Small Wind Turbine Blade Design Report

Alex Jenkins, Charlie Hart, Priya Abiram

Executive summary

This project aimed to design, fabricate, and test a 6-inch wind turbine blade that maximizes aerodynamic efficiency while satisfying geometric, structural, and manufacturability constraints. Using Blade Element Momentum Theory (BEMT), experimentally validated airfoil data, and an iterative design process, we developed a NACA 4412-based blade with smoothed chord and twist profiles, constrained by a 2-inch axial projection limit, 44 MPa flexural-stress limit, and 3D-printing requirements.

The design process included airfoil characterization at three Reynolds numbers, selection of an energy-weighted design wind speed, initialization of geometry, full-span BEMT convergence, tip and root smoothing, and structural verification. Predicted performance at 812 RPM suggested a power output of ~1 W. Experimental testing demonstrated peak power of 1.29 W near 2900 RPM, with the blade maintaining structural integrity and achieving TSR ≈ 6: double the TSR it was originally designed for.

While all structural and geometric constraints were satisfied, several unexpected trends emerged, including the absence of a clear performance peak, resonance phenomena near 2100–2500 RPM, and a higher-than-anticipated operational TSR. Future iterations will increase design TSR, refine chord lengths near the outer span, and redesign geometry to avoid resonance-sensitive regions.

Description of the context, objectives and constraints for the design

1.1 Context

This project required the design of a small horizontal-axis wind turbine blade for laboratory testing. The blade needed to operate efficiently within the wind-speed ranges created by the course's fan system and remain structurally safe under torque-brake loading. The deliverables included a manufacturable 3D-printed blade and a performance evaluation based on experimental data.

1.2 Objectives

1. Maximize aerodynamic efficiency and total power extraction.
2. Ensure manufacturability using a 3D printer with 0.1 mm resolution.
3. Maintain smooth and continuous chord and twist geometry along the blade.
4. Ensure that the blade meets all geometric and structural constraints.

1.3 Constraints

1. Geometric: radius less than or equal to 6 inches, axial projection less than or equal to 2 inches, chord between 6 mm and 60 mm, use of a NACA 4412 airfoil.
2. Structural: flexural stress must remain below 44 MPa.

3. Aerodynamic: must perform well under wind speeds characterized by a Weibull distribution with given parameters. Used energy weighted velocity: 5.04 m/s
4. Manufacturing: blade must be printable without overhang failures and must retain continuous surface geometry.

Description of your design process and the rationale behind your design choices

2.1 Determining the Energy-Weighted Design Wind Speed

Because extractable wind power scales with the cube of the wind speed, we calculated an energy-weighted average wind speed using the Weibull probability distribution. This provided a representative wind speed for optimizing blade geometry.

$$U_{energy} = \frac{\int_0^\infty u^3 p(u)\,du}{\int_0^\infty u^2 p(u)\,du}$$

U_energy_weighted = 5.04m/s

2.2 Key Assumptions

1. The material behaves isotropically.
2. The incoming flow is steady and uniform.
3. Airfoil aerodynamics at each station can be approximated using quasi-2D methods.
4. Prandtl and Glauert tip-loss models apply for 3D correction.

2.3 Initial Hypotheses

We hypothesized that maintaining a relatively larger chord farther out along the blade would increase torque production due to higher local velocities. Pitch was selected near the optimal lift-generating angle of roughly 8.5 degrees for NACA 4412 without risking stall.

2.4 Airfoil Data and Reynolds Number Interpolation

NACA 4412 lift and drag data were imported at Reynolds numbers of 50,000, 100,000, and 200,000. Interpolation allowed us to match airfoil characteristics to local flow conditions along the blade.

