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BOARD # 181: Integrated Wind Turbine Blade Design Education: Combining Theory, Simulation, CAD, and Experimental Testing

Dr. Rachmadian Wulandana, State University of New York at New Paltz

My primary teaching assignments in SUNY New Paltz are in the thermal-fluid areas such as Thermodynamics, Thermal System Designs, Fluid Dynamics, and Heat Transfer. As I believe in active learning, group activities in classroom and team projects are the two teaching tools that I utilize most to enhance students mastery on the subjects. Examples of team projects undertaken by students are designs of thermal devices and energy systems and projects inspired by contemporary scientific investigation.

My current research topics are motivated by improvement and innovation of engineering designs evolved in sustainable technology. Undergoing research projects include investigations of vortex-induced blade-less turbines and Tesla turbines for renewable energy applications, utilization of thermoelectric semiconductors for cooling, and research on supercritical carbon dioxide and refrigerants for green power generation. Relevant research interest includes numerical simulation of thermal-fluid interaction and biomimetic designs.

Graham Werner, State University of New York at New Paltz

Graham Werner is an assistant lecturer, who teaches engineering labs and lectures for the Division of Engineering Programs at SUNY New Paltz. He primarily develops curriculum for mechanical engineering laboratory courses, and is interested in promoting STEM education in local K-12 communities.

Brandon Gardner, State University of New York at New Paltz

Integrated Wind Turbine Blade Design Education: Combining Theory, Simulation, CAD, and Experimental Testing

1. Introduction

Renewable energy is becoming an increasingly popular source of electricity due to its eco-friendliness, cost-effectiveness, and sustainability. For instance, in October 2023, Governor Kathy Hochul announced the nation's largest-ever state investment in renewable energy, which includes three offshore wind and 22 land-based renewable energy projects totaling 6.4 gigawatts. These projects are expected to power 2.6 million New York homes and deliver approximately 12% of the state's electricity needs once completed. This initiative supports progress toward New York's goal for 70% of the state's electricity to come from renewable sources by 2030 and contributes to the path toward a zero-emission grid as required by the CLCPA [1]. The development of wind energy in New York is expected to create jobs and stimulate economic growth. A report by the New York State Energy Research and Development Authority (NYSERDA) estimated that the development of 9,000 MW of offshore wind energy could support up to 20,000 jobs and generate $7 billion in economic activity [2] [3]. Anticipating the massive needs of workers in the clean energy sector, Governor Cuomo of New York provided $ 15 million investment in education and training in this area through various schools such as the State University of New York (SUNY) Clean Energy Workforce Development and Training Programs [4]. Funded by the program, SUNY New Paltz in collaboration with SUNY Polytechnic formed the New York Clean Energy Workforce Training Team (NYCEWATT) to develop online education modules that focus on renewable wind energy technology [5].

Understanding the complexity of wind energy technology and the science behind it can be challenging. One of the most effective ways to grasp this knowledge is through hands-on experiential learning. Hands-on experiential learning involves actively engaging in a task or activity to gain knowledge and develop skills. In the context of renewable wind energy, this could involve building a small wind turbine, conducting experiments to understand wind speed and direction, or analyzing data collected from a real wind farm. When students actively engage in a task or activity, they are more likely to remember the information they have learned. In the case of renewable wind energy, hands-on experiential learning allows students to see the principles they are learning in action [6]. Students can feel the wind, observe the turbine blades turning, and understand how energy is being generated. This type of sensory experience is much more memorable than simply reading or listening to information. During hands-on activity, students are forced to think critically and come up with solutions to challenges that arise during the activity. This type of learning allows students to develop their problem-solving skills, which can be useful in other areas of their academic and professional lives. Hands-on experiential learning often involves group work and an interactive learning environment that is expected to enhance learning efficiency [7]. More importantly, hands-on experiential learning is quite engaging, which can increase students' interest in the subject matter [8]. Interested students are more likely to ask questions, participate actively in class, and seek out additional information. This type of learning is expected to inspire students to pursue careers in renewable energy and contribute to the transition to a sustainable future [9].

2. Proposed Education Framework

The proposed framework attempts to provide a comprehensive learning environment for studying wind turbines, particularly fundamentals of blade designs. The integrated learning system consists of three pillars of engineering education and practice: (1) theoretical foundation, (2) computational aided design and numerical analysis as well as (3) hands-on experimentation using a small-scale commercial wind turbine model. Designated for junior and senior undergraduate levels, the platform focuses on practical applications and lifelong learning engagement. The condensed version of the proposed course could be offered for three credits, while the more comprehensive version might carry up to six to nine credits. For a 3-credit course, the total hour per semester, for a 15-week course, is 135 hours (each hour is 50 minutes).

Table 1 presents a proposed compilation of pertinent theoretical foundations for the analysis of wind turbine blades, accompanied by estimated instructional hours allocated to each topic. Historical context is incorporated to enhance student engagement and to situate the technical content within a broader developmental framework. It is estimated that the total class hours are 15 hours per semester that must be accompanied by 30 hours for study outside the classroom. Totally, the theoretical part can take 45 hours per semester, one third of total hours per semester.

