A Framework for Aerostructural Analysis of Wind Turbine Blades

Benjamin Yan
Institute for Aerospace Studies
University of Toronto

A thesis submitted for the degree of
Master of Applied Science

Copyright 2011
Abstract

A Framework for Aerostructural Analysis of Wind Turbine Blades
A thesis submitted as part of the requirements for the degree of Master of Applied Science
Benjamin Yan
2011
University of Toronto Institute for Aerospace Studies (UTIAS)
University of Toronto

As international growth in wind energy steadily increases and the world gradually moves away from fossil fuels, advanced computational tools are required to produce accurate and fast predictions in wind turbine performance, and to allow efficient design cycles using advanced materials and manufacturing methods. Currently, aerostructural analysis often employs the relatively fast but inaccurate Blade Element Momentum (BEM) theory, while accurate but slower Computational Fluid Dynamics (CFD) methods are generally used for aerodynamic analysis alone. To bridge the gap between speed and accuracy, a 3D panel code, TriPan, was coupled with an advanced structural Finite Element Method (FEM) code, TACS, to perform aerostructural analysis for wind turbine blades. In addition, the framework allows the replacement of the panel solver by higher fidelity solvers to increase the accuracy of the overall aerostructural solution.
A tremendous thank you goes to my supervisor, Professor J. R. R. A. Martins, for his critical guidance over the past few years. In fact, a major reason for the pursuit of my Master’s degree was his teachings in two of my undergraduate courses and his guidance for my undergraduate thesis that really inspired me, and made me see the “big picture” of aircraft design. It is difficult to encompass all of my gratitude in words.

I must also thank all of my lab mates for their help throughout my research, as well as a constant intellectual stimulation. Specifically, Sandy, Graeme, and Gaetan were always available to assist me with the various codes and computational tools used in this project, and I could not have done this without them.

Thanks to all of my close friends for making the past few years an incredibly fun experience, and for your emotional support, especially during my injury. Because of you, the years have gone by in a flash.

Finally, and most importantly, thank you, mom and dad, for all your sacrifices throughout my life. I probably haven’t made it extremely easy, but I will be sure to repay you to the best of my ability, with the dedication of this thesis as a start.
## Contents

**List of Figures** vi

**List of Tables** x

1 **Introduction** 1
   1.1 Motivation .............................................. 1
   1.2 Research Methodology ................................... 3

2 **Aerostructural Tools** 7
   2.1 Introduction .............................................. 7
   2.2 TriPan .................................................... 8
      2.2.1 Solver Description .................................. 9
      2.2.2 TriPan Analysis of an Aircraft Wing ............... 10
      2.2.3 TriPan analysis of the NREL Phase VI blade ....... 13
   2.3 pySUmb ................................................... 14
      2.3.1 Solver Description .................................. 15
      2.3.2 pySUmb Analysis of the NREL Phase VI Blade ...... 16
      2.3.3 Summary of Aerodynamic Solvers and Comparison of Results . 20
   2.4 pyTACS .................................................... 25
      2.4.1 Solver Description .................................. 25
      2.4.2 Problem Setup ....................................... 31
   2.5 Summary .................................................. 36

3 **Geometry and Mesh Generation** 39
   3.1 Introduction .............................................. 39
   3.2 Baseline Geometry Generation ............................ 39
List of Figures

1.1 Total world installed capacity of wind turbines in megawatts at end of 2010 ........................................ 2
1.2 Cost distributions of two industrial turbines .......................................................... 2

2.1 Diagram showing the basic configuration of the NREL turbine [1] ................................. 8
2.2 NACA 0012 wing mesh and steady TriPan solution .................................................. 11
2.3 Unsteady TriPan solution for NACA 0012 wing ....................................................... 12
2.4 Comparison of the $C_p$ values between steady (blue) and unsteady (red) solutions for the NACA wing at $\eta = 0.25$, left; $\eta = 0.50$, centre; and $\eta = 0.75$, right .... 12
2.5 TriPan solution of the NREL blade with wake ......................................................... 14
2.6 NREL Phase VI turbine in wind tunnel showing wake [2] ........................................ 15
2.7 SUmb speedup relative to 200 processors for a full turbofan wheel RANS solution with 88 million cells [3] .......................................................... 16
2.8 CFD mesh over the blade surface .............................................................................. 18
2.9 Pressure distributions for the NREL blade: pressure side, top, and suction side, bottom .......................................................... 19
2.10 Flow solutions for the NREL blade: OVERFLOW, left, and NSU3D, right [4] .... 21
2.11 TriPan solution for the NREL blade at 15 m/s ....................................................... 21
2.12 Section $C_p$ for the NREL blade for OVERFLOW and NSU3D solutions [4] ... 23
2.13 Sectional $C_p$ distributions for NREL blade by TriPan ........................................ 24
2.14 Nodal density distribution over the centrifugal test structure .................................. 26
2.15 Nodal displacements of analytical, truss, and shell models due to centrifugal loading 28
2.16 Relative error in nodal displacements for the truss and shell models ................. 29
2.17 Vertical displacements of analytical and shell models due to gravity loading .... 30
2.18 Cross-sectional layout of the WindPACT blade [5] .................................................. 33
2.19 Spanwise thickness distribution for the WindPACT blade spar caps (see Appendix A) 34
LIST OF FIGURES

2.20 Inlaid structure for NACA wing with clear aerodynamic mesh and shaded structural surface ........................................... 35
2.21 Inlaid structure for NREL blade, top, and WPACT blade, bottom, with clear aerodynamic meshes and shaded structural surfaces ........................................... 37

3.1 Linearized geometry of typical wind turbine blade generated by pyACDT ................................. 40
3.2 Comparison of basic mesh generated by pyACDT, above, and mesh smoothed by pyGeo, below ........................................... 42
3.3 Finalized geometry viewed in ICEM CFD ...................................................................................... 43
3.4 TriPan mesh of the turbine blade, left, and tip, right .................................................................. 44
3.5 Blocking and meshing scheme for the tip of the NREL blade ..................................................... 45
3.6 Boundary geometry and meshing for the NREL Blade (blade surface in purple) ............................. 46
3.7 Edge labels of NREL blade for structure generation ................................................................. 47
3.8 Imaginary domain surface for the NREL blade shown in grey as viewed from top of the blade ............................................................................. 48
3.9 Cross-section of the NREL blade [1] ......................................................................................... 49
3.10 Finalized structural model of the NREL blade: mesh of the shell elements, top, and mesh of the shell elements with internal nodes, bottom ........................................... 50

4.1 Rigid links for the NACA wing: the aerodynamic mesh in black, the structural surface in grey, and the rigid links in red ........................................... 52
4.2 Rigid links for the NREL blade: the aerodynamic mesh in black, the structural surface omitted for clarity, and the rigid links in red ........................................... 53
4.3 Rigid links for the WindPACT blade ......................................................................................... 53
4.4 Detail of the rigid links for the WindPACT blade at the tip ......................................................... 54
4.5 Iterative aerostructural process: loads and displacements are passed back and forth between aerodynamic and structural solvers to achieve convergence ........................................... 55
4.7 Aerostructural plot for the NACA wing: the left side of the wing shows the structural mesh with the inverse of the load-to-fail factor; the right side of the wing shows the $C_p$ distribution over the aerodynamic surface, with the wake mesh in grey and undeformed wingtip outline ........................................... 56
LIST OF FIGURES

4.8 Aerostructural plot for the NREL blade: exploded surfaces denote the structural mesh with the inverse load-to-fail factor contour; unexploded surface denotes the aerodynamic surface with $C_p$ distribution, with undisplaced tip and wake mesh .

4.9 Convergence plot for the NREL blade aerostructural test case run on a single processor .

4.10 Aerostructural plot for the WindPACT blade: exploded surfaces denote the structural mesh with the inverse load-to-fail factor contour; unexploded surface denotes the aerodynamic surface with $C_p$ distribution, with undisplaced tip and wake mesh .

4.11 Details at the tip for the WindPACT blade .

4.12 Convergence plot for the WindPACT blade case run on a single processor .

4.13 Vertical displacement for the NACA wing .

4.14 Spanwise rotational displacement in degrees for the NACA wing .

4.15 High load concentration at the NACA wing tip .

4.16 Spanwise displacements for the NREL blade: vertical displacement, left, and rotational displacement in degrees, right .

4.17 Stress distribution at the NREL blade root .

4.18 Aerostructural solution of NREL blade at 15 m/s windspeed .

4.19 Comparison of the thrust and torque forces for the NREL blade at 10 m/s and 15 m/s windspeed .

4.20 Spanwise displacements for the WindPACT blade: vertical displacement, left, and rotational displacement in degrees, right .

4.21 Spanwise rotational displacement at the WindPACT blade tip .

4.22 Axial rotational displacement in degrees for the WindPACT blade .

4.23 Spanwise thrust and torque curves for the WindPACT blade .

4.24 Stress distribution detail for the WindPACT blade at the root. Higher loads are concentrated at geometric discontinuities, such as the base of the spar and where the spar bends .

4.25 Section $C_p$ distributions for the WindPACT blade: initial solution shown in red and converged solution shown in blue .

4.26 Comparison of aerostructural results for the NREL blade with inertial loading, top, and without inertial loading, bottom .
4.27 Spanwise displacements comparison for the NREL blade between solutions with inertial loading and without: vertical displacement, left, and rotational displacement in degrees, right ........................................... 71
4.28 Comparison of aerostructural results for the NREL blade with inertial loading, top, and without inertial loading, bottom .......................................................... 71
4.29 Spanwise displacements comparison for the WindPACT blade between solutions with inertial loading and without: vertical displacement, left, and rotational displacement, right .......................................................... 72
5.1 Tunnel view for a baseline rotor blade, left, and flatback rotor blade, right 71 ... 74
5.2 CFD simulation of vortex shedding for the flatback airfoil 8 ..................... 75
5.3 Example of turbine blade with curved planform 9 ................................. 75
List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>TriPan flow conditions for NACA wing</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>TriPan flow conditions for NREL Phase VI blade</td>
<td>13</td>
</tr>
<tr>
<td>2.3</td>
<td>pySUmb flow conditions for NREL blade</td>
<td>17</td>
</tr>
<tr>
<td>2.4</td>
<td>Structural data for the NACA wing</td>
<td>31</td>
</tr>
<tr>
<td>2.5</td>
<td>Mechanical properties of carbon fibre</td>
<td>32</td>
</tr>
<tr>
<td>2.6</td>
<td>Mechanical properties of unidirectional E-glass</td>
<td>32</td>
</tr>
<tr>
<td>2.7</td>
<td>Structural thicknesses for the WindPACT blade</td>
<td>33</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Motivation

As the world oil reserves steadily deplete, analysts have predicted oil prices per barrel to be as high as $200–$250 per barrel, with the trend continuing for at least 2–3 years [10]. At the same time, demand for wind power worldwide has increased explosively over the past decade. As Figure (1.1) shows, the total installed capacity of wind power over the world has increased by nearly 40 GW over the 2009–2010 period. The World Wind Energy Association expects the total installation to reach 240 GW by end of 2011 [11]. Internationally, the annual growth rate of wind energy production over the past decade has hovered between 21% and over 41%. Clearly, the worldwide potential for wind energy growth is immense. While occupying only a fraction of the world landmass, Europe currently produces about 43.7% of the world’s wind energy, with wind power constituting 21% of the total power production in Denmark. In comparison to Europe, population density is much lower in North America, and the availability of wind is similar, so extensive development of wind power is promising. In Canada, wind generation has increased by 40.1% in 2009 and 21% in 2010.