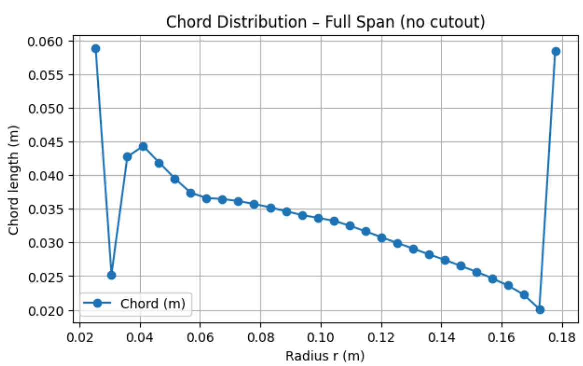
2.5 Initial Geometry Setup

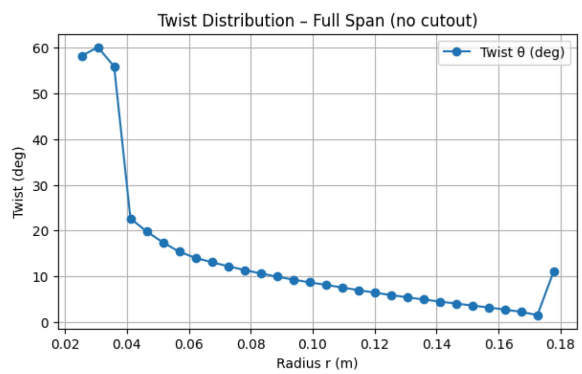
- Blade radius: 6 inches
- Initial design TSR: 3
- Initial chord: linear taper from 12 percent of the radius at the root to 4 percent at the tip

- Initial twist: uniform 8.5 degrees (slightly below peak lift angle to avoid stall)

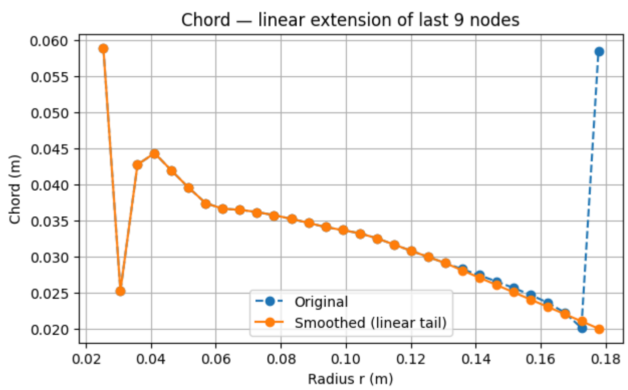
2.6 First-Pass BEMT
Blade Element Momentum Theory iterates for values of axial and tangential induction factors that cause our two predicted thrust and torque to converge. These induction factors are used for calculating the pitch and chord of each of our stations. A diagnostic BEMT run identified unstable behavior near the root and tip, especially within the inner 25 percent of the span where TSR becomes small. This guided later smoothing steps.

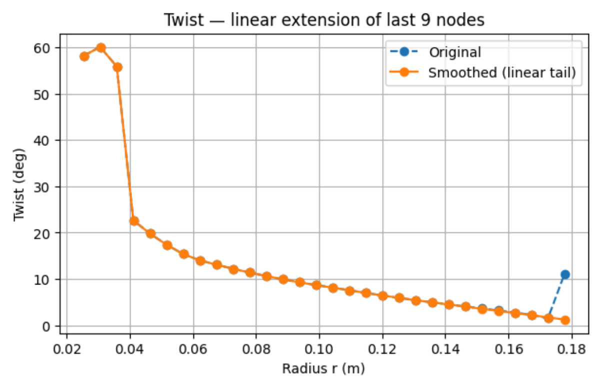
2.7 Full-Span BEMT
Thirty stations along the blade were solved iteratively to convergence for induction factors. The resulting chord and twist profiles contained numerical outliers at both ends of the blade.



