its surface, engineers can minimize energy losses due to turbulence and flow separation. This results in higher efficiency, reduced fuel consumption, and improved overall performance. Additionally, aerodynamic blades help reduce noise and mechanical stress, leading to longer equipment life and lower maintenance costs. This design principle is widely used in both aerospace and industrial applications to enhance operational efficiency and reliability.

2.1 Aerofoil Geometry Interpretation (from NACA 9417):

9- Indicates the series (laminar flow series)

4- Position of maximum camber as 40% of the chord

17- Maximum thickness is 17% of the chord

NACA 9417 is a symmetric aerofoil, so camber is actually 0%, and lift is generated only with an angle of attack.

2.2 Input Parameters for Blade Design:

Rated wind speed (V) = 3 m/s

Rotor radius (R) = 0.16 m

Number of blades (N) = 3

Tip-speed ratio (λ) = 5

Air density (ρ) = 1.225 kg/m³

Chord length (c) = varies along the blade

Angle of attack (α) = 4°–8° for best lift/drag ratio for NACA 9417

Reynolds number, $Re = \frac{\rho V c}{\mu}$, Where, μ=1.81×10−5 Pa-s (air viscosity)

$$Re = \frac{1.225\times3\times1005}{1.81\times10^{-5}} = 2.04 \times 10^{8}$$

Re> 10^5, so the flow of air is considered as turbulent.

2.3 Lift and Drag Coefficients:

From experimental or XFOIL simulations:

Cl (Lift coefficient) ≈ 0.8 at α = 6°

Cd (Drag coefficient) ≈ 0.03 at α = 6°

Cl/Cd ratio is used to optimize blade twist and chord distribution.

2.4 Blade Element Momentum Theory (BEMT) Inputs:

For each blade section at radius r:

(i) Local tip-speed ratio:

$\lambda(r) = \frac{\omega r}{V}$

$$\omega = \frac{2\pi N}{60}, Where\ N = \frac{60V}{\pi D} = \frac{60 \times 3}{\pi \times 0.32} \approx 180\ rpm$$

$$\lambda(r) = \frac{180 \times 0.16}{3} = 9.6$$

(ii) Chord distribution (c):

C(r) = $\frac{8\pi r}{NC(L)}(1 - cos\emptyset)$

$$\emptyset = \tan^{-1}\frac{3}{180 \times 0.16} = 5.94°$$

C(r) =$\frac{8\pi \times 0.16}{180 \times 0.8}(1 - \cos 5.94°)$= 1.5×10^-4

(iii) Twist angle (θ):

$$\theta(r) = \alpha - \emptyset = 6 - 5.94 = 0.06°$$

3. Structural Analysis

For running the performance analysis of a micro wind turbine on ANSYS, the procedure is initiated with geometry creation. The design of the model of the blades, hub, and tower for the turbine may be created utilizing ANSYS Design Modeler or read from CAD packages. In this step, the precision in the model used will directly have an influence upon the simulation outputs. After the geometry is prepared, the subsequent step is meshing. A high-quality mesh is created to accurately capture the aerodynamic features, with more detailed mesh elements near the blades and on the surface to enhance accuracy. This allows accurate flow patterns to be simulated correctly.

The simulation stage consists of performing steady or unsteady simulations to analyse lift, drag, and power output. Turbulence models such as k-ε or SST are employed to enhance accuracy in the complex flow areas. Lastly, post-processing assists in the analysis of the simulation output. Important performance metrics such as the power coefficient, aerodynamic forces, and structural stresses are analyzed to determine the efficiency and reliability of the micro wind turbine

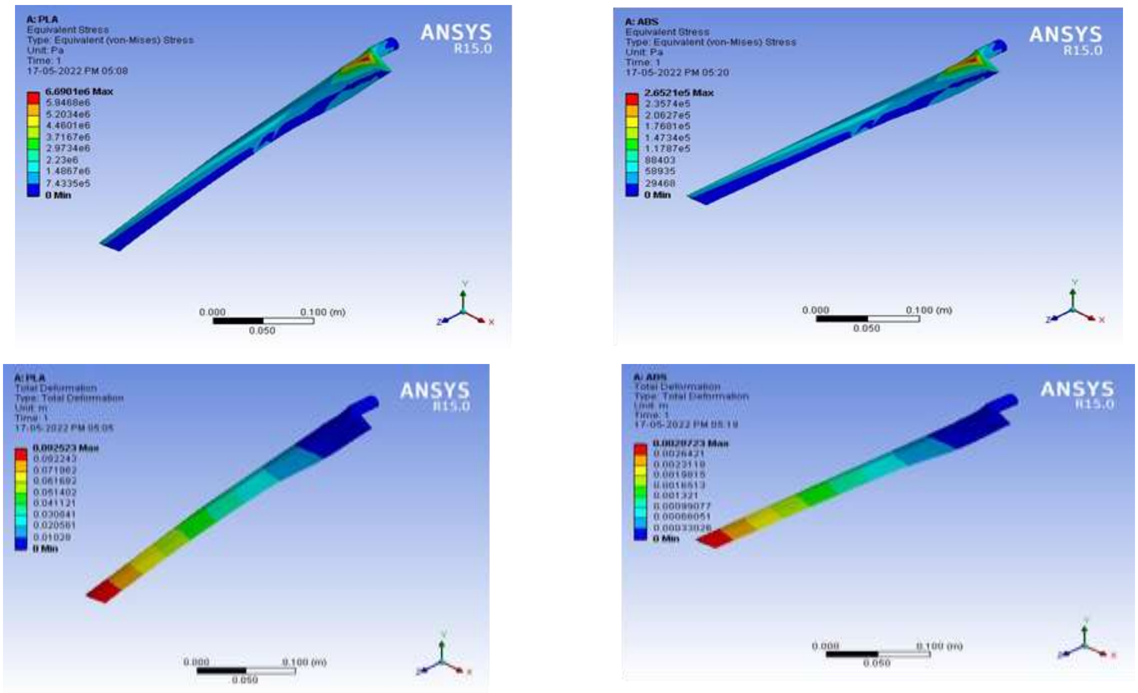

Fig.2: Response values from simulated results. Deformation (DN) for (a) ABS; (b) PLA. Stress intensity (SS), in Pa, for (c) ABS; (d) PLA