Table 1 Distribution of Theoretical Foundation materials and their learning functionality

Materials	Functions	Class Hours
Fundamental Theories		
Conservation Laws	Reviews	1.5
Bernoulli Equations	Reviews	1.5
Lift and Drag Basic	Reviews	1.5
Modeling and Similitude	Reviews	1.5
History of wind turbines		
Old to pre-modern era	Learning Engagement	0.75
Early Modern era history	Learning Engagement	0.75
Modern era history	Learning Engagement	0.75
Wind turbine manufacturing	Learning Engagement	0.75
Theory of Turbine Blades		
Actuator Disc Theory	Core Material	1.5
Blade element Theory	Core Material	1.5
Rotor Wake models	Core Material	1.5
Kutta-Joukowski Theory	Core Material	1.5
Total classroom hours		15.0
Total hours outside classroom		30.0
Total hours per semester for Theory and Engagement		45.0

Furthermore, given the course's emphasis on hands-on applications and design, it is essential to allocate instructional time for the introduction of relevant computational tools. Table 2 outlines the proposed software to be used in the course, along with the estimated class hours required for their introduction. The total introduction time in classroom dedicated to these tools is projected to be approximately 15 hours. This amounts to a cumulative total of 45 hours per semester after the practice and application time outside the classroom is considered.

The remaining 45 hours are allocated to a range of hands-on activities, including 3D printing and preparing blade models, conducting experiments, collecting and analyzing data, and preparing reports. In this compact 3-credit course structure, approximately two-thirds of the instructional time is devoted to practical and hands-on applications. The theoretical content may need to be further condensed—or selectively reduced—should additional time be required for the application-based components of the course. For instance, the 3D printing and preparation of blade models can extend over several days, depending on class size as well as the availability of printers and materials. Similarly, significant instructional time may be needed for software-related activities, particularly given that many students may have limited prior experience with the computational tools used in the course.

Table 2 List of software supporting the proposed framework and total class hours for introduction of the software

Applications	Functions	Licensing	Class hours
airfoiltools.com	Airfoil generator for blade profiles	Open source, website	1.5
QBlade	Airfoil fluid analysis	Open source, application	3.0
Rhinoceros (Rhino)	3D CAD designs	Paid Licensing with special discount for academic usage	3.0
ANSYS	Finite element analysis for structural and fluid	Free Education licensing with limited features	3.0
VDAS and Wind Turbine Module	DAQ tool for the wind turbine module	Packaged with the wind turbine module	1.5
Excel and Matlab	Data Analysis, Plotting	Academic licensing	3.0
Total classroom hours			15.0
Total hours outside classroom			30.0
Total per semester for introduction to tools			45.0

An extended 6-credit course structure may offer a more robust and pedagogically effective alternative to the compact model, particularly in cases of high student enrollment or increased demand for hands-on learning. This extended format allows for a clear separation between theoretical aspects and hands-on applications of the course. The first 3-credit segment would be dedicated to establishing a solid theoretical foundation, covering essential topics such as aerodynamics, blade element theory, and structural mechanics, alongside the introduction of relevant computer-aided design (CAD) tools. This phase ensures that students are well-equipped with the analytical and technical skills necessary for effective design and simulation.

The second 3-credit segment would function as an advanced continuation of the course, offering students the opportunity to deepen their understanding through extended experimental work, comprehensive data analysis, and computer simulations. Potentially, this portion could be used to incorporate advanced materials such as computational fluid dynamics (CFD), structural analysis, modeling of composite materials, and noise analysis thereby aligning with real-world engineering practices and industry expectations. By distributing the workload across two well-defined phases, the 6-credit model allows for greater depth in both theoretical instruction and practical implementation, ultimately providing a more comprehensive and immersive educational experience.

2.1 Theoretical Foundation

Selected topics on wind blade theory are focused on application and examples of formulations, instead of a lengthy derivation of theories of turbine blades, for example, Beam Element Momentum theory, which combines both Blade element theory and Momentum theory or Actuator Disk theory. Reviews and applications of engineering fundamentals, particularly ones that are taught in Fluid Mechanics, Thermodynamics, and Mechanics of Materials, such as Mass, Momentum, and Energy Conservation Laws along with practical Bernoulli equations and Euler-Bernoulli beam equations are carried out to provide an essential learning step for advanced materials. The review section also provides opportunities for strengthening foundational knowledge, reinforcing key concepts learned during the sophomore year, and building confidence in applying these principles to more advanced topics, such as the blade designs.

Additionally, to increase learning engagement, historical accounts of wind turbines construction and technology development – focusing on the horizontal axis wind turbines – are included in the teaching materials. Abundant open education resources and video documentaries on wind turbines reduce the cost and increase engagements. For example, experts from Technical University of Denmark will walk you through the basics of wind energy—from measuring and forecasting wind to turbine design, materials, structures, and the financial and electrical systems behind it - all via a free 16-module course in Coursera [10]. Lecture videos on foundation of fluid mechanics developed by National Committee for Fluid Mechanics Films and sponsored by National Science Foundation, for example on the topic of Eulerian and Lagrangian description of fluid motion [11], are available on YouTube for free and certainly can be added as engaging materials.

2.2 Computational Analysis and Designs

Computational analysis and designs for the proposed course of wind turbine blade design are carried out using several software: Airfoiltools.com, QBlade, Rhinoceros, VDAS, and ANSYS as well as basic software such as Excel and Matlab. Table 2 above summarizes the functionalities and licensing of these computer programs. The Rhinoceros for CAD perhaps is the most expensive software on the list. The VDAS software functions as data acquisition software exclusive for the wind turbine lab module AE1005V Wind Turbine Dynamics by TecQuipment [12].