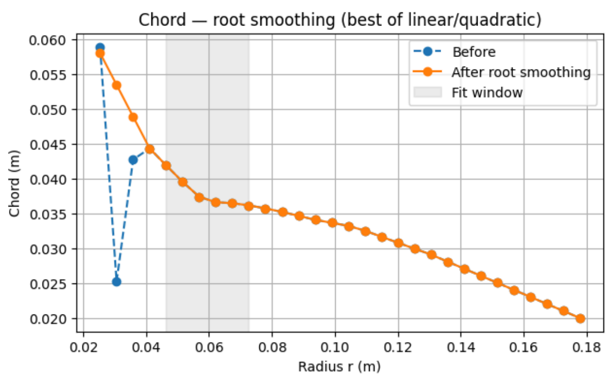


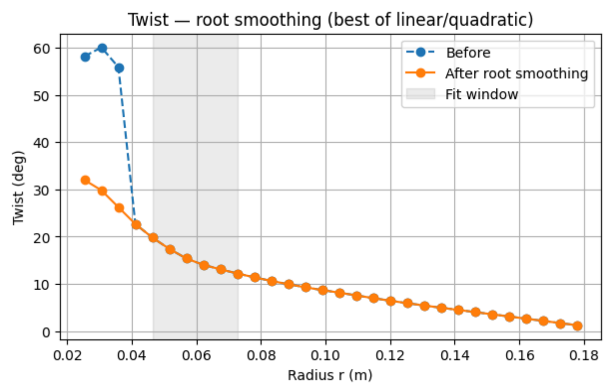
2.8 Root and Tip Smoothing
Tip smoothing was performed using a linear extrapolation of the final nine stable points.
Root smoothing used a quadratic extrapolation of the closest stable upstream data.
Both ensured smooth and manufacturable geometry while preserving aerodynamic fidelity.
Tip Smoothing:





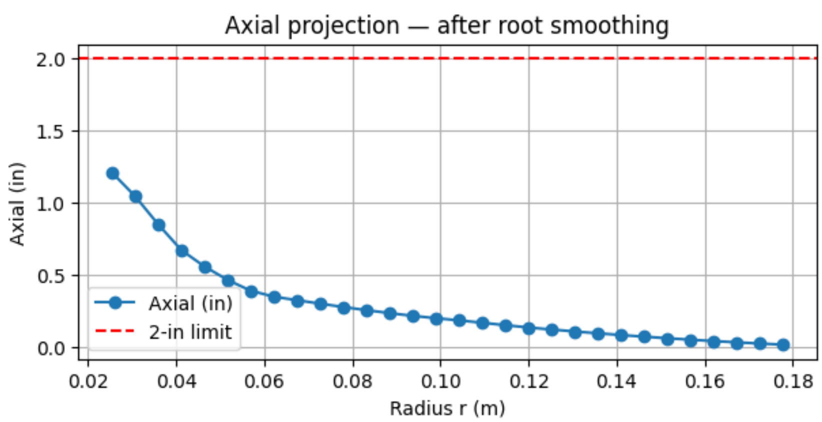
Root Smoothing:





2.9 Axial Projection Verification

We calculated axial projection at each station and confirmed it remained below the 2-inch limit after smoothing.



Performance Prediction: At our chosen Tip Speed Ratio and RPM (~812 RPM):

Our predicted torque is 0.0117 Nm

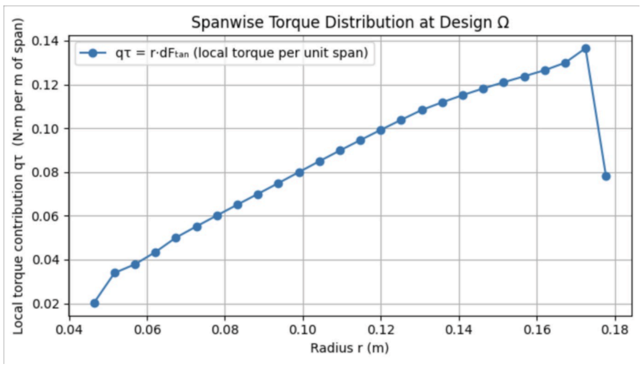
Our predicted power is 0.998 W

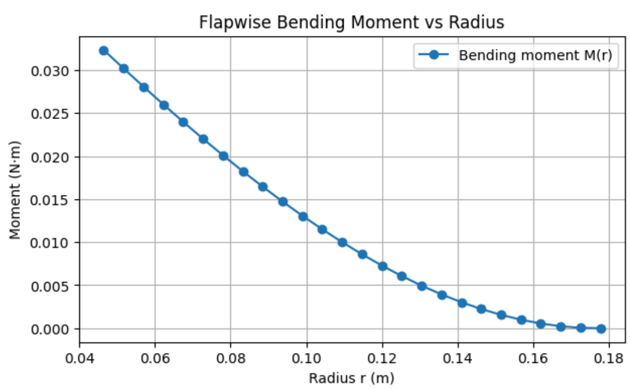
2.10 Structural Stress Analysis

Using flapwise bending moment distribution and a rectangular-section stress approximation, we verified stresses remained well below the 44 MPa allowable limit.