Despite the recent financial recession, demand remains extremely high for wind turbine production. Interestingly, the individual cost of turbine rotors has been steadily increasing. Over the 2005–2008 period, the price of offshore turbines rose 48%, while the price of land-based turbines rose 74%. The increase in commodity prices only played a partial role in this rise in cost [13]; thus, studies in the minimization of turbine cost become increasingly important. However, to accurately predict the actual capital cost of a whole turbine system can be difficult. For example, a simplistic model would predict that machine costs increase exponentially with
In the year 2010, the wind capacity reached worldwide 19,663 MW after 15,905 MW in 2009, 12,093 MW in 2008, and 9,393 MW in 2007.

Investment in new wind turbines saw a decline in many parts of the world. For the first time in more than two decades, the market for new wind turbines was smaller than in the previous year and reached an overall size of 3,764 MW, after 3,831 MW in 2009.

China accounted for more than half of the world wind market 2010. Without taking into account China, the world market shrank by one third and decreased from 24,512 MW to 18,714 MW.

Still and in spite of the slowdown, the trend continued that the installed wind capacity more than doubled every third year.

In the year 2010, altogether 83 countries, one more than in 2009, used wind energy for electricity generation. 52 countries increased their total installed capacity, after 49 in the previous year.

The turnover of the wind sector worldwide reached 40 billion (!) (55 billion US$) in 2010, after 50 billion (!) (70 billion US$) in the year 2009. The decrease is due to lower prices for wind turbines and a shift towards China.

The decrease in new capacity outside China can be seen as a result of insufficient political support for wind energy utilisation. In a paradox situation, more and more policymakers are declaring their support for increased use of wind energy, but such statements do not go hand in hand with the necessary political decisions.

While the year 2009 had seen two major milestones – the first North American feed-in law in Ontario and the introduction of the first feed-in tariff in Africa – the year 2010 did not bring comparable breakthrough decisions in national or international policies.

Especially in the USA, there is major regulatory uncertainty and not enough focus on renewable energy. Also in many developing countries there is still a huge policy gap and there is not yet enough stability and reliability in market frameworks, next to a lack of financial resources.

In addition, the necessary international frameworks for renewable energy have not yet been established.

Figure 1.1: Total world installed capacity of wind turbines in megawatts at end of 2010 [11]

Figure 1.2: Cost distributions of two industrial turbines [12]
the radius of the turbine, with a power of 0.5–0.65. However, as historical trends have shown, the cost of wind energy production (cost per kWh, rather than per turbine system) has decreased, while turbine radii have steadily increased [14]. Of course, this is not necessarily the cause: as turbine research advances over time, it logically leads to lower cost of energy; at the same time, research leads to more advanced materials and designs that allow the development of larger blades. However, it can only be said that the decrease in cost of energy and increase in blade diameter are both enabled by new technology, without a mutual causal relationship, especially considering that the cost of the turbine blades is only around 15 – 25% of the whole, as seen in Figure (1.2) [12]. As suggested by Ashwill and Laird [15], the blade weight to diameter for earlier designs follow a power law of roughly 3, while later designs have a power law of close to 2.5. While blade weight isn’t a direct indicator of cost of energy, it can be inferred that cost and blade diameter both vary greatly over time. Thus, it is a difficult problem to develop an accurate cost model. Since all of a wind turbine’s power originates from the blades, in order to create novel turbine designs that effectively minimize the cost of energy, it is imperative to have high fidelity analysis tools that not only accurately predict the aerostructural behaviour of the turbine blade, but also does this efficiently, so that design optimization can be performed.

1.2 Research Methodology

While the design of a real commercial wind turbine system involves a wide array of disciplines including aerodynamics, structural mechanics, acoustics, electrical systems, materials, and manufacturing methods, the limitations in expertise and the scope of the project currently allows the analysis and design of the turbine blades alone, and the disciplines involved are limited to aerodynamics and structural mechanics. Acoustics, in particular, is a closely related discipline and its inclusion is planned for the future design of the “next generation quiet turbine”, but is not in the scope of the current project. For the purpose of aerodynamic analysis of wind turbines, other authors have used various types of flow solvers. For example, Sezer–Uzol et al. explored a 3D time-accurate RANS solver in the analysis of the National Renewable Energy Laboratories (NREL) Phase VI blade [16]; Laursen et al. used the commercially available ANSYS–CFX software with RANS equations [17]; similarly, Gomez-Iradi et al. developed a CFD code solving the compressible URANS equations [18]. In general, recent research involving aerodynamic analysis alone has extensively used high fidelity Navier–Stokes codes. However, these codes are not yet practical for an aerostructural solution due to their high computational costs.
CHAPTER 1. INTRODUCTION

For aeroelastic simulations, McTavish, Feszty, and Nitzsche employed a discrete vortex method [19], while Jureczko et al. employed the common Blade Element Momentum (BEM) theory [20]. Guerri et al. explored the fluid structure interaction of wind turbine airfoils using a CFD solution, but this aeroelastic solution is only in 2D [21]. Similarly, Kachra and Nadarajah presented aeroelastic solutions of an airfoil using the nonlinear frequency-domain method in 2D [22]. Roura et al. presented a free-wake panel method for aeroelastic rotor predictions, but did not present a structural solver to be coupled with this panel method [23]. Streiner et al. performed an aeroelastic frequency analysis of wind turbines, including tower, using CFD results, but the modelling of the structure is relatively simplistic [24]. Gordnier and Fthen presented a very high fidelity coupling of a nonlinear structural method with a Navier–Stokes solver, but the analysis has been restricted to very simple, small cases [25].

For this project, analysis tools of varying fidelity have been explored: a previous turbine blade optimization framework used BEM theory and empirical approximations for the blade tip effects to calculate the aerodynamic performance [26], while the current project initially explored the use of Symb [3], an Euler code, to perform the aerodynamic analysis. Later, Symb is replaced by TriPan, a 3D panel code, for its low computational cost. For the structural analysis, TACS (Toolbox for the Analysis of Composite Structures) is used to generate a 3D structural model composed of high-order shell elements considered appropriate for the analysis of thin composite structures. In addition to static structural analysis, TACS is capable of calculating dynamic response and buckling behaviour; one caveat is that the analyses are linear, so the accuracy in predicting large deflections of long turbine blades is subject to future investigation.

In order to generate the meshes required for the aerodynamic and structural analyses, several design tools are used. Initially, a linear spline model is created using the geometry package in pyACDT, an in-house tool for the low fidelity design of a complete aircraft [27]. Once the linear model is created, it is further modified and smoothed using pyPSG [28], another in-house tool for the generation and manipulation of high-order 3D splines, and translated into a point data format compatible with ANSYS IcemCFD software. Using IcemCFD, the spline geometries are again modified to create various types of meshes, including 3D and surface meshing.

Although currently explored designs are relatively contemporary, the process allows for the exploration of very large and novel designs. At the same time, Euler or Navier–Stokes CFD codes may be used instead of the current panel code to increase the fidelity. The following outlines the aerostructural analysis procedure and results of a small-scale wind turbine blade for the NREL Phase VI study [1] and a medium-scale blade for the WindPACT study [5].
CHAPTER 1. INTRODUCTION

This thesis is organized as follows: Chapter Two describes the various analysis tools used throughout the project, with some examples of aerodynamic solutions and comparisons to results by other authors. Chapter Three describes the methods used to generate and manipulate the meshes. Chapter Four presents the aerostructural solutions of various cases, and discusses them in detail. Finally, Chapter Five concludes the thesis with future work and closing remarks.
Chapter 2

Aerostructural Tools

2.1 Introduction

The aerostructural analysis in this framework involves two main disciplines, the aerodynamic analysis and the structural analysis. First, the aerodynamic solution is obtained, and the loads are passed to the structural solver to obtain the displacements, which are then passed back to the aerodynamic solver to displace the mesh and reevaluate the aerodynamic solution. This process iterates until a convergence criterion is met. The aerodynamic solver used in this project is TriPan, a 3D panel code that is developed in house. Other than TriPan, alternative aerodynamic solvers can be used, provided that they generate the outputs required by the structural solvers, and are capable of accepting various inputs required for mesh warping. The Euler code, Stanford University multiblock (SUmb), is explored as an alternative solver, but its use is discontinued due to the long time required for solver convergence. The long convergence time is caused by both the relatively complex shape of the turbine blades and the large size of mesh domain required to generate a smooth grid. The structural solution is performed by the Toolbox for Analysis of Composite Structures (TACS). Each of these parts will be discussed below; they are exemplified through two test cases: the analysis of a NACA-based wing, and the National Renewable Energy Laboratories (NREL) Phase VI blade. The WindPACT blade case is not used to describe the aerodynamic tools because it is procedurally identical to the NREL blade; it is only discussed in the structural section.

The NREL Phase VI turbine was used for NREL’s Unsteady Aerodynamics Experiment (UAE), the purpose of which was to “acquire accurate quantitative aerodynamic and structural measurements on a wind turbine, geometrically and dynamically representative of full-scale
machines, in an environment free from pronounced inflow anomalies” [1]. The turbine is two-bladed with full-span pitch control in either downwind or upwind configuration; the coning and teetering angles are also variable. A diagram of the turbine is shown in Figure (2.1). For the numeric simulation, however, the geometry of the turbine is simplified by retaining only one blade with no hub section, and no variation in pitch, coning, yawing or teetering.

\[
\phi_3 + \phi_1 + \tau = \alpha
\]

Where,
\( \phi_3 \) = Blade 3 flap angle,
\( \phi_1 \) = Blade 1 flap angle,
\( \tau \) = Teeter angle, and
\( 2\alpha \) = Angle subtended by blades.

Figure 2.1: Diagram showing the basic configuration of the NREL turbine [1]

2.2 TriPan

TriPan is a 3D panel code developed in-house [6]. It is capable of handling the basic aerodynamic analyses of structured or unstructured surface meshes in either steady or unsteady mode. In addition to the surface mesh, TriPan requires the specification of the wake location on the trailing edge, but this is done almost automatically and the details of the process are omitted here. A significant limitation of TriPan and panel methods in general is the inability to predict stall and
account for other viscous effects. This needs to be considered during the analysis process, by limiting the angle of attack, for example.

2.2.1 Solver Description

TriPan is a 3D steady and unsteady potential flow panel method designed as an efficient aerodynamic solver with close coupling and high compatibility to structural analysis by pyTACS. Compared to more computationally demanding CFD methods, the steady TriPan solution requires several orders of magnitude less memory and computation time, while the unsteady solution requires roughly an order of magnitude more computation time.

The underlying principles of TriPan are similar to other potential flow methods, such as the unsteady code developed by Palmiter and Katz \[29\]. Given a 3D surface discretized into triangular or quadrilateral panels, the solution to the aerodynamic problem becomes the solution of the incompressible continuity equation

\[ \nabla^2 \Phi = 0, \quad (2.1) \]

where \( \Phi \) is the velocity potential in the inertial frame. Since we require the flow component normal to the solid surface to be zero, we set the boundary condition

\[ \Phi_i = 0, \quad (2.2) \]

where \( \Phi_i \) is the velocity potential inside the solid surface. For a discretized problem with \( M \) panels, the sum of the influences due to all the sources and doublets is zero:

\[ \sum_{k=1}^{M} B_{jk} \sigma_k + C_{jk} \mu_k = 0, \quad (2.3) \]

where \( \sigma_k \) are the sources, \( \mu_k \) are the doublets, and \( B_{jk} \) and \( C_{jk} \) are the influence coefficients due to the sources and doublets, respectively. Solving this system of equations for \( \mu \) allows the calculation of local velocity components:

\[ q_l = -\frac{\partial \mu}{\partial l}, \quad q_m = -\frac{\partial \mu}{\partial m}. \quad (2.4) \]

in local coordinates \((l, m, n)\). \( q_n \) is zero since the flow is parallel to the panel surface. Once the velocities are obtained, the coefficient of pressure at each panel can be calculated as:

\[ C_p = 1 - \frac{q_n^2}{U_{Ref}^2} + \frac{2}{U_{Ref}^2} \frac{\partial \Phi}{\partial t}, \quad (2.5) \]
where

\[ U_{\text{Ref}} = U_{\infty} + r\Omega. \]  

(2.6)

In Equation (2.6), \( r \) is the position of the panel relative to the origin, and \( \Omega \) is the rotational velocity of the panel in the inertial frame. Note that \( \frac{\partial \Phi}{\partial t} = 0 \) for the steady solution.

