Multi Body Approach to Dynamical System:

The Case of Wind Turbine

By

Mohamad Bakhit Aiman Bin Harun

19466

Dissertation submitted in partial fulfillment of

the requirement for the

Bachelor of Engineering (Hons)

(Civil)

SEPTEMBER 2017

Universiti Teknologi PETRONAS,

32610, Seri Iskandar,

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Multibody Approach To Dynamical System: The Case Of Wind Turbine

By

Mohamad Bakhit Aiman Bin Harun

19466

A project dissertation to the

Civil Engineering Programme

Universiti Teknologi PETRONAS

In partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (hons)

(CIVIL)

Approved by,

____

(AP DR INDRA SATI HAMONANGAN HARAHAP)

UNIVERSITI TEKNOLOGI PETRONAS

SERI ISKANDAR, PERAK

September 2017

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgments, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMAD BAKHIT AIMAN BIN HARUN

ABSTRACT

This study focuses on the development and analysis of foundation of a wind turbine using multibody approaches as design method. By using multibody system, the model is divided into three main bodies which are the blade, tower, and the foundation. The connection between these bodies will describe the motions of the wind turbine when dynamical loads are applied to the blade. Modeling using fixed tower omitting the effect of the foundation due to the pitching and yawing motions. One objective is to simulate the wind turbine dynamical deformations thus see the effect on the foundation. For this project, MATLAB and Simulink is used to model and simulate the effect of the foundation by applied dynamic forces through the streamtubes of the blade after it was divided into several elements using Blade Element Momentum Theory. The effect on the foundation is then determined by performing parametric study based on the wind speed, surface area of pile, and different length of pile foundation. The effect on the foundation is then analyze by the displacement of the pile occur under lateral load due to the movement of the tower.

ACKNOWLEDGEMENT

All praises to God the Almighty which always guide me and give me strength to complete my Final Year Project (FYP) in Universiti Teknologi PETRONAS starting from May 2017 to Disember 2017.

I would like to express my gratitude and sincere thanks to my respectable supervisor, Dr. Indra Sati Hamonangan Harahap for his guidance and supervision along the way for this 8 months. Under his supervision, I gained a lot of experiences and knowledge as a student and a learner. With all his support and encouragement, I got the chances to increase my knowledge in programming field.

Finally, I would like to express my gratitude to my parents, family and friends that always be with me in ups and down. They always give me positive support in which develop myself to become more persevere and mature. Without the commitment and support from all parties that involved directly or indirectly, it is impossible for me to complete the project successfully.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1. Background of Study

Wind power is a fast growing form of alternative energy and has a potential to make an impact on community. Today, wind power looked as the high prospect in producing renewable energy to replace the conventional energy which mainly uses oil and gas. In addition, as the oil prices currently drop and wind energy has the prospective in replacing the consumption of oil to produce a sustainable and clean energy. Since the era of easy oil has ended, the energy demand is expected to increase in 2040. Wind turbines are manufactured in a wide range of vertical and horizontal axis types. The smallest wind turbines are used for applications such as battery charging for auxiliary power for boats or to power traffic warning signs. Slightly larger turbines can be used for making contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. An array of large wind turbines, also known as wind farms are becoming an increasingly important source of intermittent renewable energy and are used by many countries as part of a strategy to reduce their reliance on fossil fuels. Nowadays, the developments of wind turbines have increasing rapidly in term of their sizes and performance. The tallest onshore wind turbine was recorded is 230m and a hub height of 164m was installed in July 2016 by one of the wind turbine manufacturer, Nordex SE. Thus, there are such methods were used to design the structural of the wind turbine such as Finite Element Analysis and Multibody Method. However, these two methods have their advantages and disadvantages to be used in the design procedure of the wind turbine. In the design basis of a wind turbine, there are several factors affecting the structure such as environmental conditions, operational conditions, and temporary conditions. Hence, the load cases are need to be specified for each conditions of the wind turbine whether it is in normal operation, extreme external conditions or during transportation, installation, and maintenance situations. Therefore, design as fixed tower allows the structure undergoes resonance effects that cause vibrations and deflection will occur in between the distance of blade and tower. To avoid resonance the stiffness of the components need to be considered and also the soil-structure interaction. The eigenfrequency of the system between blade, tower, foundation, and soil shall not be in the range of the variable frequencies. To ensure this requirement a minimum stiffness of foundation and soil is necessary. The foundation of a wind turbine must be strong enough to withstand the lateral forces subjected to the wind turbine tower. For this project, MATLAB and Simulink software is used to model the structure of the wind turbine and therefore predict and evaluate the effect on the foundation when the structure of the wind turbine was affected to the dynamic forces.

1.2. Problem Statements

Modeling using fixed tower omitting the effect of foundation. The effect is significant contributing to the dynamic resistance of the wind turbine when it is exceeding the operational limits. The dynamic forces that acting on the blades has causes the strength of the foundation reduces over time. Early work by (Currie, M., Saafi, M., Tachtatzis, C., & Quail, F. 2015) was concerned with “ the effect of fatigue on the foundation at the section level produced a change in stress distribution”. However, to get the satisfactory analysis on the displacement of the foundation, the overall analysis and factors need to be considered.

1.3. Objectives

This FYP aims:

1. To simulate the wind turbine dynamical deformation.
2. To study the effect of wind load on the pile foundation for onshore wind turbine structure.