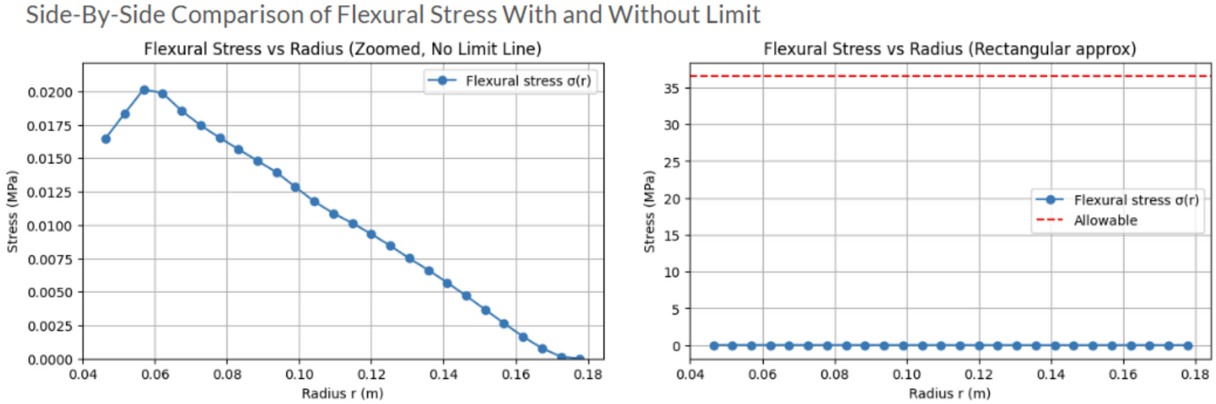
```
================ DESIGN-POINT TORQUE SUMMARY ================
Tip-Speed Ratio (λ_design): 3.00
Angular speed Ω_design    : 85.04 rad/s  (812 RPM)
Total torque Q_design     : 0.0117 N·m
Power at design speed     : 0.998 W

Torque rises with radius because outer sections:
  • experience higher relative velocity  → greater dynamic pressure, and
  • act through a longer lever arm  → larger moment contribution.
The final drop near the tip is geometric: as the Prandtl tip-loss
factor → 0, local loading vanishes even though radius is largest.
==============================================================
```





Side-By-Side Comparison of Flexural Stress With and Without Limit



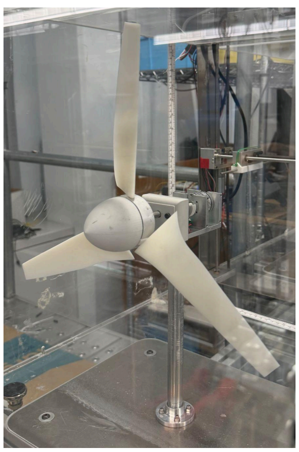
Description of the approach you followed to assess the actual performance of your design.

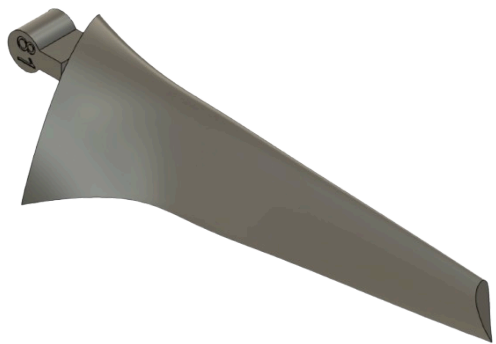
3.1 Pre-Test Planning

1. Set design setpoints:
    - Radius = 6 inches
    - Swept area = pi*R^2
    - Air density = 1.225 kg/m^3
    - Initial design RPM = 800, design TSR = 3
    - Adjusted operating RPM = about 1500, observed TSR ≈ 6

2. Establish safe operating envelope:
    - Map fan frequency to wind speed
    - Maintain torque brake voltage below 10 V
    - Maintain rotational speed below 30,000 RPM

3. Calibration:
    - Use torque-versus-current calibration curves from sweep-up data.





3.2 Data Collection

- Record fan frequency, measured wind speed, rotational speed, brake current, and notes.
- Hold each condition for 10 to 20 seconds for steady-state accuracy.
- All data were recorded on increasing-load (UP) sweeps.