For the unsteady solution, wake panels are shed at each time step, and the shape of the wake is obtained by solving for a force-free state. The force acting on panel \( k \) is given by

\[ F_k = -C_{pk} \left( \frac{1}{2} \rho U_{\text{Ref}}^2 \right) S_k n_k, \]

(2.7)

where \( S_k \) is the area of the panel and \( n_k \) is the normal vector. Since this solution must be obtained iteratively, the solution time is significantly longer than that of the steady solution, which assumes a flat wake. Given the pressure distributions over the surface of the solid, the aerodynamic loading can be calculated by integrating over the total area and passed to the structural solver.

### 2.2.2 TriPan Analysis of an Aircraft Wing

As a first example of the capabilities of TriPan, we examine the steady and unsteady flow solutions for a simple wing with a NACA 0012 airfoil and no sweep or taper. One half of the 8 m span wing is modelled, with a symmetry plane at \( Z=0 \). This is an important step before performing the analysis of a turbine blade because the flow conditions are comparatively simple, and the high speed, irrotational flow is highly suited for TriPan. The flow conditions for this problem are listed in Table (2.1).

<table>
<thead>
<tr>
<th></th>
<th>( m/s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference velocity, ( U_{\text{Ref}} )</td>
<td>100.0</td>
</tr>
<tr>
<td>Angle of attack, ( \alpha )</td>
<td>5.0</td>
</tr>
<tr>
<td>Sideslip, ( \beta )</td>
<td>0.0</td>
</tr>
<tr>
<td>Rotation about origin, ( \Omega )</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 2.1: TriPan flow conditions for NACA wing

For the steady case, the solution is relatively straightforward. The unstructured mesh, wake, and flow solution is shown in Figure (2.2). Since the angle of attack is nonzero, the plot shows a low pressure zone at the top of the leading edge, and a high pressure zone at the top of the trailing edge. Figure (2.2) also demonstrates the increase in mesh density of the wake in the
region closer to the wing. The purpose of this refinement is to increase accuracy and convergence of the solution for the steady case. As distance from the wing increases, the wake mesh can become coarser without having any significant impact on the panels near or on the wing. An important result should be noted here: because the wingtip mesh is smooth and rounded, the pressure variation in this region is also smooth, since the calculations performed by TriPan are gradient-based. This is realistic because sharp pressure gradients are generally alleviated by smooth surfaces in real flows.

![Figure 2.2: NACA 0012 wing mesh and steady TriPan solution](image)

In comparison to the steady case, the unsteady analysis of the same wing under identical conditions results in a similar solution, as shown in Figure (2.3). A more detailed comparison of the $C_p$ results are shown in Figure (2.4) at three different span locations, with the steady solution in blue, and unsteady solution in red. As the plot shows, the pressure distributions for the two cases are nearly identical: the $C_p$ values for the steady solution are only marginally higher than that of the unsteady solution. Examining the results in Figure (2.3) closely, it is noteworthy that the wake rolls up behind the wingtip due to the vortices generated by the lift of the wing. In fact, this rollup carries over to the rear end of the wake sheet, indicating that the wake sheet needs to be sufficiently long such that the rollup at the end does not disturb the solution near the wing. The wake sheet is well behaved away from the edges, which indicates that the solution is highly converged.
Given that the results from the steady and unsteady cases are extremely close, and considering that the solution time for the unsteady case is an order of magnitude higher than that of the steady case, it is concluded that performing the unsteady analysis is not worthwhile in an aerostructural solution, since this in turn requires a high computational cost, even though steady wind and attached flow are assumed. Thus, only the steady analysis will be used for the aerostructural analysis of turbine blades, especially considering that the mesh size of a turbine blade is significantly larger than that of the NACA wing.
2.2.3 TriPan analysis of the NREL Phase VI blade

Next we examine the rotating flow over the NREL Phase VI blade. The basic flow conditions are given in Table 2.2.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference velocity, $U_{\text{Ref}}$ (m/s)</td>
<td>10.0</td>
</tr>
<tr>
<td>Angle of attack, $\alpha$ (°)</td>
<td>0.0</td>
</tr>
<tr>
<td>Sideslip, $\beta$ (°)</td>
<td>−90.0</td>
</tr>
<tr>
<td>Rotation about origin, $\Omega$ (rad/s)</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Table 2.2: TriPan flow conditions for NREL Phase VI blade

Note that the freestream velocity is no longer in the chordwise direction as expected in the flow over an aircraft wing, but instead it is approximately perpendicular to the planform of the blade. Additionally, the wake is no longer straight but spirals behind the blade due to the rotation. Figure 2.5 shows the solution and the orientation of the blade relative to the wake. As in the previous case for the NACA wing, the wake mesh behind the blade becomes coarser as distance from the blade increases. Instead of the uniform spanwise mesh for the NACA wing, the mesh density of both the blade surface and wake increases at the root and the tip, as shown by the darker bands in those regions. This is done to increase the accuracy of the solution in the tip and root sections because of the discontinuities in geometry. Even so, Figure 2.5 shows sharp contrasts between the airfoil surface and the flat perpendicular tip. This seems to indicate that the rotating NREL blade case is more complex than the NACA wing case.

Note that the flow around a turbine blade is not truly steady. In fact, as Figure 2.6 shows, the wake in the real NREL turbine system is in an unsteady state due to interactions with the turbine tower [19]. However, there is no way to treat this using TriPan, because the inclusion of the entire turbine structure would require both static and rotating panels, which is beyond the current capabilities of the solver. In addition, it is not clear how the wake sheet would behave upon intersection with surface panels around the tower. Thus, if it is assumed that no such interactions occur, it is logical to assume a steady state flow where the wake is well-behaved, as demonstrated. Since modern turbines are generally in the upwind configuration, i.e. the blades are positioned upwind relative to the tower, the steadiness of the flow is a reasonable assumption on a single-turbine basis. In a wind farm, the wakes from the upwind turbines may significantly affect the flows downwind, but this is a much more complex problem that is beyond the scope of this project.
In summary, the capabilities of the TriPan aerodynamic solver are described and demonstrated. As previously mentioned, the aerostructural analysis is performed using the steady flow analysis from TriPan. In addition, it is possible to conduct the same aerostructural analysis using a higher fidelity aerodynamic solver, and the analysis of the NREL blade using Euler equations by pySUmb as presented below.

2.3 pySUmb

pySUmb is a Python-wrapped version of the SUmb (Stanford University multiblock) flow solver that is capable of analyzing rotating mesh block families and to warp mesh. Although the Euler equations are used instead of the Navier-Stokes equations, and viscous effects are not accurately modelled, the flow analysis by pySUmb presents a significant increase in fidelity compared to the TriPan analysis. A major drawback currently prevents the use of pySUmb in the aerostructural analysis process: the solution time of the NREL blade for a single iteration using pySUmb is on the order of 10 minutes, while the solution time using TriPan for the same problem is on the order of 10 seconds. Additionally, there were difficulties in handling the aerodynamic load and displacement transfer using pySUmb at the time. Nonetheless, it is worthwhile to examine the solutions generated by this method, since it is possible to replace
2.3.1 Solver Description

SUmb is a multiblock solver designed for massively parallel systems running on several thousand processors [3]. As Figure (2.7) shows, the parallel speedup follows linear speedup quite closely for both the single-grid case and multi-grid case. Not only is SUmb capable of solving the Euler, laminar Navier-Stokes and Reynolds-averaged Navier-Stokes equations, it is capable of performing the solutions in unsteady mode using backwards difference formulae or a time-spectral approach [30].

For this project, only the Euler equations are solved. In vector form, they are:

\[
\frac{\partial \mathbf{m}}{\partial t} + \frac{\partial \mathbf{f}_x}{\partial x} + \frac{\partial \mathbf{f}_y}{\partial y} + \frac{\partial \mathbf{f}_z}{\partial z} = 0,
\]

where

\[
\mathbf{m} = \begin{pmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ E \end{pmatrix}, \quad \mathbf{f}_x = \begin{pmatrix} \rho u \\ \rho u p + \rho u^2 \\ \rho uv \\ \rho uw \\ u(E + p) \end{pmatrix}, \quad \mathbf{f}_y = \begin{pmatrix} \rho v \\ \rho u v + \rho v^2 \\ \rho vw \\ \rho vw \\ v(E + p) \end{pmatrix}, \quad \mathbf{f}_z = \begin{pmatrix} \rho w \\ \rho u w + \rho w^2 \\ \rho vw \\ \rho vw \\ w(E + p) \end{pmatrix}.
\]

As mentioned before, the input grid used by pySUmb is in CGNS format. Discretization schemes available are central or upwind; central schemes must be accompanied by a choice of
However when the number of blocks is just marginally larger than the number of processors, a case that usually occurs when running a multi-block solver on a massively parallel machine, the assumptions used in the algorithms in Metis are violated and problems can be expected. Indeed, experience has shown that for more than 50 processors empty partitions can occur and for \( O(1,000) \) processors approximately 10 percent of the partitions are empty, which is clearly undesirable. However, it was found that Metis can still be used for these cases if the cost of communication is neglected, i.e. the number of neighbors is set to zero for every vertex of the graph. This is not the best solution possible, but for the cases shown in section III it works reasonably well and better than other solutions attempted, such as Greedy algorithms.

Figure 4 shows the speed up relative to 200 processors for a full wheel turbine simulation for both single-grid and multi-grid (using a three level W-cycle) computations. The grid consists of 496 blocks and 88 million cells and is considered coarse as the average number of cells per blade passage is only 250,000. This case was run on 200, 400, 600, 800, 1,200 and 1,800 processors on the ALC Linux cluster at the Lawrence Livermore National Laboratory. The speed up is perfect as long as an acceptable load balance could be obtained. The deviations from the linear curve in figure 4 are solely caused by load imbalance. It was found that on systems like ALC a linear speed up was obtained as long as at least 20,000 cells are stored per processor. For BlueGene/L, which has relatively slow processors compared to its communication network, this number could be reduced to 5,000.

B. Parallel IO

The SUmb flow solver has IO filters for both CGNS and PLOT3D. Due to the large amount of data that must be read and written for unsteady simulations of entire compressors and turbines, parallel IO is an absolute necessity. Despite the recent efforts to create a parallel IO option for CGNS, this is not applicable yet to the problems considered in this work and therefore the discussion in this section will be limited to the PLOT3D format.

One possibility for parallel IO is that every processors reads/writes the information it is responsible for. The advantage of this approach is that the method is local, i.e. no explicit communication is required, and therefore easy to implement. If blocks are not split during runtime this indeed is the most efficient solution, because the PLOT3D format stores the information contiguously on a block by block basis and the size of a block is usually big enough to guarantee good performance of the MPI IO routines.