Airfoiltools.com

The early step of blade designs involves analysis of airfoils, the cross section of wind turbine blades. Airfoiltools.com is a web-based platform [13] that serves as a comprehensive resource for exploring, analyzing, and comparing airfoils—ideal for engineers, researchers, students, and aviation hobbyists. It provides a large, searchable database of over 1,600 airfoil profiles from reputable sources such as NACA, Selig, Eppler, and NASA. Each airfoil entry includes coordinate files that can be downloaded for use in simulations or modeling software. What sets the site apart is its built-in analysis functionality using the JavaFoil solver, which allows users to simulate and visualize key aerodynamic performance metrics like lift coefficient across a range of conditions, including different Reynolds numbers and angles of attack. Students can also compare the performance of multiple airfoils side-by-side to identify optimal shapes for specific applications. The platform is especially useful for preliminary design of aircraft wings, wind turbine blades, or drone airframes, offering an intuitive way to test how various airfoil geometries behave aerodynamically—though results are 2D approximations and best used for low-speed conditions or early-stage design decisions.

AirfoilTools.com provides an extensive suite of tools and a comprehensive airfoil database that surpass the instructional scope typically achievable within a standard 3-credit course. Hence, it is suggested that the proposed course simply focuses on one airfoil generator. The NACA [14] system employs numerical designations to define airfoil geometries. The 4-digit system uses four digits to convey fundamental shape characteristics. The first digit indicates the maximum camber as a percentage of the chord length, signifying the airfoil's curvature and its ability to generate lift. For instance, in the NACA 2412 airfoil, the '2' denotes a maximum camber of 2% of the chord. The second digit specifies the position of this maximum camber along the chord, measured from the leading edge in tenths of the chord. So, in NACA 2412, the '4' indicates that the maximum camber is located at 40% of the chord. The final two digits represent the maximum thickness of the airfoil as a percentage of the chord. So, the '12' digit of NACA 2412 indicates the maximum thickness of 12% of the chord. This straightforward system allows for the definition and categorization of a wide array of basic airfoil shapes based on these three key geometric parameters. geometries beyond those already included on the platform [15] While NACA airfoils are primarily known for their application in aircraft wing design, their versatility has led to their adoption in numerous other fields. Wind turbines commonly utilize NACA airfoil designs for their blades, leveraging their well-characterized aerodynamic properties at lower Reynolds numbers. The principles of airfoil design, including NACA profiles, are also directly applicable to propellers for aircraft and boats, as well as helicopter rotor blades. Hydrofoils, which are underwater lifting surfaces used in high-speed watercraft, can also incorporate NACA airfoil sections.

The AirfoilTools.com allows users to save the airfoil's coordinate data as text files (Dat files) and 2D images (png or jpeg files). Image files can be imported using Picture tool into Rhino for further CAD processing. On the other hand, the data files can be useful for QBlade software.

The NACA 2412 airfoil is a popular choice for wind turbine blades due to its moderate camber and thickness distribution, which provide a good balance between lift and drag. The 2% camber enhances its ability to generate lift at low angles of attack, making it efficient for capturing wind energy in moderate wind conditions. Additionally, the 12% thickness ensures structural integrity while minimizing drag, allowing for smooth airflow over the blade surface. This airfoil is especially suitable for small to medium-sized wind turbines that require steady performance and good lift-to-drag characteristics.

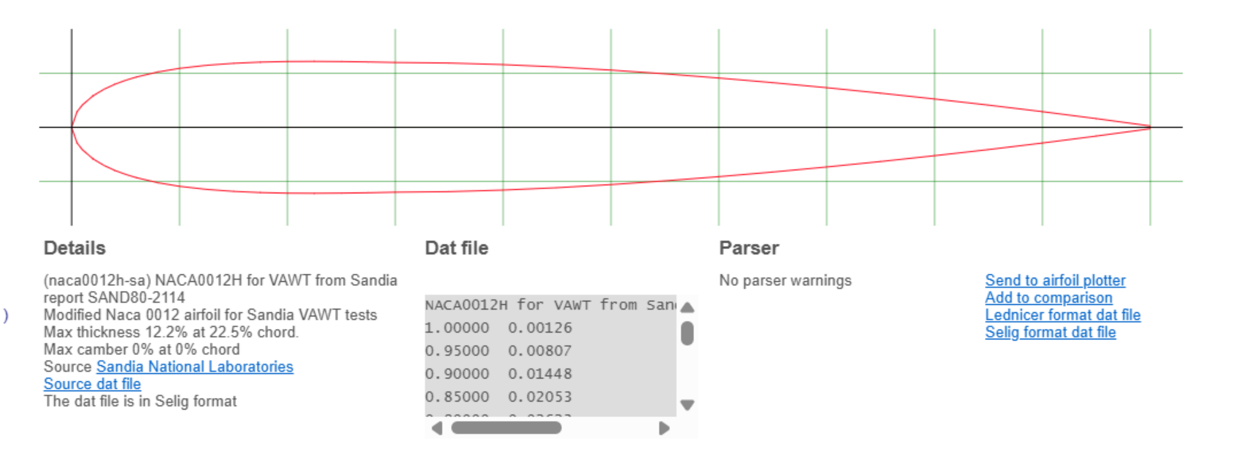

Figure 1 A snapshot of airfoil NACA0012H opened in AirfoilTools.com along with a portion of Dat file of the coordinate data in Selig format

On the other hand, NACA 0012 airfoil is a symmetrical airfoil, meaning it has no camber and performs equally well in both directions. This makes it an excellent choice for wind turbines with variable pitch control or vertical-axis wind turbines where bidirectional performance is necessary. Despite its lack of camber, it can still produce lift at appropriate angles of attack, though it requires higher angles compared to cambered airfoils. The 12% thickness offers good structural strength, making it a durable option for wind turbine applications where simplicity and stability are key concerns.