1.4. Scope of Study

The scope of the study covers for this project is constructing the wind turbine model using MATLAB and Simulink software. Once the wind turbine model is created, the wind loads are applied to the substructures which are the blades using Blade Element Momentum (BEM) Theory. Before the wind loads are applied to the blades, the blades will be divided into several elements through the concentric annular stream tubes of the blade. This study also uses some governing equations to describe the equations of motion from Blade Element Momentum Theory (BEM) and derivation of equations for the power output. In a common exercise, to produce a better outcome in terms of the variations of wind speed, chord and twist along a blade, the number of stream tubes should be large enough. The effect on the foundation of the wind turbine is then determined by different wind speeds are applied to the blades thus causes the displacement of the fixed tower due to the pitching and yawing motions. The analyses will emphasis on the pile foundation of the onshore wind turbine with different length of pile and variations of wind speed.

CHAPTER 2

THEORY/LITERATURE REVIEW

2.1. Multibody Systems

Multibody system consists of interconnected bodies that can be rigid or flexible. The bodies may have translational and rotational displacements. Furthermore, the bodies are connected by force and joint elements that describe their dynamics and kinematic constraints. In multibody system, is basically the study of the dynamic behavior of interconnected bodies that led to a large number of important multibody formalisms in the field of mechanics. The simplest bodies or elements of a multibody system were preserved by Newton (free particle) and Euler (rigid body). Basically, the motion of bodies is described by their kinematic behavior. The dynamic behavior results from the equilibrium of applied forces and the rate of change of momentum. Nowadays, the term multibody system is related to a large number of engineering fields of research, especially in robotics and vehicle dynamics. As an important feature, multibody system formalisms usually offer an algorithmic, computer-aided way to model, analyze, simulate and optimize the arbitrary motion of possibly thousands of interconnected bodies.

2.2. Dynamical Systems of Wind Turbine

Dynamic analysis for wind turbines incorporates exploratory modular analysis and hypothetical modular analysis. The theoretical modal analysis can be applied more easily and widely. The fundamental test in dissecting the dynamic properties of wind turbines with the hypothetical model is evaluating the parameters of the model. For experimental analysis, it considers the dynamic properties of a kinetic system by measuring and analyzing the input and response signal. But there are restrictions to implement experimental test for large-scale wind turbines because of the unapproachability and difficulty in the construction of wind turbine (Wang, et al.2017). The rotor blade of the wind turbine will undergo the wind turbulence that creating the aerodynamic uplift force and the drag forces.

Wind turbine blade using airfoil to generate mechanical power. By using airfoil terminology, it is easy to understand the dynamic system of how the blade rotate that causes by the uplift and drag forces acting to the blade. There are several terms used to explain and airfoil as shown in Figure 1.

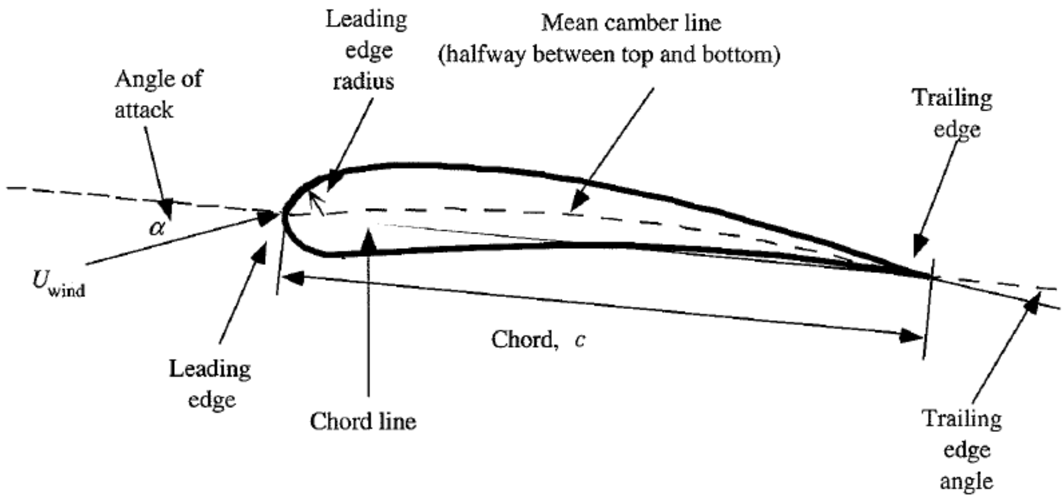


Figure 1: Airfoil Nomenclature

Dynamic Stall

When a wind turbine is subjected to the time varying fluctuations in the wind or control actions, it will induce frequent changes of angle of attack. This dynamic stall vortex results in further increase in the lift and drag forces generated by the airfoil. The overall loss of lift due to dynamic stall causes the wind turbine in pitching and yawing motions.

2.3. Soil Structure Interaction

In determination the stiffness of foundation, several factors need to think through in the design or analysis especially when dealing with soil which required a good assumption. Today, in the design of foundation for onshore wind turbine, mono-pile is widely used in design of foundation for onshore wind turbine to support the structure. So, the soil structure interaction plays an important role in determination of the soil parameters (Arany, et al.2014). However, a typical onshore wind turbine foundation is designed as fixed support.(Adhikari & Bhattacharya, 2011) has demonstrated that soil structure interaction need to take into consideration to design the foundation of wind turbine in order to predict the natural frequency of the wind turbine system that frequently fluctuating in arrears to the change in behavior of the soil and the cyclic loading. Furthermore, in this case, it will affect the overall system of the wind turbine causes increasing or decreasing in bending moment and deflection at the high level of the tower.