Figure 2.7: SUmb speedup relative to 200 processors for a full turbofan wheel RANS solution with 88 million cells [3]

dissipation scheme between scalar, matrix or CUSP. Multigrid cycles are possible: predefined strategies are single grid, nV, or nW, where n denotes the number of levels in multigrid. In addition, it is possible to specify an arbitrary multigrid strategy in the pysUmb input file. Further information and details on pysUmb can be found in [3] and [30].

2.3.2 pySUmb Analysis of the NREL Phase VI Blade

Problem Setup

The NREL blade solver conditions are listed in Table (2.3). They are identical to the TriPan solver conditions, except the windspeed is slightly increased.

A central discretization scheme is chosen over an upwind discretization because the convergence appeared to be higher and less oscillatory, and the 3W multigrid strategy improves both convergence rate and quality. In order to achieve this, it becomes imperative that the number of cells in each dimension for every block in the grid is equal to \( 2^k \) with \( k \geq 3 \). The mesh over the surface of the NREL blade is shown in Figure (2.8). As stated previously, only the outer section of the blade is analyzed. The inclusion of the root section of the blade prevents the convergence of the solver due to it’s inability to solve the separated flow around the cylindrical root section.
In order to improve convergence, some of the above conditions are obtained by trial and error. First, the freestream velocity is increased to about 12.5 m/s because pySUmb appears to be unable to converge at lower flow speeds. As Chao and van Dam have stated [31], at a freestream wind speed of 10 m/s, the Reynolds number for this case is $0.4 \times 10^6$, and in combination with the low Mach numbers, it would be challenging to obtain acceptable solutions. Chao and van Dam’s solution to this problem is to increase the Reynolds number to 1 million, rather than to increase the wind speed. A similar treatment of the Reynolds number is used by Winnemöller and van Dam [32]. The same effect for improving the CFD convergence can be achieved by increasing the rotation rate, but the results are not presented here. Although changing the wind speed or rate of rotation causes a fundamental difference in the flow, a change in the Reynolds number would not be without consequence either. As Lanzafame and Messina pointed out [33], the aerodynamic performance for the NREL blade’s S809 airfoil can vary drastically between $Re = 300,000$ and $Re = 1,000,000$.

**Analysis Results**

The pySUmb solution for the above problem is shown in Figure (2.9), showing the pressure distributions on the pressure (top) and suction (bottom) sides of the NREL blade. Note that the coefficient of pressure values are normalized using the freestream velocity, which causes an inflation in the values. In a similar fashion to the solution in TriPan, the blade tip shows sharp variations in pressure, particularly at the juncture of the blade surface to the flat tip. Physically, this is expected because the front and rear of the tip are not perfectly parallel to the flow due to the rotation of the blade, even when spanwise flow is ignored. In addition, the most significant pressure variations occur near the leading edge, as shown by the dark red and blue bands.
Figure 2.8: CFD mesh over the blade surface
Figure 2.9: Pressure distributions for the NREL blade: pressure side, top, and suction side, bottom
2.3.3 Summary of Aerodynamic Solvers and Comparison of Results

So far, two methods for the calculation of pressure distributions over a turbine blade have been examined. The steady 3D panel method is ultimately chosen as the aerodynamic solver in the optimization process due to the much faster iteration rate compared to the unsteady panel method and the steady Euler method.

For a comparison of results, the pressure and streamline contour solutions obtained by Potsdam and Mavriplis using RANS solvers [4], OVERFLOW and NSU3D, are presented in Figure (2.10) to give an idea of the trends; unfortunately, the original of Figure (2.10) does not include a legend, so precise values cannot be compared. Note that significant differences exist between the RANS solutions and the Euler solution by pySUmb, shown in Figure (2.9), because the RANS solutions include the root section of the blade, and the geometry at the blade tip is rounded, so the sharp variations seen in the pySUmb solution do not exist in the RANS solutions. For 15 m/s and 25 m/s conditions, significant interference by the root section on the blade surface becomes very noticeable, but this is not modelled in the pySUmb solution. In addition, a similar plot for the TriPan solution is shown in Figure (2.11). Note that this solution is for the 15 m/s case.

To perform a more detailed comparison, we examine the pressure coefficient plots for the TriPan solution in comparison to the OVERFLOW and NSU3D solutions. Figure (2.12) shows the various solutions by Potsdam and Mavriplis for three flow conditions: 7 m/s, 10 m/s, and 25 m/s, at three spanwise locations. A similar plot is produced for TriPan and is shown in Figure (2.13). For the 7 m/s and 10 m/s cases, the leading edge values for the TriPan solutions are similar to that shown in Figure (2.12). However, from approximately the middle of the airfoil to the trailing edge, the values become very different. For the TriPan solutions, the pressure at the top of the trailing edge is actually higher than that on the bottom surface, and are not equal at the tip of the trailing edge. This suggests that the assumption of the steady wake is inaccurate, leading to a non-force-free wake. For this particular case, at least, an unsteady solution would in fact obtain more accurate results. Another important conclusion is that the aerodynamic load calculated by TriPan is likely to be lower due to the lower pressures on the bottom surface of the blade.

The figures for the 25 m/s case are quite different; this is likely because at a freestream speed of 25 m/s, the effective angle of attack at any point along the blade is much higher than that at 7 or 10 m/s. Since TriPan is unable to predict stall and simulate real flows under high angle
Figure 2.10: Flow solutions for the NREL blade: OVERFLOW, left, and NSU3D, right [4]

Figure 2.11: TriPan solution for the NREL blade at 15 m/s
of attack conditions, the aerodynamic solution becomes unreliable under very high windspeed conditions. As such, this inaccuracy only applies to the rotating case where the angle of attack is affected by the freestream speed. Thus, the current aerostructural framework should only be used to simulate non-stalled conditions. Next, we discuss the structural solver used in the framework.
Figure 2.12: Section $C_p$ for the NREL blade for OVERFLOW and NSU3D solutions [4]
Figure 2.13: Section $C_p$ distributions for NREL blade by TriPan
CHAPTER 2. AEROSTRUCTURAL TOOLS

2.4 pyTACS

pyTACS is the Python-wrapped version of the Toolbox for the Analysis of Composite Structures (TACS), an in-house structural solver developed for the dynamic and static analyses with a specific focus on accurate stress prediction in composite structures, with various types of high order elements [6]. To demonstrate the capabilities of TACS, we consider three examples: the NACA wing structure simplified as a flat tapered plate, a wing box structure based on the NREL Phase VI turbine blade structure, and the WindPACT blade structure.

2.4.1 Solver Description

TACS is a powerful finite element structural solver capable of performing static, buckling and frequency analyses for composite structures. A variety of element types can be used, including beam, 3D solid, plate, and shell elements. For this project, only the static analysis is considered. Ultimately, the static solution for the displacements is found by solving the following equation:

\[ \mathbf{Ku} - \mathbf{f} = R_s(u), \]  

(2.10)

where \( \mathbf{K} \) is the stiffness matrix, \( \mathbf{u} \) are the structural displacements, \( \mathbf{f} \) are the structural loads, and \( R_s \) is the structural residual as a function of \( u \). The solution to this problem is obtained iteratively by minimizing the absolute value of the residual.

Centrifugal and Gravity Loading

During this project, the author’s contribution to TACS is the implementation of centrifugal and gravity loading for shell elements. These loads are applied to each structural element as a surface traction, in a similar fashion to the surface pressure loads. More specifically, a pressure-like load is applied at each node over the element. Although centrifugal and gravity forces are actually body forces, treating them like pressure loads allows the interpolation of these forces over the entire shell element using Gauss quadrature, increasing the model accuracy of shells with varying thicknesses. These nodal forces for each element are subsequently subtracted from the structural residual, which is equivalent to adding the forces to the force vector due to Equation (2.10). For centrifugal loading, this pressure-like load at each node is calculated as:

\[ \mathbf{p}_c = -m \mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{r}), \]  

(2.11)
where \( p_c \) is the pressure-like load due to centrifugal forces, \( m \) is the mass per unit area of the shell at the node, \( \Omega \) is the rotation vector of the structure in inertial frame, and \( r \) is the radial vector from the centre of rotation to the node.

Similarly, the gravity loading is given by:

\[
p_g = mgn, \tag{2.12}
\]

where \( g \) is the acceleration due to gravity, and \( n \) is an arbitrary unit vector in inertial frame used to denote the direction of gravity.

**Verification of Centrifugal Loading**

To verify the validity and accuracy of the centrifugal loading formulation, a test case is generated to compare the solutions from an analytical method, a truss model, and a shell model. The structure for the test case is a linear truss loaded only by centrifugal forces. The structure is 9 m in length, with 101 nodes distributed logarithmically. The nodal distribution over the length of the structure is shown in Figure (2.14). The cross-sectional area of the structure is dependent on the radial distance from the origin, i.e.:

\[
A = 1/r. \tag{2.13}
\]

![Figure 2.14: Nodal density distribution over the centrifugal test structure](image-url)
This structure is chosen because of its complexity but relatively simple analytical solution; the drawback is that it is not a realistic structure, as the area approaches infinity at \( r = 0 \). Using the method of minimal potential energy, the analytical solution to this problem can be written as:

\[
  u(r) = -\frac{\rho \Omega^2}{3E} r^3 + \frac{\rho \Omega^2 L}{2E} r^2,
\]

(2.14)

where \( u(r) \) is the displacement at \( r \), \( \rho \) is the density of the material, \( \Omega \) is the rotational rate of the structure about the origin, \( L \) is the length of the structure, and \( E \) is Young’s Modulus of the material.

For the truss element model, the elements are considered to be non-constant in cross-section. Therefore, new consistent force vectors and stiffness matrices are derived. The consistent force vector for each element can be written as:

\[
  f = \rho A l^2 \left( \frac{r_1}{r_2} + \frac{l^2}{3} + \frac{l^2}{3} \right),
\]

(2.15)

where \( r_1 \) is the location of node 1 of the element, and \( l \) is the length of the element. Similarly, the stiffness matrix for each element can be written as:

\[
  k = \frac{E \ln(r_2) - \ln(r_1)}{l^2} \left( \begin{array}{cc} 1 & -1 \\ -1 & 1 \end{array} \right),
\]

(2.16)

where \( r_2 \) is the location of node 2 of the element. Note that the root element cannot use this formulation because \( \ln(0) \) is undefined, so a constant cross-section element is used.

For the shell element model, constant cross-section first-order elements are used. The width of the structure, \( w \), is set as \( 1 \times 10^{-4} \) m to model a thin structure. Since \( A \) is defined by Equation (2.13), the thickness of each element, \( t \), is given by:

\[
  t = A/w.
\]

(2.17)

The solutions of the three methods are presented in Figure (2.15). As the figure shows, differences between the three results are nearly indistinguishable. Thus, the errors of the truss and shell models relative to the analytical results are shown in Figure (2.16). The errors are relatively high at the root, but remain bounded, which is a reasonable result considering that the structural stiffness approaches infinity at the root. It is interesting to note that the shell model produces lower errors than the truss model for the half of the structure closer to the beam, but
the error increases beyond the halfway point. It is also interesting that both models have a sharp drop in error sizes at some point along the structure. However, this occurs near the root for the shell model, and near the tip for the truss model. Overall, the errors in displacement prediction for both models remain under 0.1% of the length of the element over the vast majority of the structure. Thus, the formulation for the centrifugal loading is verified.

