Fluid-structure Interaction and Multidisciplinary Design Analysis Optimization of Composite Wind Turbine Blade

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FLUID-STRUCTURE INTERACTION AND MULTIDISCIPLINARY DESIGN
ANALYSIS OPTIMIZATION OF COMPOSITE WIND TURBINE BLADE

by

Naishadh G. Vasjaliya

A Thesis Submitted to the College of Engineering Department of Aerospace Engineering
In Partial Fulfillment of the Requirements for the Degree of
Masters of Science in Aerospace Engineering

Embry-Riddle Aeronautical University
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This thesis was prepared under the direction of the candidate's Thesis Committee Chair, Dr. Sathya Gangadharan, Professor, Daytona Beach Campus, and Thesis Committee Members Dr. Reda R. Mankbadi Distinguished Professor, Daytona Beach Campus, and Dr. Somanath Nagendra, Principal Engineer, System Design and Optimization, Pratt and Whitney and has been approved by the Thesis Committee. It was submitted to the Department of Aerospace Engineering in partial fulfillment of the requirements for the degree of Masters of Science in Aerospace Engineering

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Dedication

This thesis is dedicated to my parents. To my late mother, Ushaben Vasjaliya, had been a source of motivation and strength during moments of despair and discouragement, without her continuous support and encouragement I never would have been able to achieve my goals. This one is for you mom! To my father, Gordhanbhai Vasjaliya, who has instilled the value of ambition, dedication, and showed me unique ways to comprehend that success cannot be achieved without love and support.
I would never have been able to finish my dissertation without the guidance of my committee members, help from friends, and support from my family.

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I would like to thank my friends, my parents and sister for giving me their unequivocal support throughout, as always, for which my mere expression of thanks likewise does not suffice.
A multidisciplinary design analysis optimization (MDAO) process is defined for a composite wind turbine blade to optimize its aerodynamic and structural performance by developing a fluid-structural interaction (FSI) system. The objectives are to maximize aerodynamic efficiency and structural robustness while reducing blade mass and total cost. In the previous research, a MDO process of a composite wind turbine blade has been pioneered as an effective process to develop structurally optimized blade design. Present MDAO process is defined in conjunction with structural and aerodynamic performance of the blade which is divided into three steps and the design variables considered are related to the shape parameters, twist distributions, pitch angle, material and the relative thickness based on number of composite layers at different blade sections. Maximum allowable tip deformations, modal frequencies and allowable stresses are set as design constraints. The results of the first step are aerodynamically optimal angle of attack of airfoils for the blade cross-sections along the blade span wise direction, and the uniform pressure distribution along the blade at maximum lift and wind conditions. Airfoil performance is predicted with 2D airfoils analysis, while 3D CFD analysis is performed by ANSYS CFX software. The second step yields optimal material, composite layup distribution of the blade and involves fluid structure interaction
system hence actual pressure loads on the blade can be used for the structural analysis. A parameterized finite element model of the blade created in ANSYS ACP composite prepost and used to define the composite layups of the blade. At the last step, the results of the CFD and the structural analysis are used for the optimization process accompanied by the cost estimation to obtain a compromised solution between aerodynamic performance and structural robustness. For the MDAO process number of design of experiments (DOEs) is defined by G-optimality method and a response surface is created. Additionally, by consideration of maximum power output, minimum weight and cost as prior objectives, an optimal blade design is found within the pre-defined design variable parameters and structural constraints. Sensitivity analysis is performed to observe the impact of input parameter on each output parameters for enhanced control of the MDAO process. Further, to improve aerodynamic performance of the blade, new design approach with modified Tip (winglet) and rotor section is studied and substantial improvement in power generated over high quality baseline wind turbine blade is presented.
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Chapter: 1

Introduction

The world’s primary energy needs are projected to grow by 56% between 2005 and 2030, by an average annual rate of 1.8% per year (International Energy Agency, 2012). Energy policy has confirmed the improvement of the environment sustainability of energy as a primary objective also though increasing use of renewable sources (Increasing Wind Energy's contribution to U.S. Electricity supply, 2008). With increasing awareness about our needs and priorities, one alternative source where we can draw power would be the “Wind”. Wind energy is an abundant resource in comparison with other renewable resources. Moreover, unlike the solar energy, the utilization could not be affected by climate and weather. Wind energy research is being followed in the world as an alternative to fulfill increasing electricity power demand, United State Department of Energy is aiming to expand the wind power in the U.S. Currently, 15.4 GW of power are installed and operational, with an expected growth the U.S. wind capacity will be at 310 GW by 2030, representing 20% of the nation’s power needs (Increasing Wind Energy's contribution to U.S. Electricity supply, 2008). However, if wind energy is needed to become a mainstay of US energy needs, its cost must be first reduced drastically.

A wind turbine is a device that exploits the wind’s kinetic energy by converting it into useful mechanical energy. It basically consists of rotating aerodynamically surfaces (blades) mounted on a hub/shaft assembly, which transmits the produced mechanical power to the selected energy utilizer (e.g. milling or grinding machine, pump, generator etc.). In order to
harness the wind effectively and for the low costs, the advancement of technology over last few decades has given rise to not individual turbines but wind farms in general. Advances in materials, composites used for construction of turbines, the analysis for efficiency of aerodynamics and structures, accurate prediction of winds and their directions have provided for cost effective production of power. As technology in every area is advancing the turbine go higher and grow powerful. As Greenpeace International puts it, “behind the tall, slender towers and sleepily turning blades lays complex, interplay of lightweight materials, aerodynamics design and computer controlled electronics” (Hartwanger & Horvat, 2008).

1.1 History of Wind Turbine

Historically, the force of the wind has been harnessed in various different applications, most important for the propulsion of ships by the use of sails. This resource has also been used by windmills to grind grains or getting water out of wells for agricultural irrigation. Older wind capturing machines developed in 200 BC is considered to be the first instance where wind was as a power source for machines. The use of wind turbines to generate electricity began by the late nineteenth century, Poul La Cour, who was a professor at an adult education center in Denmark in 1891, when a 12 kW windmill generator was constructed by Brush in the United States and started doing research in this field, figure 1&2 (Cao, 2011). However, with the invention of the steam engine and the growing use of fossil fuels, these technologies took a larger part in electricity generation (Galdamez, Ferguson, & Gutierrez, 2011)
After 1940, the research and development of large and more efficient wind turbine was pursued in countries such as Germany, France, United Kingdom, Denmark and United states. As a good example of this period the 1250 Kw Smith- Putnam wind turbine constructed in the United States in 1941, figure 3 (Tiwari & Ghosal, 2005). This turbine had a 53 m diameter; full-
span pitch control and flapped blades reduce loads on the structure. The blade spar failed in 1945. However it remained the largest wind turbine constructed for around 40 years (Galdamez, Ferguson, & Gutierrez, 2011).

There are several developed efforts across the world, notably the Andrea Enfield 100 kW (U.K) in the 200 kW Gedser turbine (Denmark) built in 1956 and the 1.1 MW turbines from EDF (France) that was tested in 1963. Also, there were several prototypes developed by Hutter in Germany for lightweight designs in the 1960s (Tiwari & Ghosal, 2005). Despite of these numerous projects, there was little interest and investment in wind power until the 1973 oil crisis.

In the mid-1970s, the U.S. Department of Energy (DOE) sponsored projects in an effort to develop alternative sources of energy. This led to the development of large machines,
notable the 38 m diameter 100 kW NASA MOD-0 in 1975; Figure 4, up to the 3.2 MW 98 m diameters Boeing MOD-5B turbine, Figure 5. DOE also supported smaller projects such as a test
facility in Rocky Flats, Colorado. It is important to state the notable progress did not start until the late 1970s.

Figure 6: Enercom E-126, the world biggest wind turbine (7MW)

Figure 7: 10 MW offshore wind turbine, Norway
Nowadays, Enercon E-126, figure 6, the world biggest wind turbine can generate up to 7 MW of power under the rated wind speed. This capacity can provide the daily electricity for more than 4500 homes. Following the technology development of modern wind turbine, they can now be mounted either on the ground or on the seabed. A giant offshore wind turbine of 10 MW installed in 2011 by Enova SF in Norway, figure 7 (ENOVA Offshore NSWP 4 windfarm, 2012). As the deletion of coal and fossil oil, wind energy will play a more and more important role in this century.

1.2 Wind Turbine Development

The growth of wind generator capacities which has increased significantly in the last ten years. The total installed capacity of wind power generators was 159,213 MW at the end of 2009 (World Wind Energy Report, 2010) and by the end of 2012 cumulative growth of wind turbine power in America crocked 60000MW with the annual growth of 13+MW power generation, Figure 8.

A wind turbine consists of several main parts; the rotor, generator, driven chain, control system. The rotor is driven by the wind and rotates at predefined speed in terms of the wind speed, so that the generator can produce electric energy output under the regulation of the control system. In order to extract the maximum kinetic energy from wind, researchers put much effort on the design of effective blade design, but, now many specialized airfoils have been invented and used for wind turbine blade design, a rotor blade may have different airfoils in different sections in order to improve the efficiency. So the modern blades are more complicated and efficient compared to early wind turbine blades.
In the early stage, the research on wind turbine blade design was limited on theoretical study, field testing and wind tunnel testing which need a lot of efforts and resource. Due to the development of computer aided design codes, they provide another way to design and analyses the wind turbine blades. Aerodynamics performance of wind turbine blades can be analyzed using computational fluid dynamics (CFD). Meanwhile, finite element method (FEM) can be used for the blade structural analysis. Comparing to traditional theoretical and experimental methods; numerical methods, saves money and time for the performance, analysis and give optimal design of wind turbine blades.