Wind Turbine Types and Components

There are generally two types of wind turbine horizontal and vertical axis. These two types of wind turbine are differentiated by the axis of rotation of the rotor shaft. The horizontal axis wind turbine has a horizontal rotor shaft while the vertical axis wind turbine is made with vertical rotor shaft. The electrical generator for horizontal axis type is located at the top of the tower whereas vertical axis type is located at the bottom of the turbine. Vertical axis wind turbine has a distinctive shaped rotor blade to produce the power from the wind at any direction. Figure 2 below shows the different type of vertical and horizontal axis wind turbines.

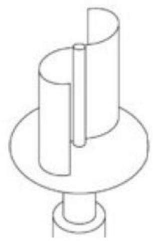
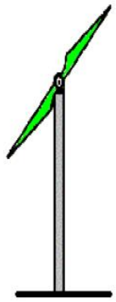
Savonius VAWT	Helical VAWT	Darrieus VAWT	3-blades HAWT	2 blades HAWT
				

Figure 2: Types of Horizontal and Vertical Axis Wind Turbines

CHAPTER 3

METHODOLOGY

3.1. Create Multi-Body Model

Structural model

The multi-body system model for the wind turbine consists of blades, hub, nacelle and tower as the substructures or components that are linked by the appropriate kinematical constraints. Each turbine component comprises one or several rigid bodies connected by the relevant connection. The structural properties of each component include mass and center of gravity.

For this project, the model of the wind turbine is created using 3D CAD Solid works software. The model of the wind turbine is assumed as a rigid body in the design. The wind turbine is divided into three major components which are the tower, rotor blade, and nacelle. Each of the components acts as the subsystem in the model which interconnected to each subsystem to provide a complete system of the wind turbine.

3.2. Apply the Load

Blade Element Momentum (BEM) theory is one of the method to predict the forces and momentum when the geometry is resolved all over the structure. According to (Ingram, 2011) “BEM equates two method of examining how a wind turbine operates. The first method is use a momentum balance on a rotating annular stream tube passing through a turbine. The second method is to determine the forces generated by the aero foil lift and drag coefficients at various sections along the blade”. This method is the easiest to explain the dynamic behavior of the blade due to the forces created from the wind turbulence. Blade element theory depends on two main rules, there are no aerodynamics interfaces among different blade elements and the forces on the blade elements are specially determined by the uplift and drag coefficients (Ingram, 2011).

When discussing blade loads, utmost of the stage the so-called overall loads are of main concern. The global loads are the loads that are transmitted from the blade into the hub or main shaft assembly, being the succeeding focal element along the load path from the rotor to the foundation of a wind turbine.

To designate the global loads acting on a rotor blade throughout operation it is appropriate to visualize the blade to be made up of isolated number of components with specific cross sections, specific structural properties, and specific masses lined up on the longitudinal axis of the blade. Each of these components cross sections alongside the blade span is an aerodynamic aero foil creating aerodynamic lift and drag forces that act in the aerodynamic center of the aero foil. The lift and drag forces are oriented perpendicular to and along the direction of the inflow, respectively.

Simultaneously, each blade element has isolated mass that, by being moved in the gravitation field of the earth and by being accelerated or decelerated in and out of the rotor plane, creates inertia forces and moments. The structural properties of the blade element, such as location of the center of gravity, location of the center of shear and location of the aerodynamic center with respect to the pitch axis of the blade, can cause a particular blade element to develop a torsion moment in operation.

3.3. Blade Element Momentum Theory (BEM)

The derivation of forces lift and drag that acting along the stream tubes of the blade using Blade Element Momentum theory is obtained from Chapter 3 Blade Element Theory for Wind Turbine by (Wood, D. (2011).

Conservation of Mass

Conservation of mass along the stream tubes after divided by the density whose flow area is approximately $2\pi r\, dr$ is given by:

$$U_0 2\pi r_0\, dr_0 = U_1 2\pi r\, dr = U_\infty 2\pi r_\infty\, dr_\infty \qquad \text{(Eqn. 1)}$$

Conservation of Momentum

The conservation of momentum is given by:

$$dT = \rho U_0 U_0 2\pi r_0\, dr_0 - \rho U_\infty U_\infty 2p r_\infty\, dr_\infty = 2\pi\rho U_1 r\,(U_0 - U_\infty)\, dr \qquad \text{(Eqn. 2)}$$

Conservation of Angular Momentum

The torque acting about the axis of rotation on the blade elements within the streamtube can be obtained as:

$$dQ = \rho r_\infty W_\infty U_\infty 2p r_\infty\, dr_\infty \qquad \text{(Eqn.3)}$$

Downstream of the blades, the angular momentum of the streamtube is conserved so $rW_2 = r_\infty W_\infty$. Using this relationship and conservation of mass

$$dQ = 2\pi\rho U_0\,(1 - a)\, W_2 r^2\, dr = 4\pi\rho U_0\,(1 - a)\, a'\Omega\, r3\, dr \qquad \text{(Eqn. 4)}$$

The Forces Acting on a Blade Element

Total or effective velocity are obtained as:

$$U_T^2 = (1 - a)^2 + [(1 + a')\,\lambda\, r\,]^2 \qquad \text{(Eqn. 5)}$$

Where λ r is the local speed ratio,

$$\lambda\, r = r\,\Omega / U_0 = \lambda\, r/R \qquad \text{(Eqn. 6)}$$

From the basic definitions of lift and drag coefficient C_l and C_d respectively:

$$\text{LIFT} = 1/2\rho U_T^2\, C_{lc} \text{ and DRAG} = 1/2\rho U^2{}_T\, C_{dc} \qquad \text{(Eqn. 7)}$$