Torque, power, tip-speed ratio, and power coefficient were computed using standard definitions.

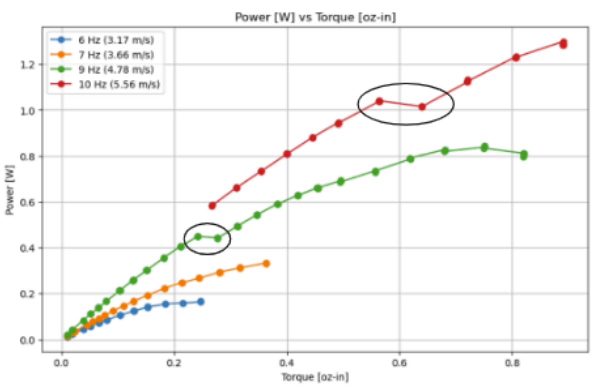
3.3 Post-Processing

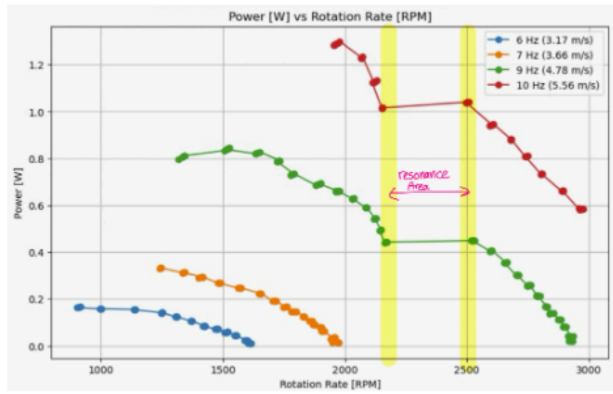
We generated all relevant power curves, torque versus RPM curves, wind speed response plots, and CP versus TSR curves. We then compared measured peak performance with predicted values from the design process.

Discussion of the results

4.1 Experimental Power Output

- Maximum measured power: 1.29 watts at 5.56 m/s
- Power increased consistently with wind speed, without showing a clear peak within the tested range
- A resonance region occurred between about 2100 and 2500 RPM, temporarily lowering measured power





Max Power = 1.29W at 5.56m/s

4.2 Tip Speed Ratio and Efficiency

Although the blade was designed for TSR = 3, the experimental turbine consistently operated near TSR = 6. Despite this mismatch, the performance remained strong. This suggests the blade could be redesigned for a higher design TSR in future iterations.

4.3 Comparison to Predicted Performance

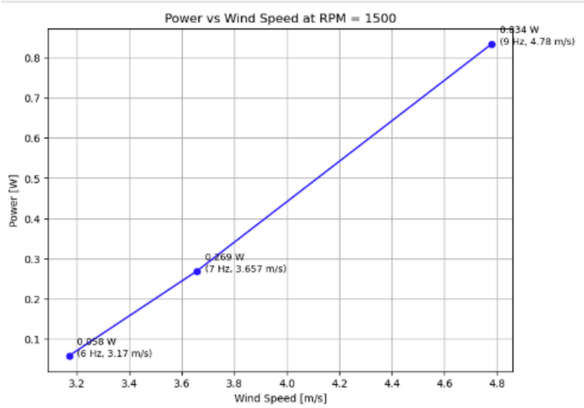
Predicted torque was 0.0117 N*m, with a predicted power of approximately 1 watt at 812 RPM. The experimental blade exceeded this prediction because it operated at significantly higher RPM and TSR.