The primary difference among these airfoils lies in their camber and thickness. Symmetrical airfoils like the NACA 0012 lack camber and require higher angles of attack to generate lift, while cambered airfoils like the NACA 4412 and 4421 produce lift more efficiently at lower angles. Thickness also varies, with the NACA 4421 being the thickest at 21%, offering superior structural strength but slightly higher drag. In contrast, the NACA 65-210 is optimized for laminar flow, reducing drag and enhancing efficiency in high-speed conditions. These differences determine their suitability for various wind turbine designs, from low-speed, high-lift applications to high-speed, low-drag configurations.

Rhinoceros

Rhinoceros, or Rhino, is a versatile 3D modeling software developed by Robert McNeel & Associates, widely used across engineering, architecture, and design industries. Specializing in Non-Uniform Rational B-Splines (NURBS) geometry, Rhino excels at modeling precise curves, surfaces, and solids, making it ideal for organic shapes and intricate structures like aerodynamic turbine blades. Its compatibility with diverse file formats, such as STL, OBJ, and IGES, ensures seamless integration with various CAD tools, crucial for blade design workflows. Most importantly, the 3dm output file of Rhino is directly readable by ANSYS Workbench. Rhino supports plugins like Grasshopper for parametric modeling and Python scripting for custom workflows, offering flexibility for users from beginners to professionals.

Most importantly, Rhino allows students to easily design turbine blades based on airfoils generated using the open source airfoiltools.com, a comprehensive online resource dedicated to airfoil data and analysis. It offers a wide range of tools, databases, and utilities specifically designed for aerodynamics, particularly in the context of wind turbines, aircraft, and other engineering applications. The website provides users with access to an extensive collection of airfoil data, which can be used for design, analysis, and optimization purposes. The website features a database of thousands of airfoils, including popular and specialized airfoils used in various industries. Each airfoil entry typically includes data such as coordinate points, airfoil geometry, and performance characteristics (e.g., lift, drag, and moment coefficients) for different angles of attack and Reynolds numbers. This data is valuable for engineers and researchers involved in aerodynamic analysis and design, as it provides insights into the airfoil's performance under different conditions.

In Rhino, the imported image file is opened in sketch mode and scaled to the desired size, either by graphically stretching it with the mouse or by entering exact dimensions in the command bar. The student then manually traces the airfoil profile using Rhino's Interpolation Curve tool, which accurately captures the contour. Once the airfoil is fully traced, the Gumball tool is used to duplicate the profile and move the copy 15 cm from the original—this distance represents the blade's length. The copied profile is then scaled down proportionally using the Scale2D command.

Next, the student connects the leading and trailing edges of both profiles using smooth curves with the Interpolation Curve tool. These curves serve as guide rails for the Sweep2 command, which generates a smooth 3D surface between the two airfoil shapes. The Cap command is used to convert the surface into a closed, solid polysurface. To attach the blade to the simulator, a pre-made hub attachment file is imported into Rhino alongside the blade. The student identifies a straight isocurve that connects the two end profiles as the optimal mounting point for the hub. This ensures proper alignment and structural integrity in the final assembly.

The final version of the CAD design is saved as stl files to be sent to the 3D-printing facility. On the other hand, the files are also saved as 3dm format so that they can be opened using ANSYS Workbench for further analysis.

3D-Printing

The blades were printed at the Hudson Valley Additive Manufacturing Center, located in New Paltz, New York, on a Stratasys J753 printer using RGDA 8425-DM material. The Stratasys J750 3D printer is a high-end PolyJet system renowned for its ability to produce full-color, multi-material prototypes with exceptional realism and precision. It supports over 500,000 color combinations, enabling the creation of models with intricate color gradients and textures. The printer can load up to six materials simultaneously, allowing for combinations of rigid, flexible, transparent, and opaque materials in a single print. With a layer thickness as fine as 14 microns, it delivers ultra-smooth surfaces and detailed features. The J750 is particularly valuable in industries like product design, healthcare, and education, where accurate, lifelike models are essential.

Figure 2 A photo of the Stratasys PolyJet printer used to print the turbine blades

RGD8425-DM is a digital material engineered for use with Stratasys PolyJet 3D printers, such as the J750. It is formulated by combining VeroWhitePlus (RGD835), a rigid opaque photopolymer, with TangoPlus (FLX930), a flexible, rubber-like material. The resulting composite offers a balance of rigidity and flexibility, making it ideal for applications that require both structural durability and pliability. This material is especially well-suited for prototyping components that mimic the mechanical behavior of final products, such as over molded parts or those with soft-touch surfaces. Once printed, the blades were thoroughly cleaned and prepared for installation into the wind turbine simulator.