To resolve the lift and drag into circumferential and axial components of interest to the wind turbine designer. The total thrust on *N* blade element is

$$dT = 1/2\, \rho U_T{}^2\, cN\, (C_l \cos \phi + C_d \sin \phi)\, dr = 1/2\, \rho U_T{}^2 cN\, C_a\, dr \qquad \text{(Eqn.8)}$$

Where $C_a = C_l \cos \phi + C_d \sin \phi$ and the torque due to the circumferential force is

$$dQ = 1/2\, \rho U_T{}^2\, cN\, (\, C_l \sin \phi - Cd \cos \phi\,)\, rdr = 1/2\, \rho U_T{}^2\, cN\, Ca'\, rdr \qquad \text{(Eqn. 9)}$$

Equation 8 and 9 are the basic blade element equations.

3.4. Power Output

The contribution to the total power from each annulus is:

$$dP = \Omega\, dT^3 \qquad \text{(Eqn. 10)}$$

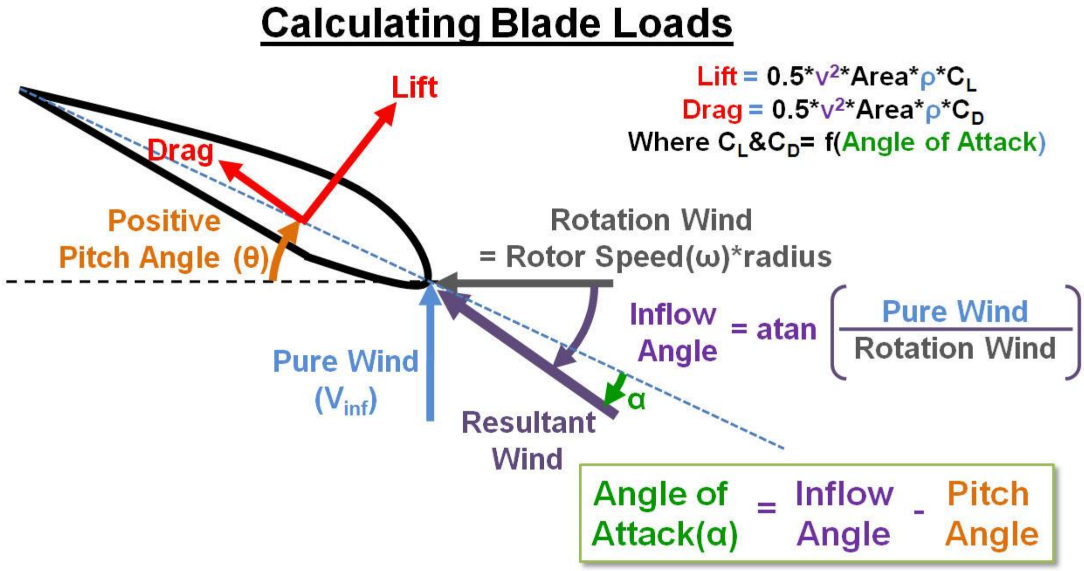
The total power from the rotor is:

$$P = \int_{rh}^{R} dP\, dr = \int_{rh}^{R} \Omega\, dT\, dr \qquad \text{(Eqn. 11)}$$

Where r_h is the hub radius. The power coefficient is given by:

$$cP = \frac{p}{pwind} = \frac{\int_{rh}^{R} \Omega\, \mathrm{dT}}{\frac{1}{2}\rho\pi R^2 V^3} \qquad \text{(Eqn. 12)}$$

The implementation of these equations in a MATLAB computer program to predict the wind turbine performance is presented in appendices at the end of this report.



3.5. Parametric Study for the Effect of Foundation

The foundation of the wind turbine is modeled as a fixed support and the stiffness of the foundation is modeled by spring which are lateral spring and rotational spring. These spring is representing as the pile foundation for the wind turbine.

The time-dependent foundation performance at the section level was affected by a number of factors such as the area of pile foundation, concrete properties, and the wind speed to the wind turbine. These are the parameters selected for the parametric study.

i. *Pile Foundation Depth/Length*
ii. *Area of Pile Foundation*
iii. *Wind speed*

The effect of wind speed to wind turbine is basically can causes in vibrations and the displacement of the tower changing with respect to time. Due to this change in position and causes the tower to move might affected to the support system which is the foundation. Thus, it causes the stress to the part of foundation which way or direction the tower is moving based on the direction and speed of the wind.

Type of Foundation for Onshore Wind Turbines

Before the foundation type is chosen to support the wind turbine structure, field assessment must be done to evaluate the soil condition at the site and provide the soil properties together with the turbine loads. The first step is usually to evaluate the suitability for support by a spread footing or mat, since this is a common and reasonably inexpensive foundation type. The distinctive purpose of spread footing is shown in Figure 3. Concrete mass and soil bearing under the toe resists the overturning forces. The weight of the soil and concrete balances the foundation to keep it from tipping.