Today, wind turbines are more powerful than early versions and employ sophisticated materials, electronics and aerodynamics (Karam, 2011). Costs have declined, making wind more
competitive clean energy source with other power generation options. Designers apply optimization tools for improving performance and operational efficiency of wind turbines, especially in early stage of product developments. It is the main aim of this research to present some fundamental issues concerning design optimization of the main wind turbine structures, practical realistic optimization models using different strategies for enhancing blade aerodynamics, structural dynamics, robustness, and aero elastic performance. Numbers of structural and aerodynamic design variables are presented in order to acquire an optimal blade design which gives higher power output with minimum cost and weight in conjunction with necessary structural constraints.

1.3 Motivation and Objective

Principal challenge for the present plus, coming decade is the efficient use of limited nonrenewable energy resource and learn to utilize growing production of the renewable sources. There are several alternatives for renewable energy besides; wind power is more affordable key source. To make wind power economically feasible, it is important to maximize the efficiency of converting wind energy into mechanical energy. Among the different aspects involved, rotor aerodynamics is a key determinant for achieving this goal as well as structural robustness of the blade is necessary to get maximum power production for a long term without damage.

Present technology and research has brought a substantial improvement in the overall efficiency and reduced capital costs.
1.3.1 Objectives

The objective of this research work is to evaluate a multidisciplinary optimization process for the wind turbine, create a Fluid-Structure interaction (FSI) system to evaluate structural robustness based on aerodynamic performance and physical wind impact on the blade and to enhance blade performance.

A SERI-8 wind turbine blade is used as a reference wind turbine blade and numbers of objectives were set as follow,

- Perform 2D and 3D CFD analysis and study the aerodynamic performance of the airfoils and baseline SERI-8 blade.
- Modify baseline blade design to achieve higher power output and study aerodynamic performance
- Add winglet at the tip of the blade and improve blade root section for better aerodynamic performance.
- Develop Fluid Structure Interaction (FSI) system for the SERI-8 blades.
- Define multidisciplinary optimization process for FSI system and obtain optimum blade design with minimum cost as well as weight and maximum power output.
Chapter: 2

Wind Turbine Design Principle and Theory

The wind turbine working principle is followed by engineers when generating power through the forces of nature. For wind turbine to work most efficiently and increase the uptime made during high velocity windy conditions, it is essential to install a strong framework that not only covers the essentials of power generation, but also reduce the effect of damage in case of strong currents. The working principle relates to the revolution process. For this, there are the blades, some of the most important part that aid to harness the oncoming forces by revolving in different degrees depending on the force applied and the direction they are facing. In order to increase the torque of the blade they should have proper dimensions and long enough in length.

Figure 9: Wind turbine components
Blades play a part in the wind turbine principle by combining with the pillar that goes down to the generator. Every time they are revolved, they import some mechanical energy on the middle part of the structure, which is shaped like a rod with coils upon it. These turn anticlockwise to the spin of the wing-like devices above in order to impart this energy through friction to the generator below. The latter is able to convert the waves into power that can be stored as electrical energy as shown in figure 9 (Plantier & Smith, 2009).

2.1 Blade Selection

The most important part in designing a wind turbine is blade and the choice of airfoils. As the entire blade is made up of airfoils sections. The lift generated from these airfoils at every section causes the rotation of the blade; also the performance of the blade is highly dependent on airfoil performance.

2.1.1 SERI-8 / Airfoil Family

The development of special-purpose airfoils for horizontal-axis wind turbines (HAWTs) began in 1984 as a joint effort between the National Renewable Energy Laboratory (NREL), formally the Solar Energy Research Institute (SERI), and Airfoils, Incorporated. Since those nine airfoils families have been designed for various size rotors using the Eppler Airfoil Design and Analysis Code (Tangler & Somers, 1995). These nine airfoils families consist of 25 airfoils. In this research SERI-8 blade has selected and the airfoils selected for SERI-8 were designed for medium size turbines rated at 20-100 kW.

The SERI-8 consist S806A, S806A, S807, S808 airfoils, figure 10. The airfoils family was designed to have a low tip Cl_{max} (1.0) for a Reynolds number just over 1,000,000. The airfoil
family is suitable for stall-regulated blades and was used on the Phoenix Industries 7.9 meter retrofit blade (Tangler & Somers, 1995). The airfoils closer to the tip of the blade generate higher lift due to the speed variation in the relative wind, while the purpose of airfoils at the root of blade is mainly structural, contributing to the aerodynamics performance of the blade but at a lower level. Thus the root of the blade is bigger and stronger than its tip.

2.2 Aerodynamic of Wind turbine

Wind turbine blades are shaped to generate the maximum power from the wind at the minimum cost. Primarily the design is driven by the aerodynamic requirements. But economics mean that the blade shape is a compromise to keep the cost of construction minimum. The blade design process starts with a “best guess” compromises between aerodynamic and structural efficiency. The choice of materials and manufacturing process will also have an influence on how thin (hence aerodynamically ideal) the blade can be built.

Just like an airplane wing, wind turbine blades work by generating lift due to their shape. The more curved side generates low air pressures while high pressure air pushes on the other side of the airfoil. The net result is a lift force perpendicular to the direction of flow of the air.
Figure 10: SERI-8 airfoils shape and dimension
2.2.1 Lift, Drag, Moment Coefficient

The force perpendicular to the incoming flows known as the lift force $L$ and the force parallel to the incoming flow is known as the drag force $D$, figure 11.

![Diagram of lift and drag forces on an airfoil](image)

**Figure 11: Lift and Drag force on airfoil**

The lift force increases as the blade is turned to present itself at a greater angle to the wind. This is called the angle of attack (AOA). At very large AOA the blade “stalls” and the lift decreases again, figure 12. So there is an optimum angle of attack to generate the maximum lift. There is, also a retarding force on the blade: the drag, parallel to the wind flow, and also increases with angle of attack. If the airfoil shape is good, the lift force is much bigger than the drag, but at very high angles of attack, especially when the blades stall, the drag increases dramatically. So at angle slightly less than the maximum lift angle, the blade reaches its maximum lift/drag ratio. The best operating point will be between these two angles.
As the drag is in downwind direction, it would create “thrust”, the force that acts parallel to the turbine axis hence has no tendency to speed up or slow down the rotor, Figure 13. However the blade’s own movement through the air means that, as far as the blade is concerned, the wind is blowing from a different angle. This is called apparent wind as shown in figure 13. The apparent wind is stronger than the true wind but its angle is less favorable. It rotates the angles of the lift and drag to reduce the effect of lift force pulling the blade round and increase the effect of drag slowing it down. It also means that the lift force contributes to the thrust on the rotor. The result of this is that, to maintain a good angle of attack, the blade must be turned further from the true wind angle which gives twist to the blade from root to tip.

2.2.2 Blade Twist

The closer to the tip of the blade you get, the faster the blade is moving through the air and so the greater the apparent wind angle is. Thus, the blade needs to be turned further at the tips than at the root; in other words it must be built with a twist along is length. Typically the twist is around 10-20 Deg from root to tip. The requirement to twist the blades has implications on the ease of manufacture, figure 14.
Figure 13: Apparent wind angles

Figure 14: Blade twist
2.2.3 Tip to Speed Ration (TSR)

The speed at which the turbine rotates is a fundamental choice in the design, and is defined in terms of the speed of the blade tips relative to the “free” wind speed. This is called the tip speed ratio (λ) and its definition is shown in equation (1).

\[
\lambda = \frac{\omega R}{v_o}
\]  

(1)

Where, \(\omega\) is the angular velocity of the wind turbine rotor, \(R\) is radius of the rotor and \(v_o\) is the free wind speed.

A higher tip speed ratio means the aerodynamics force on the blades (due to lift and drag) is almost parallel to the rotor axis, so relies on a good lift/drag ratio, figure 15. The lift/drag ratio can be affected severely by dirt or roughness on the blades.

![Figure 15: Effect of tip to speed ratio on blade performance (lift/drag)]
Low tip speed ratio would seem like a better choice but unfortunately results is lower aerodynamic efficiency, due to two effects. Because the lift force on the blades generates torque, it has an equal but opposite effect on the wind, tending to push it around tangentially in the other direction. The result is that the air downwind of the turbine has “swirl”, i.e. it spins in the opposite direction to the blades, figure 16. That swirl represents lost power so reduce the available power that can be extracted from the wind. Lower rotational speed requires higher torque for the same power output, so lower tip speed results in higher wake swirl losses.