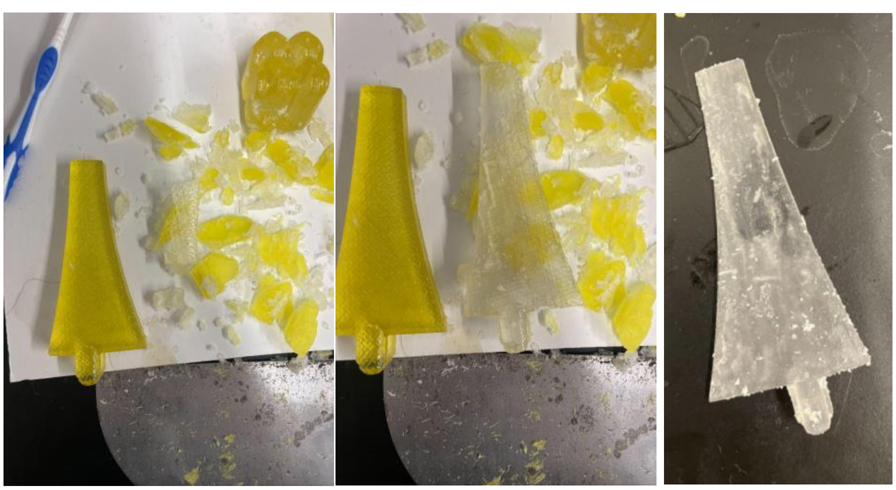

Figure 3 Snapshots of a 3d-printed blade undergoing manual cleaning to remove support materials (SUP 706 resin)

QBlade

The hands-on QBlade is open-source software developed by the Wind Energy Group at the Berlin Institute of Technology (TU Berlin), designed specifically for the design and analysis of wind turbine blades. The software is widely used in both academic and industrial settings due to its intuitive interface and robust capabilities tailored to wind energy applications. The software provides a comprehensive environment for blade design, allowing users to define geometries such as airfoil profiles, chord lengths, twist distributions, and span configurations. Its built-in optimization tools help maximize energy capture and efficiency by enabling users to design blades that perform optimally under specific operating conditions. A key feature of QBlade is its integration with the XFOIL code, which allows users to design custom airfoils, simulate their performance across varying Reynolds numbers, and seamlessly incorporate them into blade designs. The software employs Blade Element Momentum (BEM) theory for performance prediction, providing accurate calculations of power coefficients, thrust coefficients, and torque curves across different wind speeds and operational parameters.

QBlade also supports dynamic simulations, enabling the study of unsteady aerodynamics and transient effects, such as startup behavior or shutdown scenarios. The inclusion of 3D visualization tools enhances the user experience by allowing detailed inspection of blade and turbine geometries before proceeding to manufacturing or testing. In addition to supporting horizontal axis wind turbines (HAWTs), QBlade is versatile enough to accommodate vertical axis wind turbines (VAWTs) as well. Its open-source nature makes it freely accessible, with the added benefit of being modifiable to suit specific needs, which is particularly advantageous for researchers, educators, and engineers. Furthermore, QBlade enables data export, facilitating integration with other computational fluid dynamics (CFD) and general multi-physical simulation tools based on either finite element method, finite volume method, etc. The software is particularly valued in the wind energy field for its ability to handle everything from conceptual blade shapes to detailed performance analysis, making it a staple for research, education, and early-stage design. It is extensively used in universities to teach wind turbine aerodynamics and mechanics while also supporting optimization studies to explore blade configurations that maximize efficiency and energy yield. However, while QBlade is an excellent tool for aerodynamic analysis, it has certain limitations, such as the absence of structural or material analysis tools. Additionally, it requires a foundational understanding of wind turbine theory to fully leverage its advanced features, and the accuracy of its results depends on high-quality input data and the inherent assumptions of BEM theory.

This graph from QBlade shows the relationship between drag coefficient (Cd) and angle of attack (AoA) for the NACA 0012 airfoil. Cd is lowest near 0° AoA, which is expected for a symmetric airfoil, and increases gradually as the AoA deviates in either direction due to growing flow separation. A sharp rise in Cd occurs beyond approximately ±12°, indicating stall and a significant increase in pressure drag. The red curve represents a highlighted case, while the other curves—shown in various colors—represent different analysis conditions such as changes in Reynolds number or flow settings. This visualization helps define the AoA range where the airfoil maintains low drag and optimal aerodynamic performance