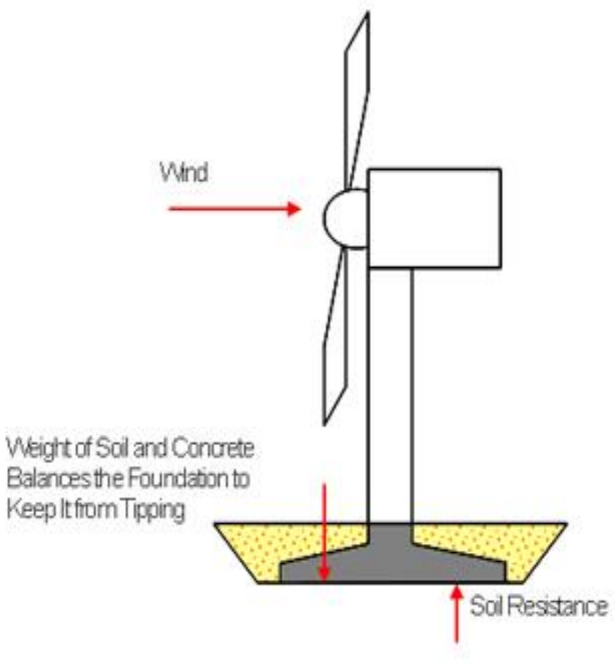


Figure 3: Spread Footing

If the circumstance of the site where soils are soft, loose or otherwise unsuitable, another foundation approaches are considered. From time to time soil improvement method is requisite to improve poor soils to them appropriate for spread footings. For other situations, deep foundations such as driven or drilled piling may be necessary. Deep foundations may include single piers, group of driven piles, or group of drilled piles. Deep foundations function differently than spread footings. Spread footings rely on soil bearing and the weight of the foundation itself and the soil backfill on top of the foundation to resists slanting under wind loads. Single piers as shown in Figure 4 below use the bending strength of the pier to resists tilting.

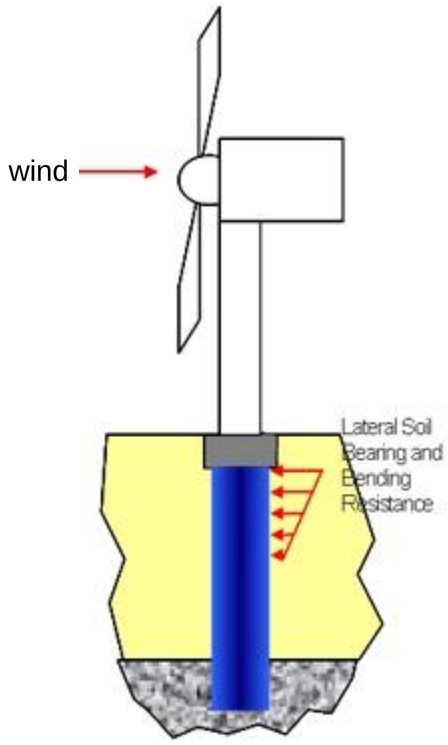


Figure 4: Single Pier

For group piles as shown in Figure 5, the tilting resistance comes from tension in the piles on one side of the foundation while piles on the other are loaded on compression.

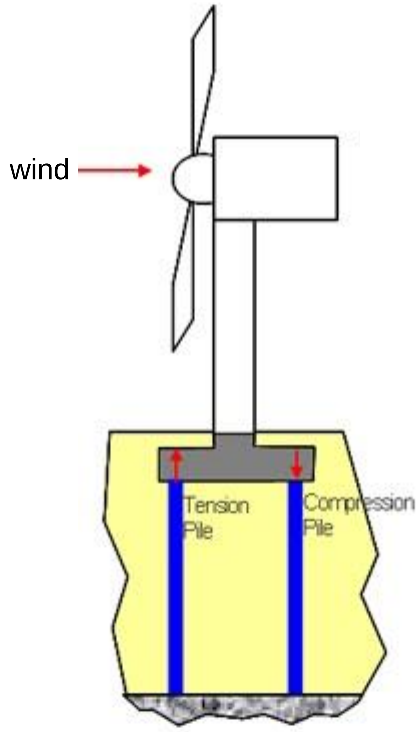


Figure 5: Pile Group

Another option is the anchored foundation. This consists of a spread footing that has anchors extending through it into bedrock as shown in Figure 6 below. This foundation eliminates the need for soil cover and takes advantage of high strength rock at the surface.