![Figure 16: Swirl in the wake](image)

The other reduction in efficiency at low tip speed ratio comes from tip losses, where high-pressure air from the upwind side of the blade escapes around the blade tip to the low-pressure side, thereby wasting energy. Since power = (force*speed), at slower rotational speed the blades need to generate more lift force to achieve the same power. To generate more lift for a given length the blade has to be wider, which means that, geometrically speaking, a
greater proportion of the blade’s length can be considered to be close to the tip. Thus more of the air contributes to tip losses such as winglets (commonly seen on airliners) which is one of the modified design parameter of this research, but few are employed in practice owing to their additional cost.

The higher lift force on a wider blade also translates to higher loads on the outer components such as the hub and bearings, so low tip speed ratio will increases the cost of these items. On the other hand the wide blade is better able to carry the lift force, so the blade itself may be cheaper.

All this means that turbine designers typically compromise on tip speed ration in the region of 7-10, so at design wind speed the blade tip can be moving around 120 m/sec. There are practical limits on the absolute tip speed too: at these speeds, bird impacts and rain erosion starts to decrease the longevity of the blades and noise increases dramatically with tip speed.

As a preliminary design consideration, the best range of tip speed ratios for a medium speed turbine is around 7 (Letcher, 2010), which ensures that the wind turbine can run at near maximum power at near maximum power coefficient. The relationship between rotational speed and tip speed ratio is given by, equation (2).

\[ \lambda = \frac{2\pi nr}{60V_0} \]  \hspace{1cm} (2)

Where, \( n \) is the rotational speed of the rotor, \( r \) is the rotor radius and \( V_0 \) is the wind speed.
2.2.4 Number of Blades

The number of blades greatly influences the HAWT performances. The limitation on the available power in the wind means that the more blades there are the less power each can extract. Further, each blade must follow and maintain aerodynamic efficiency.

The aerodynamic efficiency is lower for a two bladed rotor compared to a three bladed rotor, the rotation speed needs to be much higher to achieve same power output as three bladed rotors. The two single bladed rotors need a special kind of arrangement that is hinged or teetering hub. Each time the rotor passed the tower and in order to avoid heavy shocks the rotor is to tilt away, which could be a hazardous as time being and could hit the tower during operation. For this reason, most large machines do not have more than three blades. The other factor influencing the number of blades is aesthetics: it is generally accepted that three-blade turbine are less visually disturbing than one or two bladed turbines (Wind turbine aerodynamics, 2003).

2.3 Type of Wind Turbine

Based on the different rotational orientation, wind turbine can be categorized as vertical axis and Horizontal-axis wind turbine, figure 17. The vertical turbine is the kind where the main rotor is set vertically and perpendicular to the ground, while in horizontal wind turbine main rotor is set along the wind direction and blades rotation is perpendicular to the wind direction (VAWT vs HAWT, 2005). The few advantages of vertical axis wind turbine are:
1) Simple structure: VAWT can work without yaw system and most of them have a blade with constant chord and no twist, which makes blades easy to construct.

2) Easy to install: The driven trains can be located relative to the ground.

---

**Figure 17: HAWT and VAWT**

Compare to HAWT stall control can only be used in VAWT as it is difficult to incorporate aerodynamics control such as variable pitch and aerodynamics brakes. Hence overall power efficiency is lower. Further, their efficiency is low for large scale applications. The horizontal wind turbine is used for large scale production of power and can be used in offshore as well as on shore and can be efficient in small scale production in farms as well. Although the aerodynamics of both are the same, the most preferred in industry for large scale production of power is the horizontal axis wind turbine (HAWT).
2.4 Wind Turbine Operation

Wind turbine operating condition depends on the speed of free stream wind speed; generally, it can be divided into three operation modes,

- Cut in speed
- Operation mode
- Cut out mode

If free stream wind speed is less than the cut in speed (0-7 m/s), the wind turbine rotor will not rotate due to less available wind energy. If free stream wind speed is within a safety range between cut in and cut out wind speed rotor rotates and generate electric power. Idea average rotor operation wind speed is 12 m/s, in this research 10 m/s speed was used as an operational wind speed. And if free stream wind speed is above 25 m/s which is cut out speed for wind turbine and rotor stops rotating to prevent any damage or failure to wind turbine blade/rotor. Further, different wind speeds between 5 to 25 m/sec were considered to derive power curve for the wind turbine (Muljadi & Butterfield, 1999).
Chapter: 3

Software Details

3.1 Qblade/XFOIL

Qblade is open source wind turbine calculations software, distributed under the GPL. The software is seamlessly integrated into XFOIL, an airfoil design analysis tool. The integration in XFOIL allows the user to rapidly design custom airfoils and compute their polar, to extrapolate the polar data to a range of 360 degree, and to directly integrate them into a wind turbine rotor-simulation (Wind turbine design, 2012). The software is especially adequate for teaching, as it provides all the fundamental relationships and concepts between twist, chord, foils, turbine control blade and rotor variables for verification, compare different rotor configurations, or even to study the numerical algorithm (BEM or DMS) and the dependencies among the aerodynamic variables themselves.

3.2 CATIA v5

CATIA is an in-house development of French aircraft manufacturer Avions Marcel Dassault in 1977, at that time customer of the CAD/CAM software to develop Dassault’s Mirage fighter jet, and then was adopted in the aerospace, automotive, shipbuilding, and other industries (Dassault Systems Product, 1977). CATIA commonly referred to as a 3D Product Lifecycle Management software suite, CATIA supports multiple stage of product development, from conceptualization, design (CAD), manufacturing (CAM), and engineering (CAE). CATIA
facilities; collaborative engineering across disciplines, including surfacing & shape design, mechanical engineering, equipment and systems engineering. CATIA provides a suite of surfacing, reverse engineering, and visualization solution to create, modify, and validate complex innovative shapes. CATIA enables the creation of 3D parts, from 3D sketches, sheet metal, composites, molded, forged or tooling parts up to the definition of mechanical assemblies. It provides tools to complete product definition, including functional tolerance, as well as kinematics definition.

3.3 ANSYS Workbench 14.5

3.3.1 ACP Composite PrepPost

ANSYS Composite PrePost provides all the necessary functionalities for the analysis of composite structures. Instructive interface efficiency defines materials, plies and stacking sequences of layers. Materials can be accurately oriented on the structures using easy coordinate systems definitions. Composite PrePost offers a wide choice of state of the art failure criteria, along with post processing capabilities to allow an in-depth investigation of product behavior and predict how well the finished product will perform under real world working conditions (ANSYS Composite PrePost, 2005).

3.3.2 ANSYS CFX

ANSYS CFX is a commercial Computational Fluid Dynamics (CFD) program, used to simulate fluid in a variety of applications. The ANSYS CFX product allows engineers to test systems in a virtual environment. The scalable program has been applied to the simulation of water flowing past ship hulls, gas turbine engines (including the compressors, combustion
chamber, turbines and afterburners), aircraft aerodynamics, pumps, fans, HAVC systems, mixing vessels, hydro cyclones, vacuum cleaners, and more, (ANSYS CFX, 1970).

### 3.3.3 ANSYS Fluid-Structure Interaction (FSI)

The effect of solid motion on fluid flow can be modeled by coupling ANSYS CFX software with ANSYS structural mechanics solutions. Using the unified user environment (ANSYS Workbench) fluid—structure interaction (FSI) simulations can be easily set up. ANSYS CFX FSI solutions are an industry leader in robustness, applicability and accuracy for one way and two-way FSI.

The robust and flexible algorithm to deform a given fluid volume mesh in ANSYS CFX tolerates even very large boundary displacements. These displacements may be defined explicitly by the user or be the implicit result of an FSI simulation with ANSYS structural mechanics software or from the rigid body solver within ANSYS CFX. In all cases, boundary displacements are diffused into the interior volume mesh while ensuring that small or near-wall elements are deformed less. This maintains good boundary layer resolution and allows for larger mesh deformations with a single mesh topology.

### 3.3.4 ANSYS Design Explorer

Design Explorer is based on a method called Design of Experiments (DOE). This together with various optimization methods helps the program to develop an optimized structure based on selected input and output parameters. Input parameters can either come from DesignModeler or from various CAD systems. These parameters can be in terms of thickness, length, etc. They can also come from Mechanical in terms of forces, material properties, etc.
The output parameters are calculated in Mechanical and can for example be in terms of total mass, stress or frequency response. After setting up an analysis with a number of input parameters and output parameters there are the steps that can be run within.

### 3.3.4.1 Design of Experiments

Design of experiments is the foundation that everything within DesignXplorer is built on. What this technique is about is to determine how many and for what input values the analysis shall be run. There are various techniques for this but the same goal for all is to get as good response surface as possible with as few input combinations as possible. So basically this step defines is how many analyses that will be run. Each combination that ANSYS solves for is referred to as a Design Points.

### 3.3.4.2 Response Surface

When the Design of Experiments is run the next step is to create a response surface based on these results. A response surface will be created for each output parameter. The response surface is basically created via curve fit through the Design Points. From this response surface you can then investigate output results for input variable combinations that hasn’t been solved for.

### 3.3.4.3 Goal Driven Optimization

To help you to select the combination of input variables that satisfies your goals best, you can run a Goal Driven Optimization. Here you have the possibility to give all you parameters different objective functions on which you also can give different importance. ANSYS will then give you a number of candidates that satisfies your goals in the best way.
Chapter: 4

Design of Baseline Model

4.1 SERI-8 blade

A “SERI-8” is originally designed from NREL’s (Tangler & Somers, 1995) airfoil families for medium size turbines and SERI-8 blade model, designed by Ong and Tsai (Ong & Tsai, 2000) was considered as a baseline SERI-8 model for this research.