![Figure 2.15: Nodal displacements of analytical, truss, and shell models due to centrifugal loading](image)

Verification of Gravity Loading

To verify the validity and accuracy of the gravity loading formulation, a similar test case is used as above. The difference is that the cross-sectional area of the beam is constant. Shell elements lie in the XY plane, with cross-sectional area $A = 1.0 \text{ m}^2$ and width $w = 1.0 \text{ m}$, which means that the thickness of each shell is $t = 1.0 \text{ m}$. Gravity loading is applied perpendicular to the shell faces, in the Z direction. The analytical solution for the vertical displacement of the beam can be written as:

$$v(r) = \frac{1}{EI} \left( \frac{\rho Ar^4}{24} - \frac{\rho ALr^3}{6} + \frac{\rho AL^2r^2}{4} \right), \quad (2.18)$$

where $I$ is the moment of inertia of the beam. A comparison of the analytical solution and TACS solution is given in Figure (2.17). The relative errors for this case are larger than the
centrifugal loading case, but are within reason. These errors are expected because the accuracy of the solution is much more dependent on factors such as the aspect ratios of the elements and their thicknesses.

Figure 2.16: Relative error in nodal displacements for the truss and shell models
Figure 2.17: Vertical displacements of analytical and shell models due to gravity loading
2.4.2 Problem Setup

As mentioned above, three examples are considered for the structural analysis: the NACA-based wing, the NREL Phase VI blade, and the NREL WindPACT blade. For all the examples, third-order shell elements are used, and the degrees of freedom at the root are clamped as the boundary conditions. Note that in all cases, the shear modulus is given by:

\[ G = \frac{E}{2(1 + \nu)} \]  

(2.19)

NACA Wing

The material thickness properties for the NACA wing is given in Table (2.4). Since this example does not attempt to simulate a real case, all the values are chosen for illustration purposes only.

<table>
<thead>
<tr>
<th>Young’s Modulus, ( E ) (GPa)</th>
<th>70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s Ratio, ( \nu )</td>
<td>0.3</td>
</tr>
<tr>
<td>Yield Stress, ( \sigma_{\text{Yield}} ) (MPa)</td>
<td>450</td>
</tr>
<tr>
<td>Constant Shell Thicknesses, ( t ) (m)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 2.4: Structural data for the NACA wing

NREL Blade

As emphasized previously, no accurate structural data is available for the NREL Phase VI Blade, so the structural geometric properties are guessed from Figure (3.9). The mechanical properties for the materials are obtained from Performance Composites Ltd. The setup of the structure is problematic because TACS does not currently allow for the layup of different materials, which are common in sandwich and composite structures of turbine blades, so only the material deemed to be most load-bearing is used in the setup. This is a reasonable assumption because the strength of the material used in the fore and aft sections are significantly stronger than that of the other layer. For the D-spar section, carbon fibre is used instead of E-glass, and for the rear section, unidirectional E-glass is used instead of aramid honeycomb. The thickness of the material is retained as the partial thickness of the particular material to obtain a conservative model, i.e., the thickness of the structure in the front is equal to the thickness of the carbon fibre. The thickness of the blade shell is approximated as linearly decreasing from 4.5 mm at the
CHAPTER 2. AEROSTRUCTURAL TOOLS

root to 3.0 mm at the tip, which is roughly 2% of the chord length. The thickness of the carbon fibre is assumed to be 25% of the shell thickness, and thickness of the E-glass is assumed to be 50% of the shell thickness. Properties of the materials used are shown in Table 2.5. For all structures generated by pyPSG, \( x \) is the local spanwise coordinate, and \( y \) is the local chordwise coordinate.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus in ( x ), ( E_{1C} )</td>
<td>135.0 GPa</td>
</tr>
<tr>
<td>Young’s modulus in ( y ), ( E_{2C} )</td>
<td>10.0 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio, ( \nu_C )</td>
<td>0.3</td>
</tr>
<tr>
<td>Tensile strength in ( x ), ( X_{TC} )</td>
<td>1500 MPa</td>
</tr>
<tr>
<td>Compressive strength in ( x ), ( X_{CC} )</td>
<td>1200 MPa</td>
</tr>
<tr>
<td>Tensile strength in ( y ), ( X_{TC} )</td>
<td>50 MPa</td>
</tr>
<tr>
<td>Compressive strength in ( y ), ( X_{CC} )</td>
<td>250 MPa</td>
</tr>
<tr>
<td>Shear strength, ( S_C )</td>
<td>70 MPa</td>
</tr>
</tbody>
</table>

Table 2.5: Mechanical properties of carbon fibre

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus in ( x ), ( E_{1U} ) (GPa)</td>
<td>40.0</td>
</tr>
<tr>
<td>Young’s Modulus in ( y ), ( E_{2U} ) (GPa)</td>
<td>8.0</td>
</tr>
<tr>
<td>Poisson’s Ratio, ( \nu_U )</td>
<td>0.25</td>
</tr>
<tr>
<td>Tensile Strength in ( x ), ( X_{TU} ) (MPa)</td>
<td>1000</td>
</tr>
<tr>
<td>Compressive Strength in ( x ), ( X_{CU} ) (MPa)</td>
<td>600</td>
</tr>
<tr>
<td>Tensile Strength in ( y ), ( Y_{TU} ) (MPa)</td>
<td>30</td>
</tr>
<tr>
<td>Compressive Strength in ( y ), ( Y_{CU} ) (MPa)</td>
<td>110</td>
</tr>
<tr>
<td>Shear Strength, ( S_U ) (MPa)</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 2.6: Mechanical properties of unidirectional E-glass

WindPACT Blade

The structural model of the WindPACT blade is created in a similar fashion as the NREL blade. Figure 2.18 shows the cross-sectional layout of the blade structure. All the structural data is extracted from Appendix A courtesy of Professor Crawford at the University of Victoria; certain geometric parameters are only an estimate of the actual value, but overall the data is
the most accurate that is possible to obtain. The material properties used are based on CDB340 fabric, a triaxial E-glass based fabric that is 50% glass content by weight, and has approximately 50% of the fibres in the 0° direction and 25% of the fibres in each of the 45° and −45° directions. The mechanical properties for unidirectional E-Glass fabric and can be found in Table (2.6). The blade structure is set up as a multi-layered shell, with fibre orientations as listed above. This means that while the material by definition is a unidirectional fabric, the structural layup is composed of a 50% thickness ply of unidirectional fabric and a 50% thickness ply of ±45° cross-weave fabric. Equation (2.20) gives the spanwise thickness distribution of the shell elements corresponding to the spar caps as a polynomial fit. Note that $x$ denotes the parametric location along the blade, rather than spatial location, and the thicknesses of the top and bottom spar caps are equal.

$$t = -0.887x^5 + 3.1163x^4 - 4.1286x^3 + 2.5385x^2 - 0.7515x + 0.12$$

![Figure 2.18: Cross-sectional layout of the WindPACT blade](image)

<table>
<thead>
<tr>
<th>Spar Cap Thickness</th>
<th>See Figure (2.19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top and Bottom Skin Thickness (m)</td>
<td>0.007</td>
</tr>
<tr>
<td>Shear Web Thickness (m)</td>
<td>0.007</td>
</tr>
<tr>
<td>Blade Tip Thickness (m)</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Table 2.7: Structural thicknesses for the WindPACT blade
Figure 2.19: Spanwise thickness distribution for the WindPACT blade sparcaps (see Appendix A)
Structural Layout

Figure (2.20) shows the inlaid structure of the NACA 0012 wing with the transparent aerodynamic mesh and shaded structural surface. Note that the structure is very different compared to the aerodynamic surface due to its simplicity. The number of spanwise and chordwise elements are constant throughout the wing, and the structure is a tapered plate. The top of Figure (2.21) shows the inlaid structure of the NREL blade in the same fashion, but the structural geometry is much more similar to the aerodynamic surface. In areas where the aerodynamic surface is covered by the structural surface, the mesh cannot be seen. Lastly, the bottom of Figure (2.21) shows the structure of the WindPACT blade in the same way. The aerodynamic mesh and structural surface match closely, so very little of the mesh is covered by the structural surface. The method of generating the aerodynamic meshes and structural meshes is described in the next chapter.

Figure 2.20: Inlaid structure for NACA wing with clear aerodynamic mesh and shaded structural surface
Chapter 2. Aerostructural Tools

2.5 Summary

In this chapter we discussed the various analysis tools used in this project. Ultimately, TriPan and pyTACS are chosen as the aerodynamic and structural solvers, respectively, due to performance advantages and mutual compatibility. It is possible, however, to substitute TriPan for a higher fidelity aerodynamic solver, such as SUmb or another CFD solver. As long as the aerodynamic solver provides the necessary outputs (pressure distribution and connectivity information) and has mesh warping capability, it can be coupled with pyTACS to perform an aerostructural analysis, as explained later.
Figure 2.21: Inlaid structure for NREL blade, top, and WPACT blade, bottom, with clear aerodynamic meshes and shaded structural surfaces
Chapter 3

Geometry and Mesh Generation

3.1 Introduction

In order to create the various types of meshes required by the aerodynamics and structural analyses, the basic geometry of the blade must be first created, and then manipulated. Several types of meshes and grids were generated throughout the project for varying purposes, including structured CGNS meshes for Euler CFD analysis and multiblock 3D surface meshes for spline surface definitions in pyPSG, mesh definition in TriPan, and structural definition in pyTACS.

The following describes the process to generate the various meshes in detail for the NREL Phase VI turbine blade; other test cases for this project follow the same procedure.

3.2 Baseline Geometry Generation

The initial geometry definition is a series of linear splines via a Python script to generate an asymmetric lifting surface using pyACDT’s Geometry module [27]. The input is divided into numerous segments that individually define a section of the blade that is linearly lofted to create a 3D shape. Although each segment is linear, we found that about 25 segments gives a reasonable initial approximation for the shape of the blade, considering that no exact geometry definition is known. For each segment, the critical input parameters are as follows:

- Planform area
- Taper
- Dihedral (or coning)
- Root and tip thickness
- Location of twist axis
- Span
CHAPTER 3. GEOMETRY AND MESH GENERATION

- Leading edge sweep
- Root and tip incidence
- Root and tip airfoil

For the circular root segments, only the size and position of the circular cross-section needs to be specified. Although sweep and dihedral are derived from aircraft wing design, they are important parameters in some recent blade designs, such as the curved planform, adaptive twist blade by Sandia National Laboratories. Along with the above segment parameters, pyACDT also allows the specification of the position and orientation of the entire body. Since only the turbine blade is modelled, this is important because it allows the offset of the blade from the origin, as seen in Figure 3.1.

![Figure 3.1: Linearized geometry of typical wind turbine blade generated by pyACDT](image-url)
CHAPTER 3. GEOMETRY AND MESH GENERATION

3.3 Geometry Smoothing

After the basic geometry is generated using pyACDT, it is further modified by pyPSG, which is an in-house geometry package that is capable of creating high-order 3D spline geometries, as well as manipulating the geometries and creating 3D structural models. Since the geometry generated by pyACDT is linearly interpolated and is not $C^1$ continuous, this initial definition is improved by using pyPSG to smooth out the linearity of the geometry. This phenomenon is particularly noticeable around the leading edge, where the curvature of the surface cross-section can be relatively high, and it becomes difficult for the linearly interpolated pyACDT model to place enough points in the leading edge region to properly capture the geometry. Strictly speaking, it is possible to skip this step and use the pyACDT geometry directly in ICEM CFD, but the differences can be significant, as shown in Figure (3.2): the improved mesh is rounded at the leading edge with smooth grid lines, compared to a sharp leading edge and angled grid lines for the original mesh.