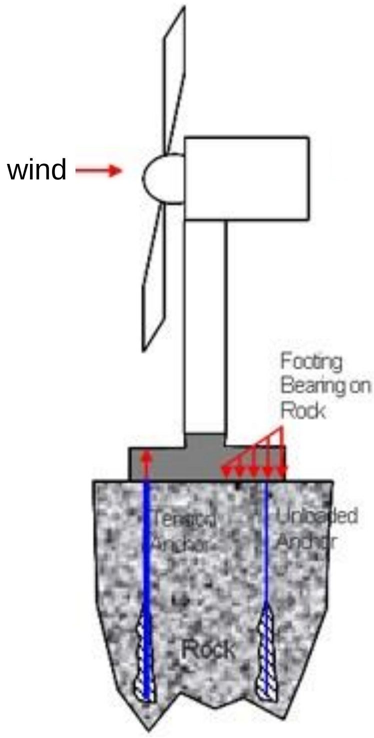
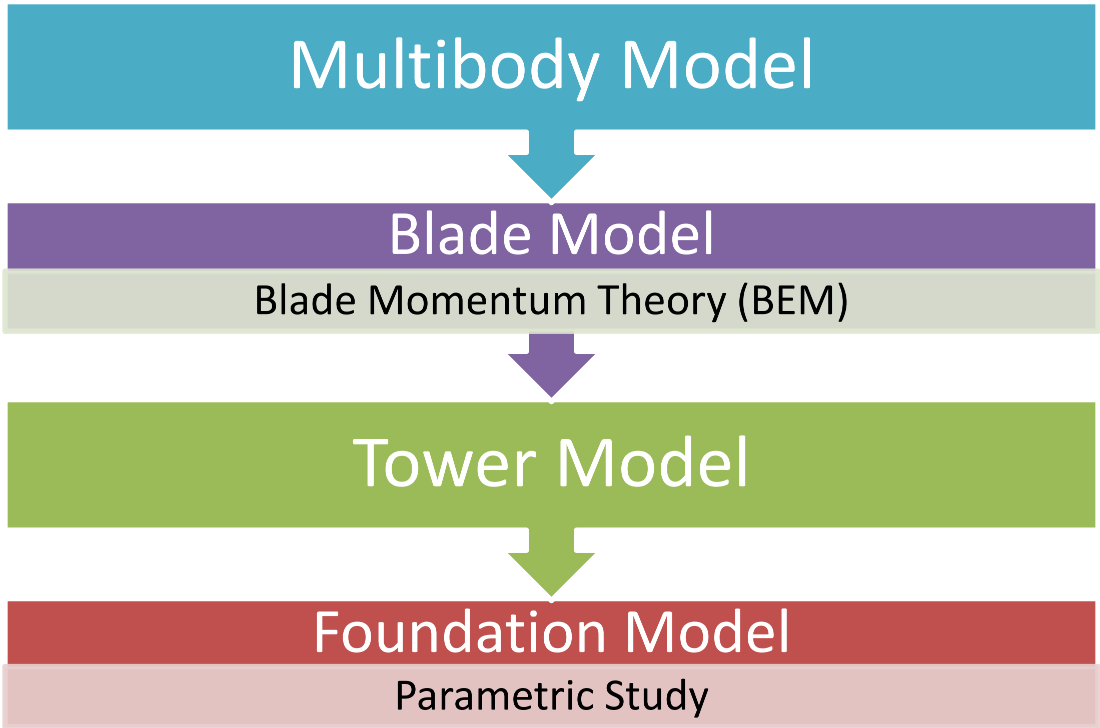


Figure 6: Anchored Footing

3.6. Development of Wind Turbine Model



3.7. Physicals Modeling in 3D CAD Solidworks Software

The figures below show the physical modelling of the wind turbine that consists of the blade model, tower model, and foundation model. Each part is assembling to produce a complete wind turbine model. Besides, the physical model will be imported into Simulink model using MATLAB software for the analysis.