4.2 Baseline Blade Geometry

The airfoils coordinate and geometry data were collected from Ong and Tsai’s paper (Ong & Tsai, 2000). A SERI-8 blade has four different airfoils (S805A, S806A, S897 and S808) along the span wise direction including different twist angles with axis of twist at 30% of chord, table 1. Based on the chord length and twist angle of the airfoils at particular distance, new coordinates were calculated and with the help of Microsoft excel macro; coordinates were imported into CATIA and 3D model was created, figure 18.

Figure 18: Baseline SERI-8 blade Catia model
The Ong and Tsai has divided SERI-8 blade into 13 equal sections with each section 24 inch long from root to tip in span wise direction, figure 18. The surface area of each section was calculated and used for the cost estimation, table 1. Further, twist and chord distribution at different blade section is shown in figure 19 and 20, respectively.

Table 1: Design parameters for SERI-8 baseline model

<table>
<thead>
<tr>
<th>Station</th>
<th>Blade location</th>
<th>Rotor Radius</th>
<th>Chord</th>
<th>Twist angle</th>
<th>Surface area (in^2)</th>
<th>Airfoils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>in</td>
<td>m</td>
<td>degree</td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>12</td>
<td>37</td>
<td>0.9398</td>
<td>17.83</td>
<td>0</td>
<td>1338.43</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
<td>61</td>
<td>1.5494</td>
<td>29.43</td>
<td>0</td>
<td>1680.68</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>85</td>
<td>2.159</td>
<td>44</td>
<td>20</td>
<td>2242.89</td>
</tr>
<tr>
<td>4</td>
<td>84</td>
<td>109</td>
<td>2.7686</td>
<td>43.09</td>
<td>14.81</td>
<td>2144.41</td>
</tr>
<tr>
<td>5</td>
<td>108</td>
<td>133</td>
<td>3.3782</td>
<td>41.42</td>
<td>10.61</td>
<td>2098.64</td>
</tr>
<tr>
<td>6</td>
<td>132</td>
<td>157</td>
<td>3.9878</td>
<td>39.27</td>
<td>7.29</td>
<td>1998.21</td>
</tr>
<tr>
<td>7</td>
<td>156</td>
<td>181</td>
<td>4.5974</td>
<td>36.71</td>
<td>4.74</td>
<td>1888.25</td>
</tr>
<tr>
<td>8</td>
<td>180</td>
<td>205</td>
<td>5.207</td>
<td>33.81</td>
<td>2.87</td>
<td>1725.36</td>
</tr>
<tr>
<td>9</td>
<td>204</td>
<td>229</td>
<td>5.8166</td>
<td>30.61</td>
<td>1.57</td>
<td>1555.25</td>
</tr>
<tr>
<td>10</td>
<td>228</td>
<td>253</td>
<td>6.4262</td>
<td>27.13</td>
<td>0.74</td>
<td>1366.47</td>
</tr>
<tr>
<td>11</td>
<td>252</td>
<td>277</td>
<td>7.0358</td>
<td>23.38</td>
<td>0.27</td>
<td>1188.74</td>
</tr>
<tr>
<td>12</td>
<td>276</td>
<td>301</td>
<td>7.6454</td>
<td>19.4</td>
<td>0.06</td>
<td>978.58</td>
</tr>
<tr>
<td>13</td>
<td>300</td>
<td>325</td>
<td>8.255</td>
<td>15.19</td>
<td>0</td>
<td>769.12</td>
</tr>
</tbody>
</table>
Figure 19: Baseline SERI-8, Twist vs r/R

Figure 20: Baseline SERI-8, Chord distribution vs r/R
4.3 Materials

4.3.1 Composite Material

Wind turbine rotor blades have historically been made of wood, but because of its sensitivity to moisture and processing costs modern materials such as fiberglass, glass epoxy, graphite epoxy and a carbon fiber being used. Generally, a composite material is composed of reinforcement (fiber, particles, flakes) embedded in a matrix (polymers or metals). The matrix holds the reinforcement to form the desired shape while the reinforcement improves the overall mechanical properties of the matrix. If the composite is designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material (Jureczko, Pawlak, & Mezyk, 2005). The main advantage of composite material is the potential for a high ratio of stiffness to weight.

Majority of wind turbine blades is made of fiberglass reinforced with polyester or epoxy resin. Construction using wood-epoxy or other materials also can be found. Lighter and more effective blades decreases material requirements for the other wind turbine components making overall cost to be lower. Longer blades require other materials to be applied, usually carbon based composites, Carbon fiber composites allow to lower blade’s mass, increasing stiffness. However, use of carbon materials requires increased and makes manufacturing costs to be higher.
4.3.2 SERI-8 Blade Material

The materials used for SERI-8 blade design were same as Ong and Tsai (Ong & Tsai, 2000) and Jin Woo Lee (Lee J. W., 2011) have used to model baseline blade design which consist, TRIAX and MAT as a skin materials and C260 glass/epoxy as the major structural material. The materials properties are shown in table 2.

<table>
<thead>
<tr>
<th>Materials</th>
<th>TRIAX</th>
<th>C260</th>
<th>MAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb/in^3)</td>
<td>0.085513</td>
<td>0.062757</td>
<td>0.010339</td>
</tr>
<tr>
<td>Mass Density (lb/in^3/g/12)</td>
<td>0.000221</td>
<td>0.000163</td>
<td>2.68E-05</td>
</tr>
<tr>
<td>E1 (psi)</td>
<td>3930000</td>
<td>6140000</td>
<td>1100000</td>
</tr>
<tr>
<td>E2 (psi)</td>
<td>1640000</td>
<td>1410000</td>
<td>1100000</td>
</tr>
<tr>
<td>G (psi)</td>
<td>940000</td>
<td>940000</td>
<td>940000</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Limit Stress Dir 1 Tension (psi)</td>
<td>88200</td>
<td>103000</td>
<td>19000</td>
</tr>
<tr>
<td>Limit Stress Dir 1 Compression (psi)</td>
<td>53100</td>
<td>49800</td>
<td>20000</td>
</tr>
<tr>
<td>Limit Stress Dir 2 Tension (psi)</td>
<td>13600</td>
<td>2300</td>
<td>19000</td>
</tr>
<tr>
<td>Limit Stress Dir 2 Compression (psi)</td>
<td>15000</td>
<td>2300</td>
<td>20000</td>
</tr>
<tr>
<td>Limit Shear Stress (psi)</td>
<td>15000</td>
<td>3600</td>
<td>13000</td>
</tr>
<tr>
<td>Limit Interlaminate Stress (psi)</td>
<td>15000</td>
<td>3600</td>
<td>13000</td>
</tr>
<tr>
<td>Thickness (in)</td>
<td>0.015</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Cost ($/lb)</td>
<td>0</td>
<td>1.5</td>
<td>0</td>
</tr>
</tbody>
</table>

4.3.3 SERI-8 Baseline Composite Model

The SERI-8 blade was divided into 13 equal sections in the span-wise direction. Each section is 24 in long and having different composite laminate layers sequences. The original
SERI-8 blade has two rib sections at 60 inch and 252 inch and which were not considered in this research. The reference fiber direction for the composite material was considered along the span direction. All section have same number of MAT skin material laminate layers while each section has different number of TRIAX and C260 materials laminate layers, the overall composite laminate layers sequence with fiber direction are as shown in table 3.

The ANSYS ACP Composite PrePost was used as a preprocessor for composite layups modeling as well as for post processing to check the failure of the composite material at different sections and layers.

Table 3: Baseline SERI-8 blade composite layups

<table>
<thead>
<tr>
<th>Station</th>
<th>Location (inch)</th>
<th>100 % Glass Fiber Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MAT</td>
<td>TRIAX</td>
</tr>
<tr>
<td>1</td>
<td>0-12</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>12-36</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>36-60</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>60-84</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>84-108</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>108-132</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>132-156</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>156-180</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>180-204</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>204-228</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>228-252</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>252-276</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>276-300</td>
<td>2</td>
</tr>
</tbody>
</table>
4.3.4 Validation of Baseline Model

The software have been used for designing and analysis in this research were CATIAv5 R20 and ANSYS 14.5, while Ong and Tsai (Ong & Tsai, 2000) analyzed their design in FE solver called, 3D-Beam, and JinWoo Lee (Lee J. W., 2011) analyzed his model in FEA solver, NX Nastran. Thus, validation of a baseline model is necessary to make sure the 3D blade design and FE model developed in this research is acceptable for further comparisons.

To calibrate baseline SERI-8 blade with respect to reference SERI-8 model (Ong & Tsai, 2000), the mass of each section was compared, figure 21. The weight of baseline SERI-8 found was very close to the weight indicated in Ong and Tsai’s model and the percentage difference was found to be 0.70%.

![Weight of the blade](image)

**Figure 21: Mass comparison of reference and baseline SERI-8 blades**

The total single blade cost for reference SERI-8 and baseline SERI-8 blade is shown in figure 22. The variation in total cost between both blades was found to be 1.5%. This
calculation was done based on similar cost values used by Ong and Tsai (Ong & Tsai, 2000) for the validation purpose which may vary based on present material cost and labor cost values.