3.4 Mesh Generation by ICEM CFD

After the conceptual geometries are generated and treated, they are transformed into meshes using the commercial package ICEM CFD. In general, after initially loading in the geometry definitions, further modifications to the geometry are necessary. These are all CAD–based modifications, however, and do not change the underlying blade shape. Examples of these changes include adding points to mark the CFD grid boundaries, projecting points and curves on the blade surface to mark edges of surface blocks, and creating a geometric surface for the tip of the blade.

3.4.1 Structural Surface Mesh

Once the geometry is completed, the creation of the meshes begins. As previously mentioned, several types of meshes need to be generated for various purposes. The most basic mesh is used by pyPSG to generate a surface definition for the creation of the structural model. This is a simple 3D surface mesh based on a multiblock topology that covers the entirety of the blade, except for the perpendicular end surface. Nodes are distributed evenly across the blade surface for the spline interpolation points to create a well-defined and smooth surface. An example of the pyPSG mesh and resultant geometry for the NREL blade is shown in Figure (3.3).
Figure 3.2: Comparison of basic mesh generated by pyACDT, above, and mesh smoothed by pyGeo, below
3.4.2 Panel Method Surface Mesh

In addition to the pyPSG mesh, another 3D surface mesh is required for the TriPan analysis. Although this is also a multiblock surface mesh, there are significant differences compared to the pyPSG mesh. The most immediately noticeable difference is that the TriPan mesh does not contain the root sections of the blade for the NREL case. This is due to the poor aerodynamic convergence properties of the cylindrical root section of the blade, which will be discussed more in detail in later sections. Another important difference is that the node spacings are not uniform. In the spanwise direction, the nodal spacings follow a bigeometric distribution to increase the node density at the root and the tip and improve the accuracy of the analysis. Otherwise, the procedures for generating the surface meshes are the same.
3.4.3 CFD Solid Mesh

Optionally, it is also possible to generate 3D volume grids that are required in CFD analyses. This process is significantly more elaborate because the concern is not only with the surface of the blade, but also the boundaries of the entire grid. Since the elements are 3D and much more numerous for a CFD grid than a panel code mesh, the distribution of nodes also becomes more troublesome. Not only does the nodal density need to increase around the perpendicular edges on the geometry, such as at the root or at the tip, it is also important to distribute the nodes well along parallel edges to avoid negative volume cells, a relatively common issue when generating meshes manually.

For the purposes of this project, the CGNS grids used for the Euler code are multiblock grids, so the grid topology also becomes a matter of interest. Specifically, the blocking around the blade tip is not easy because the blocks need to be hexahedral. The blocking scheme selected separates the perpendicular face of the blade tip into three separate blocks, such that the face is composed of three quadrilaterals, and six block faces lie around the curvature of the airfoil, as shown in Figure (3.5). Two edges lie along the leading and trailing edges, and the other four edges lie along the chord. As with the TriPan case, the nodal density near the leading edge is higher than that towards the trailing edge. In addition, it is more important to vary the cell sizes gradually in a roughly exponential fashion to increase the convergence rate for the CFD analysis.
Other than the blade surface, it is also important to treat the boundary of the overall grid. Since the flow is rotational, the grid boundaries need to be cylindrical, the axis of the cylinder being coincident with the axis of rotation. For a two-bladed turbine, the boundary is one half of the cylinder, while the boundary is a third of a cylinder for a three-bladed turbine. In addition, since only the outer section of the blade is analyzed, the inner section of the boundary is cylindrical as well, so that there are no fluid cells where the root of the blade would otherwise lie. Once all the surfaces are properly defined, the only step remaining is to specify the boundary conditions for each surface and to export the grid in the desired format, which in this case is CGNS.

Although ICEM CFD is a powerful software capable of various other tasks, such as automatically generating surface meshes or performing CFD analysis, these capabilities were not used in the current project, because the meshes and flow solutions need to be tailored to specific needs in the entire aerostructural optimization process, e.g., assignment of node indices and output of cell connectivity information.
Figure 3.6: Boundary geometry and meshing for the NREL Blade (blade surface in purple)
CHAPTER 3. GEOMETRY AND MESH GENERATION

3.5 Structural Layout Generation

After all the aerodynamic meshes are generated in ICEM CFD, the task to generate the structural model remains. Again, this is done in pyPSG: the uniform surface mesh previously generated in ICEM CFD is read in by pyLayout, a module in pyPSG, to create a structural mesh complete with skin, ribs, and spars using 3D shell elements.

Once the surface mesh is loaded by pyLayout, the first step in creating the structural mesh is to specify the edge indices for the entire trailing edge. This must be done manually by examining the output file in Tecplot. For the NREL blade shown in Figure (3.7), the trailing edge indices are 12, 14 and 16.

![Figure 3.7: Edge labels of NREL blade for structure generation](image)

Once the trailing edge is determined, the next step is to create an imaginary domain surface within the outer shell of the blade that specifies the boundaries of the rib and spar placements, as shown in Figure (3.8). Note that the domain lies much closer to the leading edge than the trailing edge. This is because the positions of the structural element edges are obtained by projecting rays at uniform angles around the leading and trailing edges of the domain. Given
the relatively high curvature of the blade surface around the leading edge, a domain far from the leading edge of the blade would result in poor structural geometry in that region. Once the domain surface is specified, pyLayout distributes structural shell elements over the surface of the blade. To create the elements that compose the ribs and spars, projections are made perpendicular to the domain surface; the projected surfaces in the spanwise direction compose the spars, and the projected surfaces in the chordwise direction compose the ribs.

Although turbine blades generally do not have ribs, the capability is retained for aircraft wing design, and the ribs are simply removed by the specification of a blanking array. Similarly, turbine blades typically only have one or two spars that only begin beyond the rounded root section, so extra spar elements also need to be removed. In this example, the blade is initially separated chordwise by three spars that run along the leading edge, center, and trailing edge of the domain, creating four zones along the blade. pyLayout allows the specification of number of chordwise elements for each of these zones; in this case, there are 2 chordwise elements on the leading edge zone, four elements on the leading half of the domain, and three elements each on the trailing half of the domain and the trailing edge zone.

As Figure (3.9) shows, the real NREL blade has a single spar running along approximately the centre of the chord. To mimic this, only the central spar in the pyLayout model is kept, and the sections of the spar at the cylindrical root section are left out. The ribs are not included, except the elements at the tip of the root, since the real blade structure does not have any ribs. This is intended to simulate the closed structure of the real blade, although the perpendicular
tip section of the NREL blade is likely to be relatively weak and not load-bearing. However, since detailed structural data on the NREL blade is not known, and certain restrictions exist for the creation of the structural model, likeness between the structural model and actual blade is highly limited, so the best effort is only a guess of the real structure. The final structural model is shown in Figure 3.10. The apparently coarse mesh shows the structure’s high order elements, while the apparently fine mesh shows the connectivity of the inner nodes of the high order elements as well.

In summary, three separate meshes are generated: a surface mesh for TriPan, a 3D multi-block grid for SUmb, and a structural mesh for pyTACS. Once the meshes are satisfactory, the aerodynamic and structural solvers are coupled to perform the aerostructural analysis, described in the next chapter.
Figure 3.10: Finalized structural model of the NREL blade: mesh of the shell elements, top, and mesh of the shell elements with internal nodes in exploded view, bottom
Chapter 4

Aerostructural Results and Discussion

In this chapter we examine the procedure and results of the aerostructural analysis for each of the three cases, and discuss the results in detail.

4.1 Aerostructural Analysis Setup

4.1.1 Displacement and Load Transfer

The structures examined here are loaded by aerodynamic, centrifugal, and gravity forces. The implementation of centrifugal and gravity loads was discussed in Section 2.4. In order to transfer the aerodynamic loads to the structure, and the displacements back to the aerodynamic mesh, TACS uses a system of rigid links that directly connects the two meshes, as developed by Brown [36]. In a similar fashion, Martins et al. used a systematic scheme to pass aerodynamic loads and displacements using an outer mould line (OML), a parametric surface representation of the aircraft geometry [37]. Since the structural mesh and aerodynamic mesh contain elements of different sizes and shapes, it is generally impossible to obtain two meshes that are coincident at every point, so the use of the rigid links allows the transfers to occur between any set of aerodynamic and structural geometries. These links originate from the nodes on the aerodynamic mesh, and are projected perpendicularly to the structural surface. Figures (4.1) and (4.2) show the rigid links for the NACA wing and NREL blade, respectively; they are zoomed in at the leading edge of the structural tip to show the relatively short links. Additionally, Figures (4.3) and (4.4) show the links over the entire WindPACT blade and the tip of the blade, respectively.
Note that the links only become relatively long at the tip surface due to the lack of structural elements in those regions. The process of displacement and load transfer, and the general aerostructural analysis, is explained here.

![Figure 4.1: Rigid links for the NACA wing: the aerodynamic mesh in black, the structural surface in grey, and the rigid links in red](image)

4.1.2 Solution Procedure

Once the TriPan and pyTACS solvers are in place, the two solvers are combined as an aerostructural solver, which performs an iterative process to solve for the coupled fluid-structure interaction. The iterative solution always begins by calling the aerodynamic solver to obtain an initial aerodynamic load; the next step in the iteration occurs when the aerostructural object passes the loads to the structural solver to obtain the structural displacements caused by the aerodynamic loading. After the structural solution has converged, the displacements are passed to the aerodynamic solver to obtain new loads, which are subsequently passed to the structural solver again. This iterative process occurs until a convergence criteria has been met, which requires the relative residuals of both aerodynamic and structural solvers to fall below a specified value, e.g., $10^{-9}$. The process is illustrated in Figure (4.5). The iterations can be performed by either the Gauss–Seidel, block-Jacobi, or Newton–Krylov method [6]. Figure (4.6) shows the solution times and relative speedup of the various methods for a blended wing-body case [6]. Although the Approximate Newton–Krylov method is superior in terms of solution time, the advantage
Figure 4.2: Rigid links for the NREL blade: the aerodynamic mesh in black, the structural surface omitted for clarity, and the rigid links in red

Figure 4.3: Rigid links for the WindPACT blade
diminishes for a smaller number of processors. In addition, the Gauss-Seidel method is simpler and more robust in terms of setting up solver parameters, so this method is chosen.

4.2 Aerostructural Analysis Results

4.2.1 NACA Wing

The aerostructural results for the NACA wing are shown in Figure (4.7). In the figure, $k$ denotes the inverse of the load-to-fail factor; the inverse is used for the contour plot because $k$ lies in the interval $[0, 1]$, rather than $[1, \infty]$. In other words, $k$ is defined as $k = \frac{\text{load}}{\text{failure load}}$, and is shown as a contour on the left side of the wing. The right side of the wing shows the $C_p$ distribution over the aerodynamic surface, with an outline of the undisplaced wingtip, and the mesh of the wake.

4.2.2 NREL Blade

The aerostructural results for the NREL Phase VI blade are shown in Figure (4.8). As in the previous case, the contour over the structural surface shows the inverse of the load-to-fail factor, $k$, and the aerodynamic surface shows the contour of the $C_p$ distribution. The outline of the
Figure 4.5: Iterative aerostructural process: loads and displacements are passed back and forth between aerodynamic and structural solvers to achieve convergence.