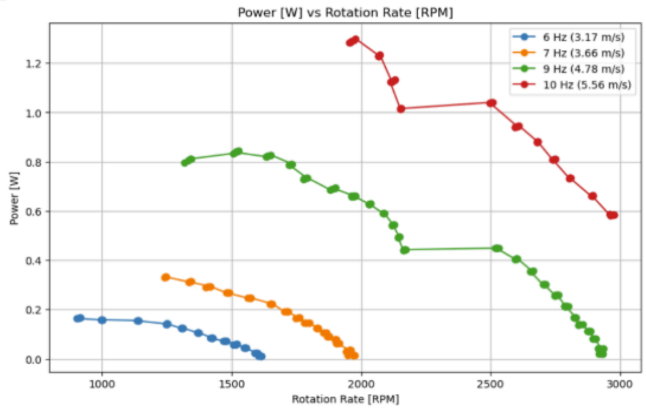
4.4 Structural Behavior

The blade exhibited no structural failure or undesirable deformation during testing. Flexural stresses remained well within the 44 MPa limit.

4.5 Unexpected Findings

- No clear performance peak occurred within the tested wind-speed range
- Resonance zones affected power stability
- The turbine operated at a TSR twice as high as the design target
- Outer-span geometry was more influential in actual performance than originally expected





4.6 Strengths of the Design Process

- The iterative BEMT approach resulted in an aerodynamically effective blade
- Structural and geometric constraints were satisfied
- The blade produced higher-than-predicted power output
- Smoothing procedures successfully produced a printable and continuous geometry

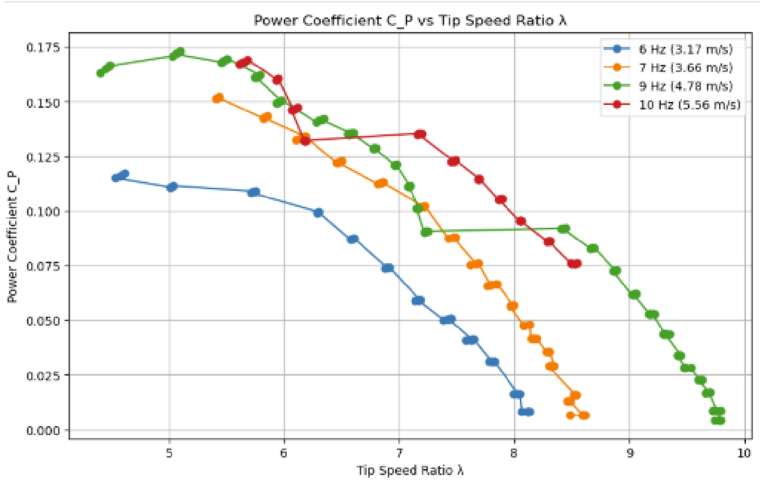
4.7 Challenges and Surprises

- Experimental operating conditions differed significantly from design assumptions
- Resonance effects influenced the measured power curves
- The absence of a peak in the power curve suggests the blade could be optimized for even higher wind speeds

4.8 Recommendations for a Second Iteration

1. Design for a higher TSR (around 6) based on experimental behavior
    a. $\lambda = \boldsymbol{\Omega R}/\boldsymbol{U}$
    b. $\boldsymbol{C}\text{P} = \boldsymbol{P} / (0.5 * \rho \boldsymbol{AU}3)$
2. Reassess chord distribution, especially at the outer span
3. Modify geometry to minimize resonance sensitivity

Improve smoothing and tapering at the root and tip for aerodynamic and manufacturing efficiency



Short conclusion

We successfully designed, manufactured, and tested a wind turbine blade that met all structural and geometric constraints and delivered higher-than-expected aerodynamic performance. The blade exceeded 1 watt of mechanical power output and operated stably across the wind-speed range. Although the turbine operated at a significantly higher TSR than originally designed, the overall experiment validated the robustness of the BEMT-based design process.

Future design cycles will incorporate an updated design TSR, enhanced outer-span chord distribution, and modifications to address resonance effects. The outcomes of this project highlight the importance of integrating simulation, manufacturability considerations, and experimental validation in small-scale wind turbine blade design.

Our group collaborated effectively, dividing responsibilities across aerodynamic modeling, geometry development, structural calculations, data collection, and analysis.

Communication remained clear throughout the project. For future work, a workflow for Python/ MATLAB and CAD files could streamline revisions and reduce duplication of effort.

Link to Code

[Colab Notebook]