![Figure 22: Total cost comparison of reference and baseline SERI-8](image1)

![Figure 23: Total displacement comparison of reference SERI-8 and baseline SERI-8](image2)
Similar constraint as Ong and Tsai (Ong & Tsai, 2000) and JinWoo Lee (Lee J. W., 2011) used; the clamped constraint, was applied at the root of the blade with same composite laminate sequences at all sections and point load of 910 lb was applied at the tip of the blade to the flapping direction for blade deflection validation. The displacement of the blade in flapping direction and results were compared with Ong and Tsai’s results, figure 23. It can be seen that the difference in displacement in less than 1%, and composite model created with ANSYS ACP Composite PrePost is in good fit with the SERi-8 blade model created by Ong and Tsai (Ong & Tsai, 2000).
Chapter: 5

Design Approach

As mentioned earlier the purpose of this research is to perform optimization: structural robustness as well as aerodynamic performance of the wind turbine blade. The aerodynamic performance of the 3D blade mostly depends on the selection of the airfoils and its aerodynamic performance. As SERI-8 blade has different airfoils along the span wise sections; 2D airfoil's aerodynamic performance at different Reynolds number and various angles of attack need to be studied to derive an optimum angle of attack for higher lift and lower drag. Qblade/XFOIL was used to predict the 2D performance of the airfoils.

5.1 2D Airfoils Performance with Qblade/XFOIL

Qblade/XFOIL is coupled panel method/boundary layer code that is often used in the wind energy community to evaluate airfoil performance parameters. XFOIL uses an $e^N$ method for transition prediction and is widely regarded as one of the best tools available for predicting transition on 2D airfoils (Hartwanger & Horvat, 2008). To predict an AOA for higher $C_l/C_d$ of the individual airfoils, all airfoils were analyzed for expected Reynolds number range $5 \times 10^5$ to $1 \times 10^6$ on the blade and AOA vary from 0 to 30 degree.
5.1.1 Lift and Drag Coefficient

The figure 24 shows $C_l$ vs Angle of Attack (0 to 30 degrees) graph of all SERI-8 airfoils. It can be observed that for a higher angle of attack, the lift coefficient increases up to a point where the airfoils experiences stall, hence sudden drop in the graph. It can also be seen that a higher lift is achieved by airfoil S808 which is thicker and its chamber is greater. Besides, it’s important to keep the value of drag coefficient less with respect to lift coefficient. Lift coefficient ($C_l$) vs Drag coefficient ($C_d$) plot is shown in figure 25, and at a particular AOA drag should be minimized for better airfoil performance.

![Figure 24: Coefficient of lift (Cl) vs Angle Of Attack (AOA)](image)
Figure 25: Coefficient of Lift (Cl) vs Coefficient of Drag (Cd)

$C_l/C_d$ ratio vs Alpha is shown in figure 26. It is interesting that the $C_l/C_d$ is higher for the S806A airfoil which is located at the edge of the blade. Although the other airfoils have higher lift, this created more drag as well given the higher chamber. It can be stated that the $C_l/C_d$ ratio is increased from the root to the tip region of the blade. This is quite logical given that performance of a wind turbine is to be completed by increasing the rotational speed, hence torque, of the rotating blades. If the $C_l/C_d$ is higher in the tip region, hence a higher torque is generated for the wind turbine (Anjuri, 2012).

Further, Qblade program is capable of generating a 3D blade model and predict aerodynamic performance. Once the specific airfoil for the cross section is set, then the twist angle and chord length can be specified, along with r/R value of that section. A 3D surface model generated in Qblade is shown in figure 27.
Figure 26: Cl/Cd vs Angle Of Attack (AOA)

Figure 27: SERI-8 blade design in Qblade
Qblade works on BEM theory and able to calculate aerodynamic performance but on the process of BEM analysis, aerodynamic data must be prepared for each blade element. It is well known that the airfoil lift coefficient of a rotating blade has a greater value than the predicted lift coefficient in 2-D or lift coefficient without rotation. Therefore, the predicted results obtained from BEMT based code do not reflect the 3-D rotating effects, especially for inboard region of blades, and some errors are inevitable (Langtry, Gola, & Menter, 2006).

5.2 Composite Blade Modeling

As mentioned in section 4.3.3 Ong and Tsai’s (Ong & Tsai, 2000) SERI-8 composite blade model was used with different number of layers at different blade sections. To model the composite layups accurately ANSYS ACP composite PrePost was used.

5.2.1 ACP Modeling

As shown in figure 28, SERI-8 blade was divided in 13 equal sections. Each section has different number of layers and material properties as mentioned in table 2 and 3.
An ACP composite model of the SERI-8 blade is shown in figure 29. The reference fiber direction for the composite material was considered along the span direction which is indicated as green arrow and composite layups direction is indicated as pink arrow, cross sections of the composite layups also shown where white straight lines show number of composite layers and the total thickness of the blade at individual section.

Figure 29: SERI-8 ACP composite model with layups and fiber direction
5.3 Computational Analysis Method

Analysis of blades using wind tunnel would be possible for small scale rotors, but the increase in diameters has called for the use of computational fluid dynamics for fluid flow over blades and prediction of loads. In this research work, a compressible Navier-Stokes solver (ANSYS CFX 14.5) was applied to predict the aerodynamic of the blades.

5.3.1 3-blades Turbine Model

The ANSYS workbench was used for this research work and different ANSYS tools and components were used to define MDAO process. Figure 30 shows the project outline of CFD analysis in ANSYS workbench. First, the CATIA blade geometry (figure 28) was imported into the ANSYS workbench – “Geometry” module. Then 3-blade turbine model with fluid and stationary domain were designed and with appropriate element size and condition, mesh was generated figure (31 and 32).

![Project schematic of ANSYS CFX in ANSYS workbench](image)

Figure 30: Project schematic of ANSYS CFX in ANSYS workbench
Figure 31: Fluid domains: stationary and rotating

3-blade with hub

Stationary Domain

Outlet

Rotating Domain

Inlet

Figure 32: Mesh generated
The region around the blade requires fine mesh with numbers of inflation layers to catch the flow separation around the blade. If occurs, we need to calculate accurate pressure values along the blade surface. Hence, fine surface mesh with 30 inflation layers was created around the blade surface and remaining regions were kept with coarse mesh, figure 33. The turbine diameter was 17 meters, rotating domain was 30 meters in diameter and 40 meters in length; stationary domain was 44 meter in diameter and 50 meters in length.

Figure 33: Fine mesh region around the blade-inflation

In the “mesh” tool, named selection for the boundary conditions like inlet, outlet, wall and blade geometry sections had been given. In “setup”, first steady state solution was set with CFX frozen-rotor model.
5.3.2 1-blade Turbine Model

The 3 blade with hub model used to study wake analysis and turbulence with back region. In order to simplify the CFD analysis and to save computational resources while FSI is running which would take more time to run a single analysis due to computational limitation. Hence, new domain with 120 degree wedge model was created with one blade, assuming symmetry boundary conditions on the left and right side of the domain, figure 34 and 35. Each side of the domain was given periodic boundary conditions, (Galdamez, Ferguson, & Gutierrez, 2011). It implies that the velocities going out from the left symmetry boundary can enter the boundary on the other side in an infinite loop. It was assumed that the flow conditions on either side of the 120 degree wedge are fully symmetric.

4 tangential inlets

periodic boundaries

Figure 34: Periodic boundary conditions
In this CFD analysis, to correctly capture the turbulent flow structures as well as the vortices created at trailing edge on at the tip. After conducting enough research on solver from research papers, the turbulence models chosen were k-w, SST (shear-stress transfer) and k-epsilon turbulence to capture the turbulence phenomena (Lee, Choi, Lee, Yoon, & Choi, 2011). The inlet boundary condition for wind speed was set as a fixed uniform entrance velocity, a
static pressure outlet boundary condition was applied with free stream wall condition and blade and hub surfaces were defined as no slip walls with rotation.

5.4 Fluid Structure Interaction (FSI)

Fluid Structure Interaction system was created to perform static analysis by using pressure load on the blade from CFX and transferred them by mapping algorithm, project on blade surface geometry in Static analysis module which is followed by global coordinate system. Therefore, the position of the blade geometry in CFX module and Static Structural module must be same with reference to the global coordinate system. Figure 36, shows “solution” (e.g. pressure loads on the blade) of the CFX module is connected to the “Setup” of Static Structural module and being used as a mechanical loads for blade static analysis. Further, Static Structural module is connected to the Modal analysis module where same geometry, properties and static results will be used to calculate modal frequencies of the blades.