Figure 4.6: Comparison of aerostructural solution times and relative speedup between Jacobi, Newton–Krylov, Gauss–Seidel, and Approximate Newton Krylov methods for blended wing-body example [6].
Figure 4.7: Aerostructural plot for the NACA wing: the left side of the wing shows the structural mesh with the inverse of the load-to-fail factor; the right side of the wing shows the $C_p$ distribution over the aerodynamic surface, with the wake mesh in grey and undeformed wingtip outline.

undisplaced blade is shown as well, along with the wake mesh. Again we note that the root of the blade is not modelled in the aerodynamic solver to improve convergence. A convergence plot for this case is shown in Figure (4.9). The test case was run on a single processor; not including setup time, the aerostructural solution required approximately 200 s.
CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION

Figure 4.8: Aerostructural plot for the NREL blade: exploded surfaces denote the structural mesh with the inverse load-to-fail factor contour; unexploded surface denotes the aerodynamic surface with $C_p$ distribution, with undisplaced tip and wake mesh.

Figure 4.9: Convergence plot for the NREL blade aerostructural test case run on a single processor.
4.2.3 WindPACT Blade

The aerostructural results for the WindPACT blade are shown in Figures (4.10) and (4.11). Figure (4.10) shows the aerostructural results of the blade in a similar fashion to the previous case, while Figure (4.11) shows the details of the results at the blade tip. The convergence plot for this case is shown in Figure (4.9). The test case was also run on a single processor, and the aerostructural solution required approximately 200 s to complete.

Figure 4.10: Aerostructural plot for the WindPACT blade: exploded surfaces denote the structural mesh with the inverse load-to-fail factor contour; unexploded surface denotes the aerodynamic surface with $C_p$ distribution, with undisplaced tip and wake mesh

4.3 Discussion

Here we discuss the aerostructural analysis results of the three cases in detail.

4.3.1 NACA Wing

The aerostructural plot (Figure (4.7)) shows the result for the wing test case. The structure deflections are easily noticeable: Figure (4.13) shows the maximum deflection is nearly 200 mm
Figure 4.11: Details at the tip for the WindPACT blade

Figure 4.12: Convergence plot for the WindPACT blade case run on a single processor
CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION

at the tip of a 4 m semispan wing. The twist is not as significant, however: Figure 4.14 shows that the maximum twist is less than 1°.

Next we examine the load distribution for the NACA wing. Figure 4.7 shows that a significant portion of the structure is loaded beyond failure. This is intended during the setup of the structure for demonstration purposes. Also, Figure 4.17 shows that the load distribution at the tip of the leading edge is higher than the surrounding regions, albeit well under the failure load. Recalling Figure 4.1, we can see that a large number of rigid links are connected to the single structural node at the edge of the plate, so a large portion of the aerodynamic load is transferred to this point, leading to significant load concentrations. The same situation occurs at the other leading edge nodes, but to a lesser degree. Thus it must be concluded that although the rigid links formulation for aerostructural coupling is not stringent on geometric coincidence of the aerodynamic and structural meshes during the aerostructural setup, it is nonetheless important to pay diligence in the meshing process to obtain useful and accurate aerostructural solutions. In comparison, in lower fidelity aerostructural analysis, e.g. where the structure may be modelled as a beam, this kind of problem would generally not occur, due to the simplicity of the model.
Figure 4.14: Spanwise rotational displacement in degrees for the NACA wing

Figure 4.15: High load concentration at the NACA wing tip
4.3.2 NREL Blade

In contrast to the previous case, the solution for the NREL blade is much more complex. Figure (4.16) plots the vertical deflection of the top skin along the spar, and shows a noticeable, albeit small, tip deflection. Further, Figure (4.16) shows that the aerodynamic shape of the blade is significantly changed, as certain regions of the structure has a rotational deflection as high as 4°. This confirms the importance of an aerostructural method: as the aerodynamic loading twists the structure, the aerodynamic behaviour of the blade is changed, requiring recalculation. This phenomenon appears particularly significant near the outer section of the blade, where aerodynamic performance is most critical.

![Graph](image1.png)

Figure 4.16: Spanwise displacements for the NREL blade: vertical displacement, left, and rotational displacement in degrees, right

In contrast to the NACA wing case, the loads over the majority of the NREL blade is negligible, so only the root section is shown in Figure (4.17). There are several areas of high load concentrations, and they are often near geometric discontinuities, such as where the spar meets the aerodynamic surface to form a right angle. The maximum loads for this solution are far from reaching the failure load. Here we recall that the structure is not completely meshed at the blade tip, and the aerodynamic mesh is neglected at the root. However, this does not seem to have a significant effect on the aerostructural results or load distributions in the same
way that geometric differences had in the NACA wing case, as there are no significant load concentrations in those regions.

![Stress distribution at the NREL blade root](image)

**Figure 4.17: Stress distribution at the NREL blade root**

It is important to note here that while the aerostructural results appear to be well-behaved, and the convergence is stable, a slight change in the structural parameters could drastically change the result. For example, a reduction in the element thickness by 10–20% causes the aerostructural solution to become unstable and divergent. However, changes in the flow condition do not affect the solution as strongly. As Figure (4.18) shows, at a freestream windspeed of 15 m/s, the increase in blade tip deflection is limited in comparison to the standard conditions of 10 m/s.

To compare the two conditions more closely, the spanwise thrust and torque for the 10 m/s and 15 m/s cases are shown in Figure (4.19). Note that these values are not in the units N and N·m; instead, they are the forces in the Z and −X directions, respectively, divided by the dynamic pressure. This is chosen because the actual forces at the blade tip would dwarf the forces at the root, due to much faster speed of flow at the tip. This should be kept in mind, as Figure (4.19) may give the first impression that aerodynamic loading is highest near the root. Comparing the two cases, we see that the torque generated at 15 m/s is significantly higher than that generated at 10 m/s, by nearly a factor of 2, indicating that much more power is captured...
CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION

Figure 4.18: Aerostructural solution of NREL blade at 15 m/s windspeed

at this windspeed. The maximum value of the thrust at 15 m/s is slightly higher for most of the span, explaining the higher tip displacement.

4.3.3 WindPACT Blade

We now consider the WindPACT blade case described in Section 4.2.3. Upon examination of Figure (4.11), it is immediately noticeable that the structural deflections here are significantly greater than that from the previous cases. In fact, Figure (4.20) shows that the tip deflection is close to 10% of the total blade length. Figure (4.20) also shows that the rotation over most of the blade is not significant. However, it is fairly high at one point on the trailing edge, and at the tip (Figure [4.21]). This may be due to the fact that the material is quite thin in front of and behind the spar caps, and the blade surface is deforming under pressure. Figure (4.22) shows that the structure rotates significantly forward (parallel to the axis of rotation) under loading, even though the direction of drag might lead one to believe the opposite. This leads to the conclusion that the rotation is caused in such a way that the upward bending of the structure also causes forward bending.

The thrust and torque forces along the length of the blade are shown in Figure (4.23).
Comparing Figure (4.23) to Figure (4.19), we see that the inclusion of the cylindrical root section of the WindPACT blade actually produces negative forces in torque at the root, as expected. This is quickly made up for, however, as the blade transitions from the cylindrical root to the airfoil. Note that the thrust forces are higher than the torque forces in this case, in contrast to the NREL blade results.

Examining the load distribution in Figure (4.24), we see that the highest loads are located on the spars. Similar to the NREL blade case, some of the load concentration are found at geometric discontinuities, such as the root of the spars, or at the joints of spars and aerodynamic surfaces. This suggests that the structures in these regions are underdesigned. This is a common phenomenon in structural design, as corners are often reinforced using ribs. The blade tip is also not completely meshed structurally, but this again does not have significant effect on the result. Compared to the yield stress of the material, the calculated stresses are significantly lower. This may be reasonable, as Griffin [5] notes that one of the two primary load cases governing the structural design is a 70 m/s gust with ±15° variation in direction, and the blade is fully feathered (parallel to freestream). This is a much more structurally demanding load than the normal operating cases we examine here.

Figure 4.19: Comparison of the thrust and torque forces for the NREL blade at 10 m/s and 15 m/s windspeed

CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION
CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION

![Graphs showing vertical displacement and rotational displacement.]

Figure 4.20: Spanwise displacements for the WindPACT blade: vertical displacement, left, and rotational displacement in degrees, right

Next we examine the aerodynamic results of the converged solution. Figure 4.25 shows the sectional $C_p$ values at select stations along the span of the blade. Both the initial and converged solutions are shown: the former in red, and the latter in blue. In general, the two solutions are similar but clearly different. Interestingly, for both solutions, a pressure spike exists just behind the leading edge towards the root section, but the spike gradually diminishes towards the tip of the blade. Otherwise, the $C_p$ plots are similar to those shown in Figures 2.12 and 2.13. The problem of discontinuous trailing edge values still exist, but is relatively small in this case. This suggests that the aerodynamic solution captures the trends well and provides an useful aerostructural analysis. The fact that the converged solution exhibits greater differences in pressure between the top and bottom surfaces is intuitive, since higher structural deflections must be caused by higher aerodynamic loading. This also implies that the effective angle of attack at each point along the blade is higher due to structural twisting, assuming that the airfoil shape is not changed significantly.

4.4 Impact of Centrifugal and Gravity Loading

Lastly, we examine the effect of inertial (centrifugal and gravity) forces on the aerostructural solution of the turbine blades. For both cases, the gravity load is set in the chordwise direction
CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION

Figure 4.21: Spanwise rotational displacement at the WindPACT blade tip

Figure 4.22: Axial rotational displacement in degrees for the WindPACT blade
Figure 4.23: Spanwise thrust and torque curves for the WindPACT blade (parallel to $\hat{x}$). This simulates the largest bending moment due to gravity during normal operations. Figure (4.26) shows the original aerostructural solution for the NREL blade with inertial loading on top, and the solution without inertial loading on bottom. Similarly, Figure (4.28) shows the WindPACT blade solution with inertial loading on top, and the solution without inertial loading on bottom.

In both cases, not including inertial loading in the aerostructural analyses significantly reduces the structural loading, as one may expect. Changes in vertical and rotational displacements are also significant for both cases, as shown in Figures (4.27) and (4.29). Since both centrifugal force and bending moment due to gravity are both directly related to $r$, it is reasonable to expect that this effect is more significant for larger blades. Indeed, the relative differences in displacements are higher for the 35 m WindPACT blade, compared to the 5.5 m NREL blade.
Figure 4.24: Stress distribution detail for the WindPACT blade at the root. Higher loads are concentrated at geometric discontinuities, such as the base of the spar and where the spar bends.
CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION

Figure 4.25: Section $C_p$ distributions for the WindPACT blade: initial solution shown in red and converged solution shown in blue

Figure 4.26: Comparison of aerostructural results for the NREL blade with inertial loading, top, and without inertial loading, bottom
CHAPTER 4. AEROSTRUCTURAL RESULTS AND DISCUSSION

Figure 4.27: Spanwise displacements comparison for the NREL blade between solutions with inertial loading and without: vertical displacement, left, and rotational displacement in degrees, right.

Figure 4.28: Comparison of aerostructural results for the NREL blade with inertial loading, top, and without inertial loading, bottom.
Figure 4.29: Spanwise displacements comparison for the WindPACT blade between solutions with inertial loading and without: vertical displacement, left, and rotational displacement, right.
Chapter 5

Conclusion

5.1 Limitations in Aerostructural Analysis

As with any modelling method, there are limitations and assumptions made for the current aerostructural analysis. It is important to examine these limitations in order to assess any potential sources of error in the analysis results.