The structural performance of the blade material is described by the deformation and stress intensity. Since the load is applied in the clockwise direction, the blade tends to deform in the axial direction, and tensile stress develops in the region of the hub. The boundary conditions were applied as follows the hub of the blade was fixed, i.e., rotation and translation were arrested at the hub. Flap-wise loading was applied on the surface of the wind turbine blade.

A static structural analysis was performed for a wind velocity ranging from 1 to 15 m/s and for various infill percentages from 10% to 100%. The deformation in the axial direction and the stress intensity at the wind velocity varied from 1–15 m/s, and various infill percentages from 10%–100% were identified for the PLA and ABS materials. Fig 2 shows sample FEA simulation results in which the simulation outputs, such as the deformation (DN) and stress intensity (SS) developed on the blade, were considered measured response values.

Fabrication and experimental testing

After slicing the components in QIDI print software the G-codes file has to be saved into the disk. Now we have to connect the 3D printer to our software and adjust the print settings like infill density, pattern, bed temperature, layer thickness, print speed, etc. In this case we used FDM printer which is most suitable and commonly used method for printing small scale yet highly accurate products.

Fused Deposition Modeling (FDM) is a 3D printing method that builds objects by heating and extruding thermoplastic filament in layers. The nozzle of the printer melts the material, which is deposited onto a build platform, hardening as it cools. FDM is favoured for its ease, affordability, and flexibility with a wide range of materials such as PLA, ABS, and PETG. It's widely utilized for rapid prototyping, functional components, and models. Although it offers high precision and ease of use, FDM can be limited in resolution and surface finish relative to other 3D printing technologies, so it is best suited to some applications but not high-detail manufacture.

Fig.3: Prototype of a 3D printed PLA micro wind turbine.

The proposed PLA material-based wind blade has better physical and structural properties. But the purpose of designing a wind blade is to be attached to the wind turbine for generating electric power. For that, the performance of the proposed wind blade has been validated in a real-time setup under different wind speeds. Apart from the physical properties, the wind blade must be efficient to generate rated power when it is used in real-time.

- **Calculation of Output Power:**

The blades that we were manufactured for the turbine are having 16 cm length. We know that the rotor diameter is double of the blade length.

∴ diameter of rotor, D_r = 32 cm.

Swept area (A) = $\pi r^2 = \pi \times (0.16)^2 = 0.0804$ m^2

We know, density of air (ρ)= 1.2 kg/m^3

Wind speed (v)= 3m/s

Assuming efficiency = 40 %

(i) Power available in the wind:

$P_{wind} = \frac{1}{2}\rho A v^3 = 0.5\times1.2\times0.0804\times3^3 = 1.3$ W

(ii) Power generated by turbine:

According to Betz's limit no wind turbine can generate more than 59.3 % of the available power in the wind. This means, for any wind turbine the efficiency is not more than 59.3% and power coefficient (C_p) is not more than 0.593.

Assuming 40% efficiency, i.e., C_p=0.4

$$P_{output} = C_p \times P_{wind} = 0.4 \times 1.3 = 0.52 \text{ W}$$

In the experimental setup, the turbine develops a power of 0.62 W. This means the turbine works more efficiently than assumed.

4. Results

After doing the experimental testing of the wind turbine at 3 m/s, the following results are obtained which are useful to analyze the performance of PLA micro wind turbine having the blade length of 16cm and rotor diameter of 32 cm.

- **Start-up Wind Speed:** The test facility shows that the wind turbine fitted with PLA-based NACA 9417 aerofoil blade begins to rotate from a low speed of 3 m/s wind. This is a significant performance parameter because it shows how the blade responds to low wind speeds, which is most crucial for tapping wind power in low-wind regions
- **Initial Power Generation:** At 3 m/s wind speed, the power generated by the wind turbine is 0.52 W with a current of 0.2 A. The performance above shows that the turbine not only spins but even produces useful electrical output at low wind speed. For micro wind power or residential scale systems, this gives a low but steady energy supply.
- **Low Wind Speed Suitability:** Use of the NACA 9417 aerofoil with PLA material is most suitable for low wind speeds. Production of power at 3 m/s from the start indicates that the shape of the blade is aerodynamic and best suited for minimum drag and high-speed lift generation. This is very important in household or rural conditions where wind is mostly in the form of moderate wind under conventional cut-in speed for conventional turbines.
- **Coefficient of power (C_p) and efficiency:** The turbine is developing 0.62 W of power, this means the coefficient of power is calculated as follows

$$C_p = P_{output} / P_{wind} = 0.62/1.3 = 0.476$$

The efficiency of the turbine is 47.6% and it is within the Betz's criteria.

5. Conclusion

This project gave the experience of designing wind turbines and renewable energy in a hands-on way. CAD designs were made for components such as blades, hub, shaft, and tower, and structural analysis was conducted with ANSYS 15 for PLA and ABS materials. PLA exhibited better structural characteristics in terms of less deformation, stress, and strain, making it the material of choice. A dynamo was then installed after assembly to provide power, and performance was tested at different wind speeds using a wind tunnel. Testing revealed that the wind turbine made from PLA operated efficiently, particularly at low wind speeds, and provided greater power output with improved structural stability compared to ABS or traditional designs.

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