Figure 36: Project schematic of Fluid-Structure Interaction (FSI) in ANSYS workbench
5.5 Cost Estimation Model

5.5.1 Single Blade Cost

In this research, the cost calculation for one blade based on Ong and Tsai (Ong & Tsai, 2000) was done. The labor cost, material cost and total cost were calculated. Assumptions were made as per Ong and Tsai’s paper (Ong & Tsai, 2000) and only major structural material C260 was used for cost estimation. Furthermore, the tooling cost was not considered in this analysis. The total labor hour for each lay-up was taken as 9.1 hours. The total cost for single blade can be calculated as follows:

\[ \text{Material cost} = \text{Material mass (lb)} \times \text{Material cost ($/lb)} \]  
\[ \text{Labor cost} = \text{Total labor hours (hr)} \times \text{Labor rate ($/hr)} \]  
\[ \text{Total cost} = \text{Material cost} + \text{Labor cost} \]

The total cost of the blade was calculated by defining new output parameter in ANSYS workbench and mentioned as a design objective to be minimized in the optimization process.
Chapter: 6

CFD Optimization

Like many aerodynamic devices such as turbine blades and wings, a better understanding of the flow field can result in design changes that can significantly improve performance. As well, it is critical that the aerodynamic characteristics of the wind turbine be known during the design phase in order to have accurate economic projections. Because of the costs associated with performing wind tunnel experiments, there is a significant amount of interest in predicting the aerodynamic characteristic of a wind turbine using computational fluid dynamics (CFD) (Carlo, 2008).

6.1 Blade Design Optimization Based on Blade Element Method (BEM)/XFOIL

6.1.1 Modified SERI-8

The AOA of airfoils (S808, S807, S805A_7A, S805A, S805A_6A, S806A) used in baseline SERI-8 design given in table 1, seems to be different from the AOA for maximum $C_l$ and $C_l/C_d$ ratio calculated by 2D airfoil analysis, figure 24 & 26. This indicates that the AOA assigned to the baseline SERI-8 design may not be an optimum AOA. Henceforth, by modifying AOA; replacing with associate angle where higher lift coefficient ($C_l$) as well as higher $C_l/C_d$ ratio values are indicated, more lift can be generated as a result and better power output can be produced. But, it is not practical to predict similar outcomes for 3D blade based on 2D airfoils analysis. So considering this as a hypothesis based on maximum lift coefficient ($C_l$) and maximum $C_l/C_d$ with
respect to AOA for individual airfoils, a new SERI-8 blade was created, it give better aerodynamic performance compared to baseline SERI-8 design and further analyses were conducted.

Furthermore, blade attach angle also need to be optimized as the twist of the blade is being changed. The twist of the blade mainly affects the stalling time of the blade. For early stall, the blade generates more power at lower wind speeds. However this power decreases drastically as the wind speed increases. On the other hand, late stall results in less power at low speeds but high power at high speed (Carlo, 2008).

The attach angle of the blade depends on wind speeds. It varies as wind speed change. Hence, optimum attach angle need to be found based on the twist and wind speed of the blade, which was a design variable need to be optimized.

| Table 4: Twist angle at different blade section |
|-----------------|-----|-----|-----|-----|-----|-----|
| Airfoils        | S808| S807| S805A_7A | S805A | S805A_6A | S806A |
| SERI-8          | 20  | 13.93 | 4.359    | 0.635  | 0.105    | 0     |
| New SERI-8      | 18  | 13.5  | 10       | 7.5    | 3.5      | 0     |

A new SERI-8 blade’s twists angles at different sections are as mentioned in table 4, figure 37 and 38. In general, the wind turbine blade’s root section needs to be strong enough to resist bending moment and should be able to generate high torque. Therefore, the twist at that region needs to be higher. In addition, to reduce noise at the tip of the blade and ease to cut the wind while rotating, the tip section needs to be parallel to wind flow direction. These are
necessary precautions need to be followed in the design process (Galdamez, Ferguson, & Gutierrez, 2011). The comparison and the chord distribution between baseline SERI-8 and new SERI-8 blade are shown in figure 39 and 40.

<table>
<thead>
<tr>
<th>S808</th>
<th>S807</th>
<th>S805A_7A</th>
<th>S805A</th>
<th>S805A/6A</th>
<th>S806A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline SERI-8 (°)</td>
<td>20</td>
<td>13.93</td>
<td>4.35</td>
<td>0.63</td>
<td>0.10</td>
</tr>
<tr>
<td>New SERI-8 (°)</td>
<td>18</td>
<td>13.5</td>
<td>10</td>
<td>7.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

**Figure 37: Blade twist at different location**

**Figure 38: New SERI-8 blade**
Figure 39: Twist distribution vs. $r/R$

Figure 40: Chord distribution vs. $r/R$
6.1.2 Comparison of the Weight of the New SERI-8 Blade

One of the objectives for this research was to minimize weight of the blade. Hence, weight of a new SERI-8 blade was compared with the reference model of SERI-8 designed by Ong and Tsai (Ong & Tsai, 2000) and baseline SERI-8 model designed for this research. It was found that the weight of new SERI-8 blade compare to the weight of the Ong and Tsai’s SERI-8 model and baseline SERI-8 model, reduced by 3.5% and 2.8%, respectively, figure 41.

![Weight of the blade](image_url)

Figure 41: Weight vs. Blade section
6.1.3 Pressure Distribution

In order to examine aerodynamic performance of the airfoils at different angle of attack for better comparison between baseline SERI-8 and new SERI-8 blade, pressure coefficient plots of airfoils were generated in Qblade. All calculations were made assuming incompressible flow and a Reynolds number of $1 \times 10^6$.

Figure 42 represents the pressure distribution plots of all airfoils at the AOA used in baseline SERI-8 blade, whereas figure 43 represents the pressure distribution of all airfoils at modified AOA for new SERI-8 blade. Whereas, airfoils S808, S807 and S806A AOA is not differ than the baseline SERI-8 blade. Therefore, $C_p$ plots looks similar and the pressure difference between pressure and suction side surface is almost ideal. However, airfoils S805A_7A and S805A in new SERI-8_Qblade indicate larger pressure coefficient difference between suction and pressure side with smooth flow translation as well as no flow separation along the chord length compared to the baseline SERI-8, which indicates that higher torque can be generated at high wind speed. Similar, S805A_6A airfoil in new SERI-8_Qblade has better pressure distribution with higher AOA compare to the baseline design and attached flow until trailing edge. However, XFOIL appears to over predict the flow separation and fully turbulent computation does not capture this phenomenon. Hence in addition to XFOIL results, a 3-D CFD simulation is required to assure and compare aerodynamic performance (Langtry, Gola, & Menter, 2006).
Figure 42: $C_p$ plot of baseline SERI-8 blade

Figure 43: $C_p$ plots of new SERI-8 blade
6.2 CFD Simulation and Results

A steady state solution with k-w (SST) turbulence model was solved for baseline SERI-8 blade turbine and new SERI-8 blade. The results were obtained at 4 different wind speeds and compared in terms of flow separation, pressure distribution and power production.

6.2.1 Comparison of Power Generated by Baseline and New SERI-8 blade

The torque and power generated are shown in table 5. Further, to make sure that the power curve for baseline SERI-8 is in acceptable range, it is required to compare with the experimental data. Hence, available experimental data of SERI-9 blade (which has same airfoils section and length of 9.2 meters) (Tangler, Smith, Kelley, & Jager, 1992) was scaled down for the comparison. From the figure 44, we can say that the power curve for SERI-9 and SERI-8 are identical. And it was concluded, the CFD analysis gives acceptable power curve and results can be compared for further analysis.

From table 5, it can be observed that torque produced by modified new SERI-8 is higher compared to the baseline SERI-8 blade design. And 3.5% higher power generated at wind turbine operating condition (10m/s). A stall phenomenon occurs at higher speed (20 m/s) which reduces the power generation and helps to prevent high speed rotation at higher wind speed as well as failure.
Table 5: Torque and Power generated

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Baseline Design SERI-8</th>
<th>New SERI-8_Qblade</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Torque (Nm)</td>
<td>Power (kw)</td>
<td>Torque (Nm)</td>
</tr>
<tr>
<td>5</td>
<td>650</td>
<td>6.64</td>
<td>670</td>
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<td>10</td>
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<td>34.71</td>
<td>3520</td>
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<tr>
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<td>5560</td>
<td>56.77</td>
<td>5730</td>
</tr>
<tr>
<td>20</td>
<td>6610</td>
<td>67.49</td>
<td>6730</td>
</tr>
</tbody>
</table>

Figure 44: Power curves

6.2.2 Comparison of Pressure Distribution

Figure 45 shows the pressure contour plots for the pressure and suction side of the baseline SERI-8 blade. And figure 46 shows the pressure contour plots for the pressure and suction side of the new SERI-8. It was found that the pressure generated in the new SERI-8 blade was higher than the baseline SERI-8 blade at same wind speed and conditions.
Figure 45: Pressure contour plots of baseline SERI-8 blade

Figure 46: Pressure contours of new SERI-8 blade
At 20 m/s, the pressure contours and streamline plots at different r/R sections for baseline SERI-8 blade are shown in figure 47, and new SERI-8 blade shown in figure 48.

![Pressure Contour Plot](image1)

![Velocity Streamlines Plot](image2)

**Figure 47: Pressure contour and velocity streamlines plot of baseline SERI-8 blade**

Figure 49 shows the vector plotting in baseline SERI-8 blade wind turbine with dense vectors around the blade region and hub.
Figure 48: Pressure contour and velocity streamlines plot of new SERI-8 blade

Figure 49: Vector plot of 3-blade model
The local pressure distribution, pressure contour and streamline plot comparison between 10 m/s and 20 m/s wind speed, for baseline SERI-8 blade at four different blade length section 25%, 50%, 75% and 95% are shown in figures 50, 51 and 52 respectively.