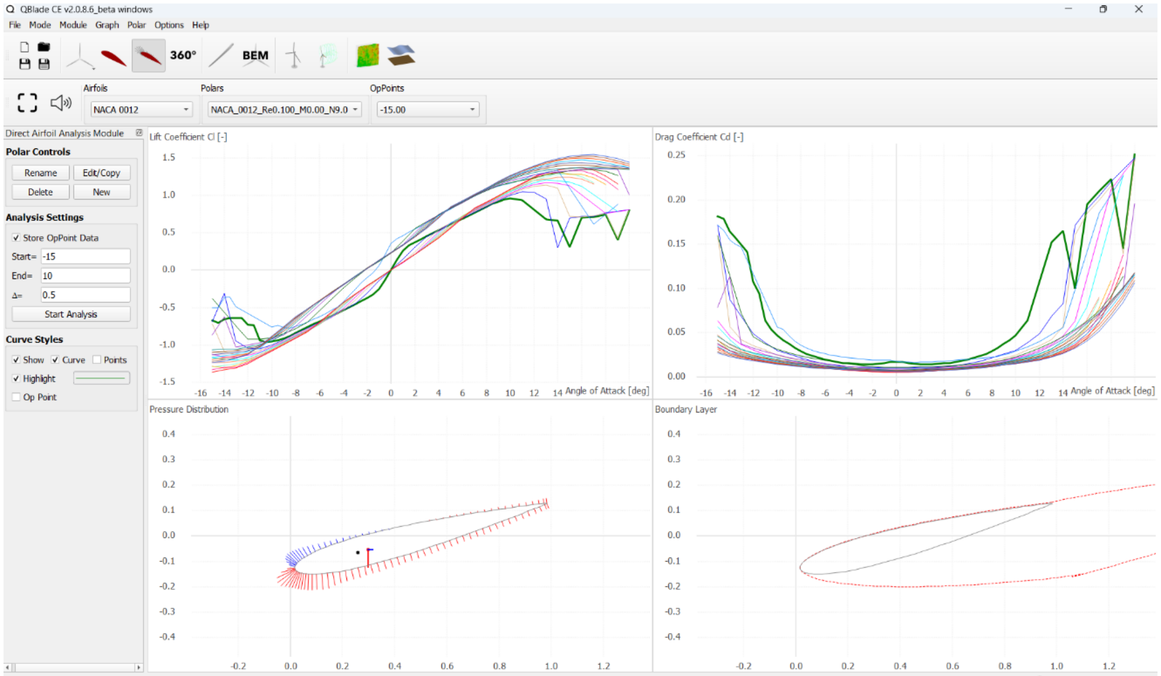

Figure 4 A snapshot of analysis results, such as pressure distribution, drag and lift coefficient for a series of angles of attacks, by QBlade on NACA 0012 airfoil. Data from QBlade can be exported as text files readable by Excel and Matlab.

ANSYS Workbench

ANSYS is a leading engineering simulation software widely used for analyzing and optimizing complex systems and components across industries. The academic version of ANSYS is free for teaching purposes and hence it is strategic to be included in the proposed platform. Known for its powerful finite element analysis (FEA) and computational fluid dynamics (CFD) capabilities, ANSYS is extensively utilized in the design and evaluation of wind turbine blades, offering a suite of tools that enable engineers to address aerodynamic, structural, and thermal challenges. In wind turbine blade design, ANSYS provides advanced tools for analyzing aerodynamic performance using CFD modules such as ANSYS Fluent and ANSYS CFX. These tools simulate airflow around the blade, assess lift and drag forces, and calculate power coefficients under various wind conditions. Engineers can use these insights to optimize blade geometry, twist, and chord distribution for maximum energy capture. Blades are subjected to complex and varying loads, including aerodynamic forces, gravitational effects, and centrifugal forces. Using tools like ANSYS Mechanical, engineers can perform static and dynamic analyses to evaluate stress distribution, deflection, fatigue, and potential failure points. Material behavior, including composites commonly used in blades, can be modeled accurately to predict performance under extreme weather conditions and over the turbine's lifecycle.

Most importantly, the 3dm file generated by Rhino can be easily imported into ANSYS and it will be recognized as a solid body with more than one surface, allowing implementation of multiple load configuration and boundary conditions. The solid body can be finely meshed either locally or globally according to our needs. If necessary, the solid body can be modified in the geometry modeler SpaceClaimm, which is a part of ANSYS Workbench.

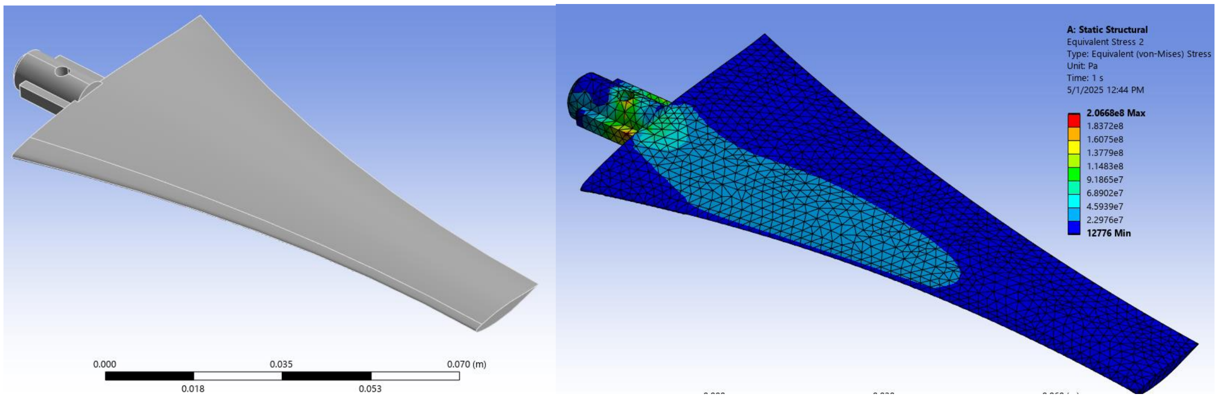

Figure 5 Snapshots of an airfoil solid body analyzed in ANSYS Workbench. The body geometry is obtained by importing a 3dm file produced by Rhino CAD software. The figure on the right shows the von-Mises stress distribution, assuming that the blade is made of stainless steel and experiencing pressure on one side of the blade.