As mentioned in previous sections, inaccuracies exist in the aerodynamic analysis. More specifically, the panel method used here is incapable of predicting stall or modelling other viscous effects. The properties of panel methods are well-documented, so they are not discussed here. In addition to these limitations in the aerodynamic solver, it has also been discussed that the analysis method used is steady, which assumes a predefined wake shape, rather than propagating the wake as in the case of the unsteady analysis. Further, the analysis does not take into account the flow interactions with the turbine tower, or wakes shed from other turbines. These interactions are assumed to be negligible in the case of a single turbine in the upwind configuration. Thus, the focus here is to examine the inaccuracies in the structural portion of the aerostructural analysis.

The most important limitation in the structural analysis is in defining geometric properties in a structure. For example, the NREL blade and WindPACT blade are both composed of sandwich structures in some regions. The D-spar of the NREL blade is encased in a shell of paramid honeycomb [1], while the entire structure of the WindPACT blade is a sandwich made from gel coat, random matrix, triaxial fabric, balsa, and sparcap mixture, in different proportions over the blade. Unfortunately, the structural solver currently does not allow the specification of multiple plies of different materials in a sandwich configuration. These differences between
the modelled layup and the real layup of materials probably cause significant changes in the bend-twist coupling of the general structure. As we have already seen, bend-twist coupling may greatly affect the aerostructural solution, because it in turn changes the aerodynamics of the problem. In addition, when multiple plies of different materials are used, design and manufacture issues may arise due to the complexity of the interactions between each layer [38], requiring additional considerations. At the same time, the failure modes in complex composite structures exhibit behaviours not normally seen in isotropic materials.

5.2 Future Work

Given the above limitations in the aerostructural analysis, considerable work lies ahead to improve the accuracy of the analysis results. First, the substitution of a higher fidelity aerodynamic solver may allow better analysis and design for turbine blades operating closer to the stall range. Several authors have explored the use of a flatback airfoil in turbine design to alleviate structural loads while maintaining aerodynamic performance (Chao, van Dam, and Berg [7], Berg and Barone [8], Paquette and Veers [39]). The tunnel view of a flatback turbine blade is shown in Figure (5.1). As Figure (5.2) shows, however, significant vortex shedding occurs for such designs. Consequently, a much higher fidelity aerodynamic solver would be required, as even an Euler code would not be able to predict such time-dependant viscous behaviour.

![Figure 5.1: Tunnel view for a baseline rotor blade, left, and flatback rotor blade, right](image_url)
CHAPTER 5. CONCLUSION

Figure 5.2: CFD simulation of vortex shedding for the flatback airfoil [8]

Regarding the structural solution, improvements could be made in material and geometric definition of the blade structure, to better predict the limiting load cases. In fact, turbine blade failure composes a significant portion of total wind turbine accidents: from the 257 accidents listed since 2000, 74 were reported as blade failures [10]. Further, aerostructural analysis may be performed for turbine blades with curved planforms, such as that investigated by Sandia National Laboratories [9]. The curved planform has aerodynamic advantages similar to that of a swept wing, but also inherits manufacturing and structural difficulties, such as the treatment of off axis composite fabrics and fibre endings at the curved leading and trailing edges. Additionally, the curvature of the structure highlights the importance of the gravity and centrifugal loading, which may be significantly higher in such a blade.

Figure 5.3: Example of turbine blade with curved planform [9]

From an academic point of view, potential future work includes the generation of gradient and adjoint information by aerodynamic and structural solvers, eventually leading to the multidisciplinary design optimization of turbine blades. More importantly, the aerostructural framework fits well within the multidisciplinary design optimization (MDO) framework. Despite
the high computational cost, the relatively high accuracy of the analysis for the aerostructural MDO may potentially yield tremendous improvements over existing designs.
Appendix A

WindPACT Blade Structural Data
### WindPACT Blade Data Sheet courtesy of Prof. Curran Crawford

#### Legend
- **Interpolation**
- **Guessing**
- Used in Model

<table>
<thead>
<tr>
<th>Airfoil</th>
<th>Circular</th>
<th>Circular</th>
<th>Interp.</th>
<th>Circular</th>
<th>Circular</th>
<th>Circular</th>
<th>Circular</th>
<th>Circular</th>
<th>Circular</th>
<th>Circular</th>
<th>Circular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade</td>
<td>35.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 1: Geometric Data

<table>
<thead>
<tr>
<th>Staion (m)</th>
<th>0 (root base)</th>
<th>5%</th>
<th>7%</th>
<th>9%</th>
<th>15%</th>
<th>24.5%</th>
<th>31.5%</th>
<th>39.25%</th>
<th>Blade Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from root (m)</td>
<td>0.00</td>
<td>0.70</td>
<td>7.00</td>
<td>15.75</td>
<td>24.50</td>
<td>31.50</td>
<td>39.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 2: Chord (m)

<table>
<thead>
<tr>
<th>Staion (m)</th>
<th>1.700</th>
<th>1.700</th>
<th>1.700</th>
<th>2.000</th>
<th>2.100</th>
<th>3.150</th>
<th>4.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interp. (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chord (m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Table 3: Twist (deg)

<table>
<thead>
<tr>
<th>Staion (m)</th>
<th>10.0</th>
<th>5.0</th>
<th>0.0</th>
<th>0.0</th>
<th>0.0</th>
<th>0.0</th>
<th>0.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airfoil thickness (%)</td>
<td></td>
<td>22%</td>
<td>21%</td>
<td>16%</td>
<td>16%</td>
<td>16%</td>
<td>16%</td>
</tr>
</tbody>
</table>

#### Table 4: Blade shell layer variable thickness

<table>
<thead>
<tr>
<th>Thickness</th>
<th>4 / 8 15%</th>
<th>4 / 15 50%</th>
<th>4 / 50 - 85%</th>
<th>85-100%</th>
<th>4 layer 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade</td>
<td>0.5% chord</td>
<td>2% chord</td>
<td>1% chord</td>
<td>assuming the same properties as an contiguous material</td>
<td></td>
</tr>
<tr>
<td>Spine cap</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Cap</td>
<td>37.6</td>
<td>238</td>
<td>18.0</td>
<td>0.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Skin</td>
<td>220</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

#### Table 5: Propellor shell thickness

<table>
<thead>
<tr>
<th>Thickness</th>
<th>4 / 8 15%</th>
<th>4 / 15 50%</th>
<th>4 / 50 - 85%</th>
<th>85-100%</th>
<th>4 layer 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade</td>
<td>0.5% chord</td>
<td>2% chord</td>
<td>1% chord</td>
<td>assuming the same properties as an contiguous material</td>
<td></td>
</tr>
<tr>
<td>Spine cap</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Coat</td>
<td>37.6</td>
<td>238</td>
<td>18.0</td>
<td>0.2</td>
<td>7.6</td>
</tr>
<tr>
<td>Skin</td>
<td>220</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

#### Table 6: Gel coat (mm)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>4 / 8 15%</th>
<th>4 / 15 50%</th>
<th>4 / 50 - 85%</th>
<th>85-100%</th>
<th>4 layer 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top layer</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

#### Table 7: Random mat

<table>
<thead>
<tr>
<th>Thickness</th>
<th>4 / 8 15%</th>
<th>4 / 15 50%</th>
<th>4 / 50 - 85%</th>
<th>85-100%</th>
<th>4 layer 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top layer</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

#### Table 8: Woven fabric (C083410)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>4 / 8 15%</th>
<th>4 / 15 50%</th>
<th>4 / 50 - 85%</th>
<th>85-100%</th>
<th>4 layer 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top layer</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

#### Table 9: Woven fabric (C083410)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>4 / 8 15%</th>
<th>4 / 15 50%</th>
<th>4 / 50 - 85%</th>
<th>85-100%</th>
<th>4 layer 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top layer</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Blade shell thickness</td>
<td>4/55-8</td>
<td>4/55-85</td>
<td>Trailing edge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------</td>
<td>---------</td>
<td>--------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Leading edge</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glue coat (mm)</td>
<td>0.510</td>
<td>0.380</td>
<td>0.100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Random mat</td>
<td>0.380</td>
<td>0.380</td>
<td>0.090</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Random mat (CDB340)</td>
<td>0.380</td>
<td>0.380</td>
<td>0.090</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balsa core</td>
<td>8.500</td>
<td>4.400</td>
<td>2.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balsa [mm]</td>
<td>0.890</td>
<td>0.890</td>
<td>0.900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balsa [mm]</td>
<td>0.890</td>
<td>0.890</td>
<td>0.900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balsa [mm]</td>
<td>0.890</td>
<td>0.890</td>
<td>0.900</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Neutral</strong></td>
<td>28.75</td>
<td>14.00</td>
<td>6.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shear web variable thickness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balsa core</td>
<td>14.00</td>
<td>7.00</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| 4/0-15%               |         |         |              |
| Glue coat (mm)        | 0.380   | 0.380   | 0.090        |
| Random mat           | 0.380   | 0.380   | 0.090        |
| Random mat (CDB340)  | 0.380   | 0.380   | 0.090        |
| Balsa core            | 8.500   | 4.400   | 2.000        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| **Neutral**           | 28.75   | 14.00   | 6.50         |

| 4/15-50%              |         |         |              |
| Glue coat (mm)        | 0.380   | 0.380   | 0.090        |
| Random mat           | 0.380   | 0.380   | 0.090        |
| Random mat (CDB340)  | 0.380   | 0.380   | 0.090        |
| Balsa core            | 8.500   | 4.400   | 2.000        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| **Neutral**           | 28.75   | 14.00   | 6.50         |

| 4/50-85%              |         |         |              |
| Glue coat (mm)        | 0.380   | 0.380   | 0.090        |
| Random mat           | 0.380   | 0.380   | 0.090        |
| Random mat (CDB340)  | 0.380   | 0.380   | 0.090        |
| Balsa core            | 8.500   | 4.400   | 2.000        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| Balsa [mm]            | 0.890   | 0.890   | 0.900        |
| **Neutral**           | 28.75   | 14.00   | 6.50         |

<table>
<thead>
<tr>
<th>Shear web variable thickness</th>
<th>4% chord</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Balsa core</td>
<td>14.00</td>
<td></td>
</tr>
<tr>
<td>Balsa core (mm)</td>
<td>0.510</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal Shear web</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Balsa core</td>
<td>0.890</td>
<td>0.890</td>
<td>0.900</td>
</tr>
<tr>
<td>Balsa [mm]</td>
<td>0.890</td>
<td>0.890</td>
<td>0.900</td>
</tr>
<tr>
<td>Balsa [mm]</td>
<td>0.890</td>
<td>0.890</td>
<td>0.900</td>
</tr>
<tr>
<td><strong>Neutral</strong></td>
<td>28.75</td>
<td>14.00</td>
<td>6.50</td>
</tr>
</tbody>
</table>
### AeroDyn Data

*File: F_DLC12_10_Ad.ipt*

|-------|----------|-------|----------|----------|-------|-----------|-----------|-------|-----------|-----------|-------|-----------|-----------|-------|-----------|


### Parametric Spanwise Location

<table>
<thead>
<tr>
<th>Location</th>
<th>0</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
<th>0.95</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness in mm</td>
<td>87.67</td>
<td>142.67</td>
<td>197.67</td>
<td>232.42</td>
<td>257.17</td>
<td>266.92</td>
</tr>
<tr>
<td></td>
<td>0.12</td>
<td>0.0375732</td>
<td>0.0296168</td>
<td>0.01825875</td>
<td>0.0091964</td>
<td>0.00763</td>
</tr>
</tbody>
</table>

![Graph 1: Twist vs. Spanwise Location](image1)

![Graph 2: Chord vs. Spanwise Location](image2)

Figure 4. Arrangement of baseline structural model

Figure 2. Typical blade planform
References


REFERENCES