Figure 50: $C_p$ plots at 10 m/s and 20 m/s wind velocity
Figure 51: Pressure contours at 10m/s and 20m/s wind speed
Figure 52: Velocity streamlines plots at 10 m/s and 20 m/s wind speed
At 10 m/s wind speed, the computed pressure distribution at all sections of the blade is in good agreement and flow is completely attached and no separation occurs. At 25% span length pressure distribution is uniform with low pressure distribution while at 50% and 75% span lengths higher pressure difference can be noticed which indicate high lift and torque generated, while at 95% span length pressure contour shows low pressure region on the suction side at middle of the span, and higher velocity can be seen at that area in the streamline plot.

At 20 m/s wind speed, there is a great discrepancy compared to 10 m/s wind speed results. The pressure contour shows very high pressure difference along the blade length. At this speed the flow separation has occurred. At 25% span length flow separation starts near to trailing edge while at 50% and 75% span lengths complete flow separation and vortices can be observed after half chord length, in the streamline plots and at the tip flow separation has vanished.

It should be noted that, since the SERI-8 blade is designed as a stall regulator wind turbine producing more power at low and moderate wind speeds, one should not be concerned about the discrepancy occurring at high wind speeds. At high wind speed SERI-8 blade starts stalling. Hence, more turbulence will be generated near the trailing edge decreasing the lift and increasing the drag on the blade. As a result, rotation of the blade will decreases.
The pressure contour plots and velocity streamline at operating wind velocity (10 m/s) for new SERI-8 blade are shown in figure 53 and 54, respectively. It was observed that the pressure difference between upper and lower surface at different r/R sections was higher than the pressure difference in baseline SERI-8 blade. This helps to produce higher torque and as a result, higher power is generated.

Figure 53: Pressure contours of new SERI-8 blade at different r/R section at 10 m/sec wind velocity
Figure 54: Velocity streamlines plot of new SERI-8 blade at different r/R section at 10 m/s speed

Figure 55: Blade surface velocity stream at 10m/s wind speed
Figure 56: Blade surface velocity stream at 15m/s wind speed

A depiction of air flow on the blade surface is given by plotting the streamlines. Figure 55 shows that the air flow can align with the blade under low wind speeds. Air flow can attach when wind speed is 10 m/s. Approaching high wind speeds of 15 m/s, the air separation occurs from the root area and the stalled area covers almost the whole blade. A distinct separation line is visible on the suction side and extends from the middle section to the tip of the blade, figure 56. For attached flow conditions (mainly for the low wind speed cases and in the inboard) the limiting streamlines appear parallel, and aligned to the main stream. Hence, the flow pattern follows there a 2D-like behavior. On the other side, the separated flow portion is characterized by the presence of secondary flow, spanwise oriented (Carlo, 2008).
6.3 Conceptual Winglet Design and Modified Hub Section

Blade tip’s flow is strongly 3-D and is often associated with separation. It means that viscous effects are key determinant. More recently, the research conducted on top blades have developed new design solution, some of them borrowed from aeronautics like the so-called winglets.

The optimum design of tip blade of a wind turbine can be pursued taking into account of the following issues:

- Noise Reduction
- Aerodynamic and Aeroelastic behavior
- Structural Robustness

6.3.1 Effect of Winglet and HUB Modification on Aerodynamic Performance

The main aim behind this is to study the effect of adding a winglet to the tip in addition to the airfoil shape hub section; on the power production of the wind turbine.

6.3.1.1 Winglet Study

The purpose behind to add the winglet is, able to carry aerodynamic loads so that the vortex caused by the winglet spreads out the effect of the tip vortex which results in decreasing the downwash and reducing the drag (Elfarra, 2011). The winglet produce a flow opposing the flow produced by the blade, this flow will tend to cancel or weaken the main flow of the blade and hence reduce the spanwise flow and consequently reduce the drag.

As shown in the figure 57. The winglet was added by extending the blade tip by 1.5% of the blade radius and then tilted the extra section. Based on the previous research by (Elfarra,
on different tilting direction, angle and shape of the winglet, the 55 degree angle tip was found to be best suitable with reduced drag and better performance.

![Figure 57: Winglet added at the tip of the blade](image)

### 6.3.1.2 HUB Modification

New concept in blade designing is to use airfoils shape in place of using circular section at the root of the blade, which helps to improve power generated at certain level and the lift loss at the hub section can be reduced by a significant amount over and above flow separation can be controlled, figure 58 and 59 (Cao, 2011).

![Figure 58: Modified hub of a new SERI-8 blade](image)
6.4 CFD Simulation and Results

A comparison between the SERI-8 blade with added winglet and modified hub section with the new SERI-8 blade was performed. The computations were run for the same wind speed range with same turbulence model and boundary conditions. The power generated and percentage of power increased is shown in table 6 while, power curve is shown in figure 60.

Table 6: Comparison of power generated

<table>
<thead>
<tr>
<th>Wind speed</th>
<th>Power (kw) Baseline Design</th>
<th>Power (kw) New SERI-8 (Qblade)</th>
<th>Power (kw) SERI-8 with Tip_hub</th>
<th>Power increase(%) in SERI-8 with Tip_Hub, w.r.t Baseline SERI-8</th>
<th>Power increase(%) in SERI-8 with Tip_Hub, w.r.t New SERI-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6.64</td>
<td>6.84</td>
<td>6.95</td>
<td>4.66</td>
<td>1.60</td>
</tr>
<tr>
<td>10</td>
<td>34.71</td>
<td>35.94</td>
<td>36.40</td>
<td>4.86</td>
<td>1.28</td>
</tr>
<tr>
<td>15</td>
<td>56.77</td>
<td>58.50</td>
<td>59.25</td>
<td>4.36</td>
<td>1.28</td>
</tr>
<tr>
<td>20</td>
<td>67.49</td>
<td>68.71</td>
<td>69.80</td>
<td>3.42</td>
<td>1.58</td>
</tr>
</tbody>
</table>
From table 6, it is clear that the power increased (by using a winglet and modified hub section) is approximately 4.5% and 1.5% more than the power generated by baseline SERI-8 blade and new SERI-8 blade design, respectively. It was noticed that there is a further power improvement due to the winglet and the airfoils shaped hub section. In addition, there is reduced turbulence and flow separation at the hub section without major impact on the structural characteristic of the blade. Further structural integrity analysis needs to be performed, which is not included in this research.

![Power curve comparison](image)

**Figure 60: Power curve comparison**

Figure 61 shows, 3-blade baseline SERI-8 blade’s CFD results with velocity streamline plot where at the hub section larger flow separation and turbulence can be observed.
Figure 61: Velocity streamline of 3-blade model with baseline SERI-8 blade

Figure 62 shows, CFD results with velocity streamline plot for the 3-blade modified tip and hub section SERI-8 blade’s where very less turbulence is generated near the hub section and attached flow throughout the blade span can be seen.

Figure 62: Velocity streamline of 3-blade SERI-8 model with modified hub and winglet
Chapter: 7

Multidisciplinary Design Analysis Optimization

Optimization of wind turbine is a multidisciplinary process including optimization of aerodynamics, structure and economics. For the wind turbine blades, the aerodynamics optimization and structure robustness is a major concern.

7.1 Aero-Structure Design Optimization

The design objective was to size the thickness of the individual blade section such that the blade has minimum weight and remains fail-safe under the extreme load distribution.

It is not possible to formulate the problem of optimum design of wind turbine blades as a single-criteria optimization task because this process requires many criteria to be taken into account. In many cases, these criteria are mutually incomparable, uncountable and sometimes even contradictory, which precludes their simultaneous optimization. The following criteria have taken into account in the process of optimal wind turbine design,

- Minimize weight of the blade
- Minimize total cost of the blade
- Minimize blade vibration and keep modal frequency at acceptable level
- Maximize power output
- Accomplishment of appropriate strength requirements
The mass and the material cost of a blade are correlated and depend on the blade structural stiffness. If the blade design robustness is at optimal level then both the criteria can be satisfied. The optimal blade thickness for different blade section helps to satisfy these criteria. Minimization of vibration is a better way to obtain optimal design of blade structure and at the same time it contributes to keep the cost low and provide high stiffness. Hence, to minimize vibration, the natural frequency of the blade should be separated from the harmonic vibration associated with rotor resonance. Therefore, mode separation constraint was setup to examine the first three natural frequencies and is separated from each other by more than ±5% of its natural frequency.

Furthermore, to meet the strength requirements of the structure, optimization of maximum displacements of the blade at the tip would have to be carried out with a limiting constraint and permissible stress should not be exceeded. To maximize a torque and hence power, blade pitch angle and shape should be optimized. Henceforth, optimal pitch angle need to be obtained to maximize the power generated.

As explained earlier, the main objective of the present work was to develop a multidisciplinary design analysis optimization procedure for SERI-8 blade. The blade needs to be optimized for optimal aerodynamic performance and structural robustness. The key objectives were to minimize mass and cost of the blade and maximize power output. The reference SERI-8 blade was aerodynamically optimized based on BEM theory with modified twist angle. The blade pitch angle was given as an input variable parameter to guarantee a good aerodynamic
performance. The numbers of layups at different sections were tagged as a structural design variable.