2.3 Hands-on Experimentation

The AE1005V Wind Turbine Dynamics by TecQuipment, Ltd. (Bonsall Street, Long Eaton, Nottingham, NG10 2AN, United Kingdom) [12] provides hands-on learning experience. The lab module occupies height, length, and depth dimensions of 1513 mm, 1700 mm, and 800 mm, respectively. The total weight of the module is about 200 kg. Figure 6 below shows the observable cylindrical test wind tunnel and the control panel of the wind turbine module. This horizontal axis three-bladed turbine model seen in the figure is securely mounted on a cylindrical tower fixed inside the 40-cm diameter tunnel. The tunnel inlet, partially seen on the left edge of Figure 1, is equipped with a bell mouth and honeycomb grid that functions to streamline the air flow drawn by a heavy-duty 1500-W fan downstream the wind turbine. The velocity measurement of the air flow is achieved by placing a stowable anemometer placed at the inlet. More importantly, the cylindrical tunnel is also furnished with two transparent sliding doors for visual observation of the turbine model during the experiments. The sliding door allows easy access for the replacement of three identical 3D-printed blades. Three blades of the same geometry and weights are secured on the rotor fixed on a cylindrical pole fixed on a base with manual yawing mechanism. This mechanism allows the control of angle between the turbine axis and the wind direction.

Figure 6 The AE1005V Wind Turbine Dynamics module and the control panel are shown on the left. The figure on the right shows a close look of the 3D-printed blades installed on the turbine hub. The glass window is closed during the operation.

Additionally, the model is equipped with a motorized blade pitching mechanism that allows us to control the relative angle between the blade and the flow direction. Besides the yaw angle of the rotor and pitch angles of the blades, the fan speed and turbine speed are the other variables that can be freely controlled. These variabilities provide a wide range of investigation and data collection. Important parameters that can be studied are summarized below:

1. The yaw angle represents the relative angle between the turbine axis and the flow direction. The yaw angle ranges from -50 to +50 degrees with fine increment.
2. The pitch angle represents the relative angle between the turbine blades and the flow direction. The pitch angle ranges from -5 to 40 degrees with fine increment.
3. Fan speed represents the average speed of air flow into the tunnel. The fan produces air flow from zero to about 15 m/s or 33.5 mph. This is more than sufficient to mimic realistic wind speed, particularly considering the small diameter of the turbine.
4. Turbine speed is the angular speed of the turbine rotor. The variation of turbine speed simulates possible internal resistance or loads by wind turbines. The turbine speed can be varied from very low rpm to its maximum of 4000 rpm with very fine increment.
5. Seven (7) anemometer positions that can be used to collect the air speed data across the inlet diameter and to generate the average velocity of the applied wind.
6. 3d-printed blade designs which are constrained by maximum radius (blade length) times width of around 108 mm x 81 mm and specific material characteristics.

The turbine module returns the following outputs that can be monitored on the control panel and recorded manually. Alternatively, the following data are displayed on the control panel:

1. Electric current produced by the turbine
2. Torque acting on the rotor shaft
3. Power output by the turbine that is limited to 62 Watts
4. Coefficient of Power (COP) of the selected turbine model

This data are recorded continuously by the VDAS desktop computer program and it can be exported easily to Excel for further analysis.

Possible investigation that can be conducted can be listed as:

1. Effects of yaw angle on the power production, torque and COP,
2. Effects of pitch angle on the power production, torque and COP, and
3. Effects of wind speed on the power production, torque and COP.

Although the list of investigations appears short, each requires comprehensive data collection across all relevant parameters, making the experiments time intensive. When various blade geometries and combinations of 3D-printing materials are considered, the same set of investigations must be repeated for each design, resulting in many potential experiments. Furthermore, using replaceable 3D-printed blades introduces additional activities, including computer-aided design (CAD) of blades and mechanical test coupons, tensile testing of the coupons, and cantilever testing of the printed blades. For brevity, this paper presents only a subset of the experimental results and design variations.

Coefficient of Power VS TSR

Coefficient of Power or Cp is one of several important fundamentals that students must learn from wind energy technology. This crucial design parameter indicates the efficiency of wind turbines, and it is defined as the ratio of realistic turbine power to the possible maximum kinetic energy generated by the rotor. Following the kinetic energy formulation, the theoretical maximum power of wind turbine is formulated as

$$P_{max} = \frac{1}{2} \rho A V^3$$

where ρ is the air density that is typically taken as 1.2 kg/m^3 and V is the mean air speed. The variable A indicates the cross-section area of the rotor swept by the blades, which is $A = \frac{1}{4} \pi D^2$ and D is the diameter of the rotor. The nominator of Cp is the realistic turbine power by the turbine model and this data is measured based on the selected turbine speed and the produced torque.

The Cp is typically plotted against the Tip Speed Ratio or TSR. This parameter represents the ratio of circumferential speed of the blade relative to the incoming flow speed. In particular, the plot below shows results from the 3D-printed blades provided by the manufacturer of the educational turbine module. The set of blades are designed based on NACA 0009 airfoil. The experiments were conducted with zero-degree yaw angle and ten-degree pitch for various wind speeds ranging from 6 to 11 m/s and various turbine speed from zero to 4000 rpm. The selected pitch angle was found to provide the best performance for a specific wind speed.