The constraints in wind turbine blade design are as follows:

- Displacement of the blade cannot exceed the set value (global stability must be ensured),
- Maximum stresses generated in the blade cannot exceed permissible stresses (appropriate strength requirements for the structure), and
- Separation of natural frequencies of the blade from harmonic vibrations associated with rotor rotation.

The design constraints, variables and objectives for this case study are summarized in Table 7.

<table>
<thead>
<tr>
<th>Table 7: Variables, Constraints and Objective for the MDO process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variables</strong></td>
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<tr>
<td></td>
</tr>
<tr>
<td><strong>Constraints</strong></td>
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<td></td>
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<tr>
<td></td>
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<tr>
<td><strong>Objectives</strong></td>
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</table>

The optimization process is shown in flowchart, figure 63. It starts with defining objectives which need to be optimized (e.g. minimize cost, minimize weight and maximize power output). It is then followed by the CAD model, Design parameters – design variables need to be optimized, FSI – static analysis using CFD pressure loads on blade, Design constraints
– to check blade robustness, Cost estimation – total cost calculation of the blade; then it will go through the optimization loop and number of different design candidates will be created based

Figure 63: MDAO process flow chart
on the response surface generated by optimization method to obtain top optimum design candidates. Design validation need to be performed and an acceptable / feasible design candidate (an optimal blade design with optimized design variables values and design constraints within limits) was obtained.

Figure 64 shows project schematic of MDAO process in ANSYS Workbench, where separate blocks for engineering data, geometry, static analysis, ACP pre, CFX, ACP post and Optimization can be seen. Design explorer module was used to carry out the MDAO where, the relationship between design variables and performance of the blade is described using Design of Experiments (DOE) combined with response surfaces and identifies the relationship between performance of the blade and input design variables. Once the response surface has been introduced, optimization parameters need to be defined; Central Composite Design-G optimality method was used and desired objectives and constraints were set within the specified domains.
Figure 64: MDAO Project schematic in ANSYS Workbench
Chapter 8

Results

8.1 Design of Experiments (DoEs)

For new SERI-8 blade, 281 DOEs were solved and a response surface was generated. Based on the created responses, 1000 design candidates were produced within the pre-defined minimum and maximum values of input variable parameters.

Figure 65: Objective parameters versus design points
Multi objectives and constraints were set with kriging algorithm. This provides an improved response quality and fits higher order variations of the output parameter and all design candidates were analyzed.

### 8.2 Feasible design candidates

Figure 65 shows value of objective parameters at each design point. Figure 66 shows tradeoff chart for two objectives; total cost vs total mass and maximum stress vs total mass. It can be observed that cost and mass of the blade is propostional to eachother. These plots include all the feasible and infeasible design candidates which can be filtered based on the design constraints. Figure 67 shows 3D tradeoff chart and relation between 3 output parameters (total mass, total displacement and total cost).

![Figure 66: Tradeoff chart of total mass versus total cost](image-url)
Figure 67: 3D Tradeoff chart of total mass, total cost and total displacement

Figure 68 shows a tradeoff chart of total cost (objective) vs total deformation (constraint) and maximum stress (objective) vs total displacement. The constraint limit was set less than 11 inches and all of the design points above this value were marked as infeasible points and remaining were feasible design points. Similar phenomena can be seen in tradeoff chart for maximum stress (objective) versus total deformation (constraint) and all of the design points with total deformation value above 11 inches were separated as infeasible design points.

Figure 68: Tradeoff charts of objective versus constraint
8.3 Optimum Design Candidates

After dividing total number of design candidates into feasible and infeasible design candidates, at the end of an optimization process top feasible as well as optimum design candidates will be highlighted. This will give optimum values of the pre-defined objectives. Table 8 shows top 3 optimum feasible design candidate's input / output variables value.

<table>
<thead>
<tr>
<th>Input parameters</th>
<th>Candidate 1</th>
<th>Candidate 2</th>
<th>Candidate 3</th>
</tr>
</thead>
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<tr>
<td>Section 12</td>
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<td>16</td>
<td>15</td>
</tr>
<tr>
<td>Blade pitch angle (°)</td>
<td>7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Output parameters</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total deformation (in)</td>
<td>10.97</td>
<td>8.56</td>
<td>8.12</td>
</tr>
<tr>
<td>Maximum stress (psi)</td>
<td>5751.98</td>
<td>5610.58</td>
<td>5520.35</td>
</tr>
<tr>
<td>Total mass (lb.)</td>
<td>315.03</td>
<td>329.34</td>
<td>339.59</td>
</tr>
<tr>
<td>Total cost ($)</td>
<td>19966</td>
<td>21082</td>
<td>22129</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>58.65</td>
<td>45.51</td>
<td>45.86</td>
</tr>
<tr>
<td>Model Frequency 1</td>
<td>4.46</td>
<td>4.54</td>
<td>4.45</td>
</tr>
<tr>
<td>Model Frequency 2</td>
<td>7.97</td>
<td>8.19</td>
<td>8.20</td>
</tr>
<tr>
<td>Model Frequency 3</td>
<td>12.80</td>
<td>12.95</td>
<td>12.99</td>
</tr>
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</table>
8.4 Sensitivity Analysis

A local sensitivity chart for this MDO process is shown in figure 69. Local sensitivity chart is plotted to observe the impact of input parameters on output parameters. It calculates the change of the output(s) based on the change of inputs independently at the current value of each input parameter. The larger the change of the output parameter(s), the more significant is the role of the input parameters that were varied. It can be observed that first three blade sections (input parameter) have maximum impact on most output parameters. These sensitive parameters can be treated accordingly to minimize critical impact of individual input parameters. It also drives attention to mid sections of the blade as the maximum blade torque is generated at this region and local sensitivity curve shows significant impact on blade deformation and stress values. Therefore, it is important to carefully design each section of the blade for better aerodynamic performance and for structural robustness.

Figure 69: Local sensitivity of input parameters to output parameters
As results from MDAO process (table 8), Candidate 1 values were used to check the aerodynamic performance and the structural strength of the optimized design. Table 9 shows a comparison between baseline and optimized SERI-8 blade.

### Table 9: Comparison between baseline design and optimum design

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Baseline Design</th>
<th>Optimum Design</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section 1</td>
<td>75</td>
<td>60</td>
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<td>Section 6</td>
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<td>Section 7</td>
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<tr>
<td>Section 9</td>
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<tr>
<td>Section 10</td>
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<td></td>
</tr>
<tr>
<td>Section 11</td>
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</tr>
<tr>
<td>Section 12</td>
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</tr>
<tr>
<td>Blade pitch angle (degree)</td>
<td>9.58</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output Parameters</th>
<th>Baseline Design</th>
<th>Optimum Design</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total deformation (in)</td>
<td>13.56</td>
<td>10.85</td>
<td>19.98 % (-)</td>
</tr>
<tr>
<td>Maximum stress (psi)</td>
<td>6532.52</td>
<td>5725.21</td>
<td>12.35 % (-)</td>
</tr>
<tr>
<td>Total mass (lb.)</td>
<td>412.68</td>
<td>315.03</td>
<td>23.67 % (-)</td>
</tr>
<tr>
<td>Total cost ($)</td>
<td>27448</td>
<td>19966</td>
<td>27.25 % (-)</td>
</tr>
<tr>
<td>Power (kW)</td>
<td>56.77</td>
<td>58.65</td>
<td>3.31 % (+)</td>
</tr>
<tr>
<td>Model Frequency 1</td>
<td>4.46</td>
<td>4.43</td>
<td></td>
</tr>
<tr>
<td>Model Frequency 2</td>
<td>7.97</td>
<td>7.91</td>
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</tr>
<tr>
<td>Model Frequency 3</td>
<td>12.80</td>
<td>12.77</td>
<td></td>
</tr>
</tbody>
</table>
Figure 70: Optimized SERI-8 blade: Pressure contour at different section at 15 m/s wind speed

Figure 70 shows the pressure distribution on the blade at different sections which is higher than the baseline model and was significantly improved. Additionally, composite failure criteria for critical layer can be seen in figure 71 for pressure and suction side with inverse and reverse failure factors respectively which were within a failure limit.

Figure 71: Optimized SERI-8: Composite failure criteria (Tsai-Wu)
Chapter 9

Conclusion

Aero-structure multidisciplinary optimization process was carried out for SERI-8 blade using Qblade for 2D aerodynamic analysis and ANSYS workbench for 3D aerodynamic and structural analysis. It can be seen that every single objective cannot simultaneously reach the optimum in multidisciplinary objective optimization, but a compromise among the objectives is needed. The aerodynamic performance of the optimized wind turbine design was improved by about 4% compared to the baseline design. In addition the following were observed in the optimized design: mass reduction of 23.67%, cost reduction of 27.25%, reduction of maximum deformation of 19.98% and maximum stress reduction of 12.35%.

This complex MDO process presented here can be applied to the design of wind turbine blades to obtain a structurally optimized blade design with optimal blade thickness distribution and maximum power output without compromising its aerodynamic performance.
References