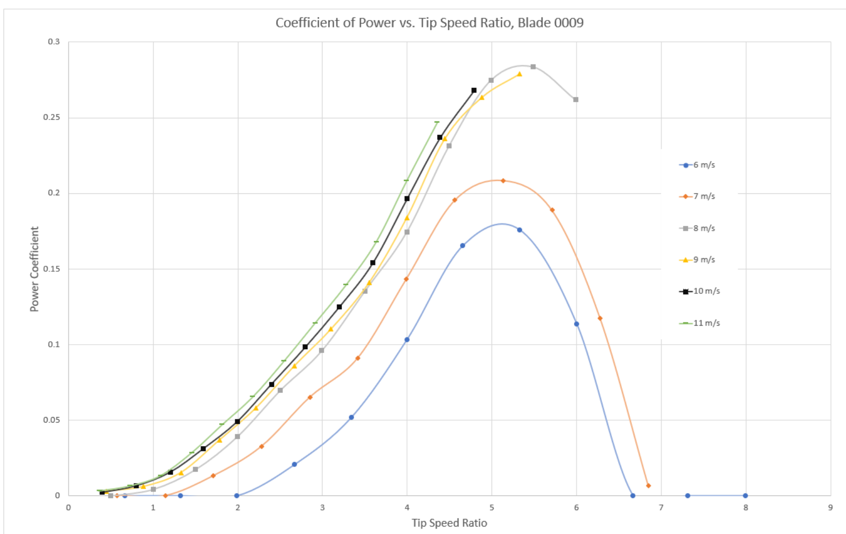

Figure 7 An experiment done to map the Cp vs. TSR graph for Blade NACA0009 at varying windspeeds. Notice that the peak for all windspeeds lies at a TSR of about 5, and a Cp ranging from .18 to .28. at yaw zero and pitch of 10 degree

The graph indicates the following important findings:

- The near-parabolic curves show local maximum indicating optimum TSR and maximum Cp for different wind speeds. The curve shapes are very typical and resemble Cp versus TSR curves obtained from full scale three-bladed turbines.
- The range of TSR obtained from this model represents a realistic range commonly found for traditional turbines. True scale three-bladed horizontal axis turbines demonstrate a range of TSR from 4 to 7 and their maximum of Cp was reported to be around 50 percent.
- The model blades used in this experiment managed to reach Cp of almost 30 percent. This is certainly low, but, more importantly, it is realistic as it is still below the Betz limit of 59 percent. The low Cp can be attributed to the blade designs and materials as well as experiment factors such as the selection of pitch angle, yaw angle, and air turbulence.
- For the selected blades, the Cp curves are saturated at high-speed flow. During experiments, the student operator noticed high instability of the blades. This may be attributed to the poor blade designs and material stiffness.

Shown below are graphs representing Coefficient of Power versus TSR for NACA 6409 blades at zero yaw and 5-degree pitch. The measurement is performed between 5 to 11 m/s of air flow speed. The curves show similar characteristics of nonlinear increase in Cp reaching to a local maximum that is followed by another nonlinear decrease in Cp. The TSR ranges 2 and 7 and the maximum occurs between TSR 4 and 5 depending on the wind speed. Again, this is very typical characteristics for realistic three-bladed horizontal axis turbine. The TSR range is slightly lower than that for NACA 0009 operated at 10=degree pitch while the Cp reaches maximum of around 50%. The coefficient here is quite high and perhaps are in the range of full-scale industrial horizontal axis turbine. Nevertheless, like previous data for NACA 0009, the curves are saturated at high wind speed. And in fact, some high-power data are missing due to safety feature of the model.

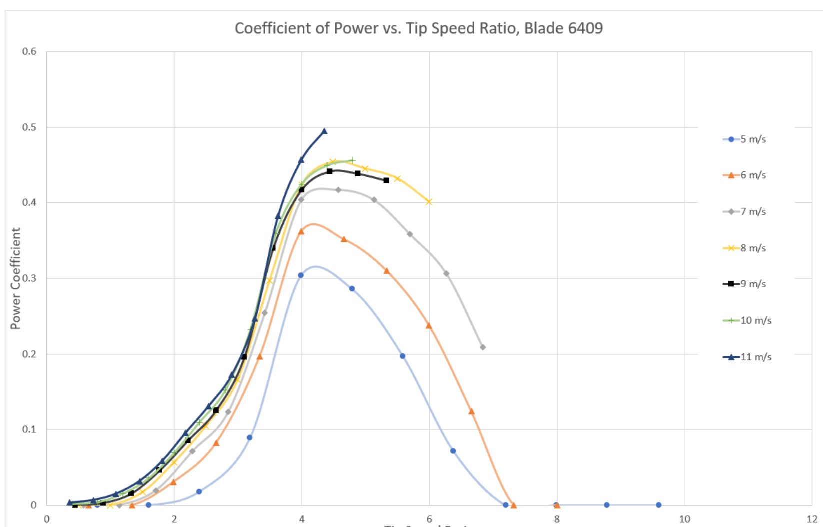

Figure 8 An experiment done to map the Cp vs. TSR graph for Blade NACA6409 at varying windspeeds. Notice that the peak for all windspeeds lies at a TSR of about 4.3 and a Cp ranging from .32 to .5 at zero yaw and pitch of 5 degrees.

Conclusion

In conclusion, this educational toolkit offers a well-rounded approach to wind turbine blade design, providing undergraduate mechanical engineering students at SUNY New Paltz with a comprehensive learning experience that integrates theory, design, simulation, and hands-on experimentation. By combining the use of CAD software, open-source simulation tools, 3D printing technology, and a small-scale wind turbine demonstrator, students can actively engage with real-world engineering challenges and gain practical insights into renewable energy systems. The toolkit not only enhances students' technical skills but also fosters a deeper understanding of the complexities of wind turbine performance. With the potential for future enhancements, including finite element analysis and vibration studies, this initiative stands to further enrich the educational experience and contribute to the development of the next generation of engineers in the field of renewable energy.

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