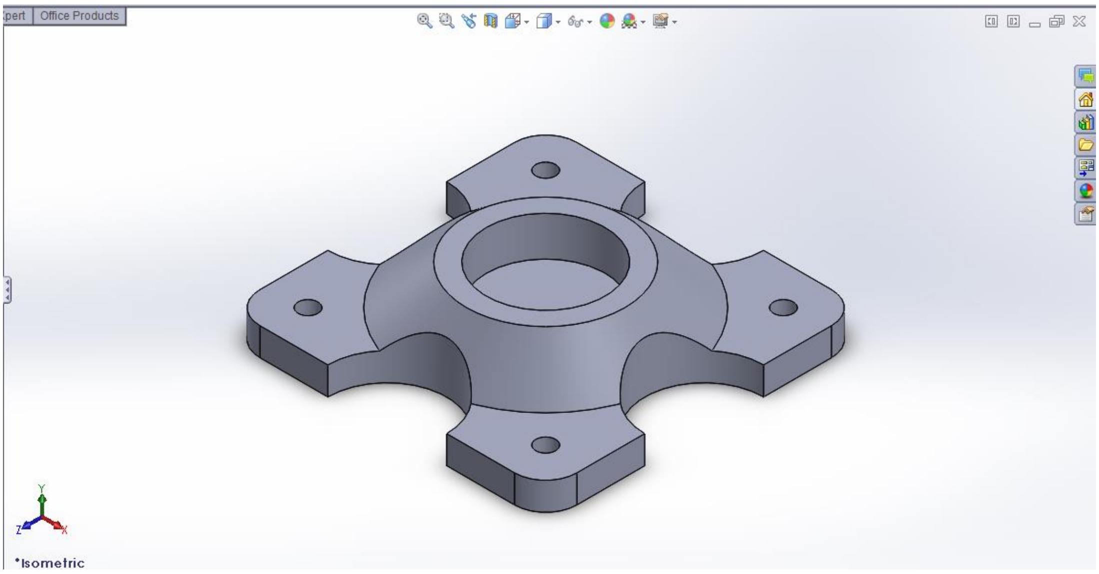


Figure 7: Foundation Model

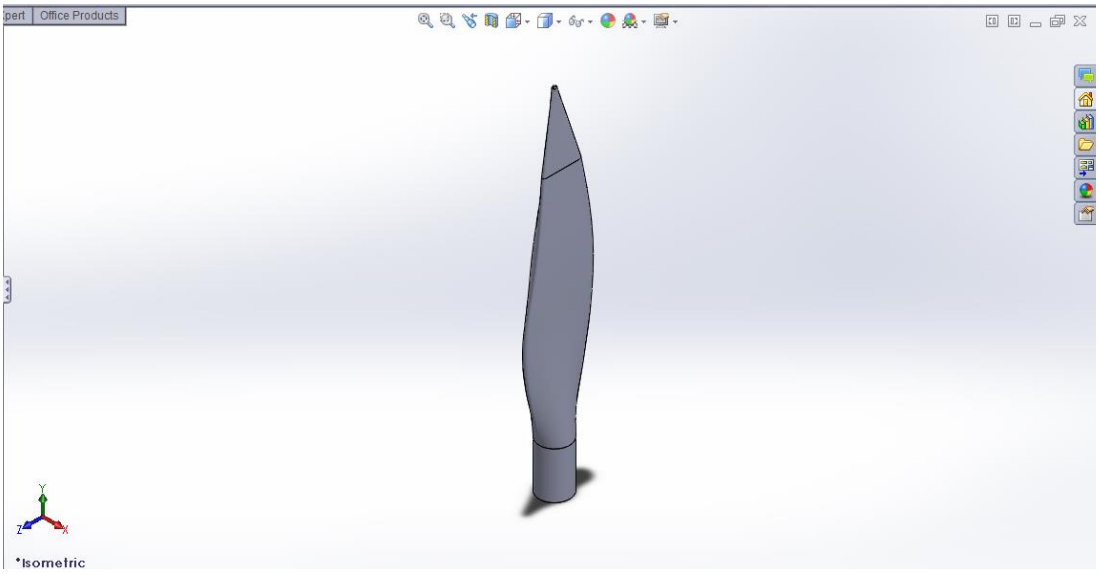


Figure 8: Blade Model

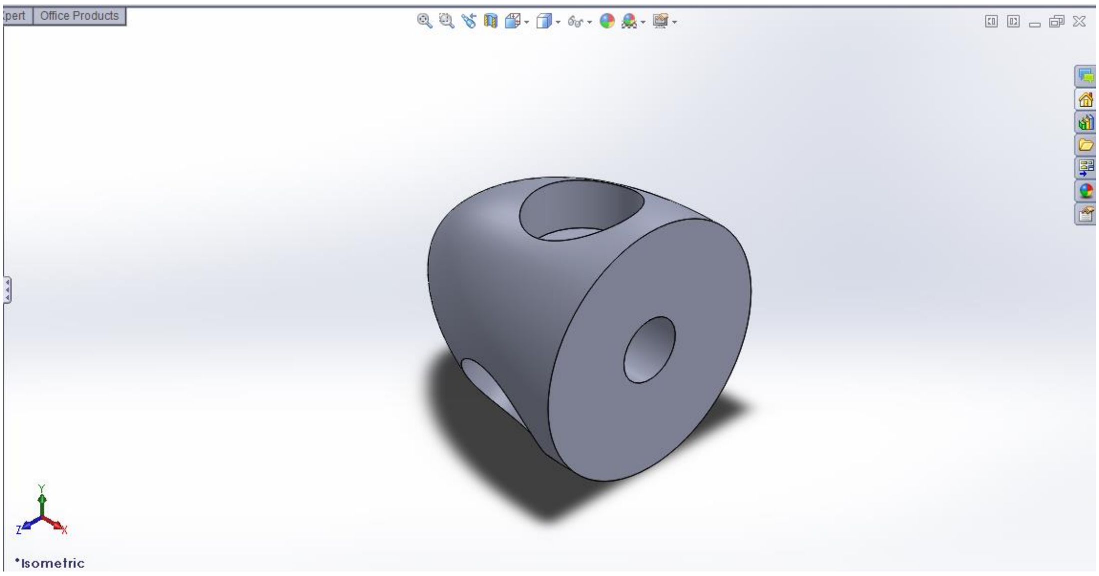


Figure 9: The Rotor Model

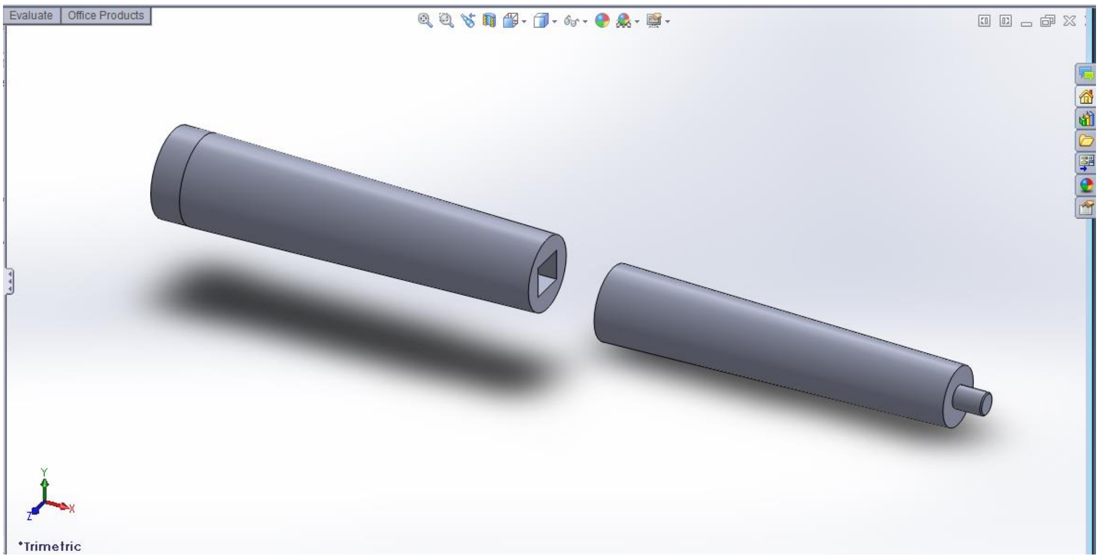


Figure 10: Tower Model

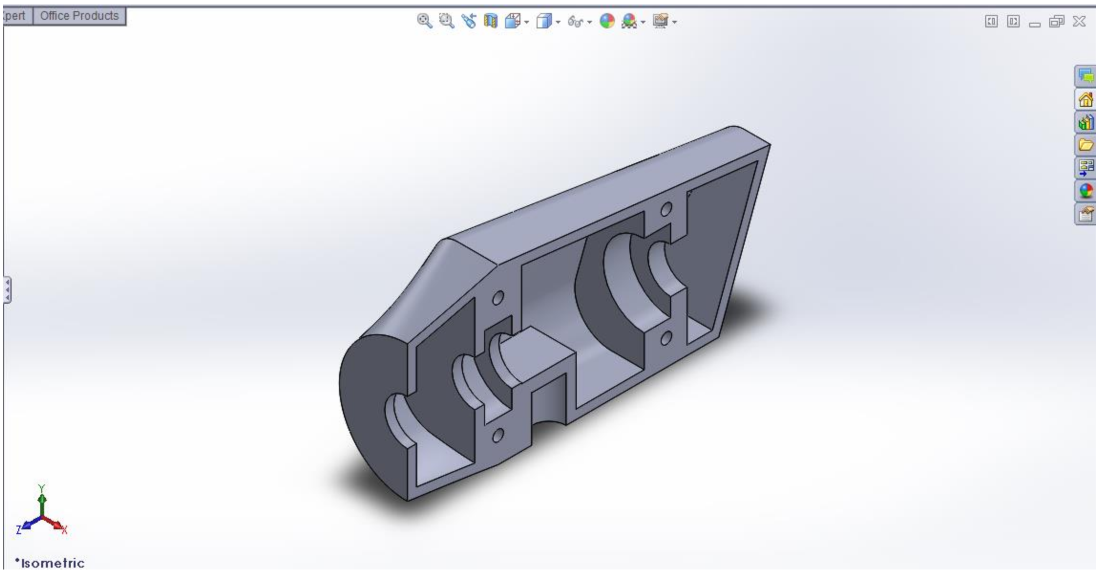


Figure 11: Nacelle

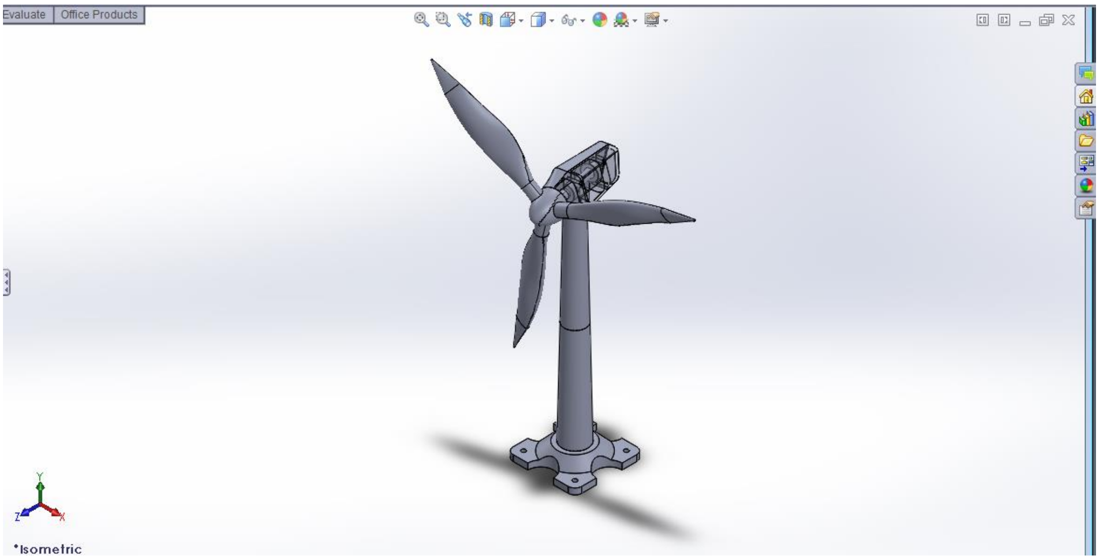


Figure 12: Assembled Wind Turbine Model

3.8. Physicals Modeling Using Simulink Blocks

The block set consists of block libraries for bodies, joints, sensors and actuators, constraints and drivers, and force elements. All blocks are configurable by the user via graphical user interfaces as known from Simulink. It is possible to extend the block library with custom blocks, if a problem is not solvable with the provided blocks. Standard Simulink blocks have distinct input and output ports. The connections between those blocks are called signal lines and represent inputs to and outputs from the mathematical functions. The figures below shows the block set of the physical modeling of the wind turbine.

In modeling of the wind turbine, custom block from simscape is used to define the solid block of each sub components which are blades, nacelle, tower, and the base. The solid blocks has standard 3 dimensional solids shape such as cylinder, sphere, and bricks that can be assemble into more complex parts. All the parts defined are completely modular. What this mean is it can quickly build complex parts and mechanism by using copy-and-paste. The transform sensor is used to measure the spatial relationship between two frames. The parameters this sensor measures include rotational and translational position, velocity, and acceleration. The figures below show the flow of the wind turbine model using simmechanics custom blocks until it is bring together into one complete multibody system of a wind turbine.

Blade Model

In modeling the blade model, the blade is divided in to seven elements in order to apply the blade load calculating from blade element momentum theory. Each elements then is revolved become one blade geometry. The figures below shows the Simulink blocks of blade model.

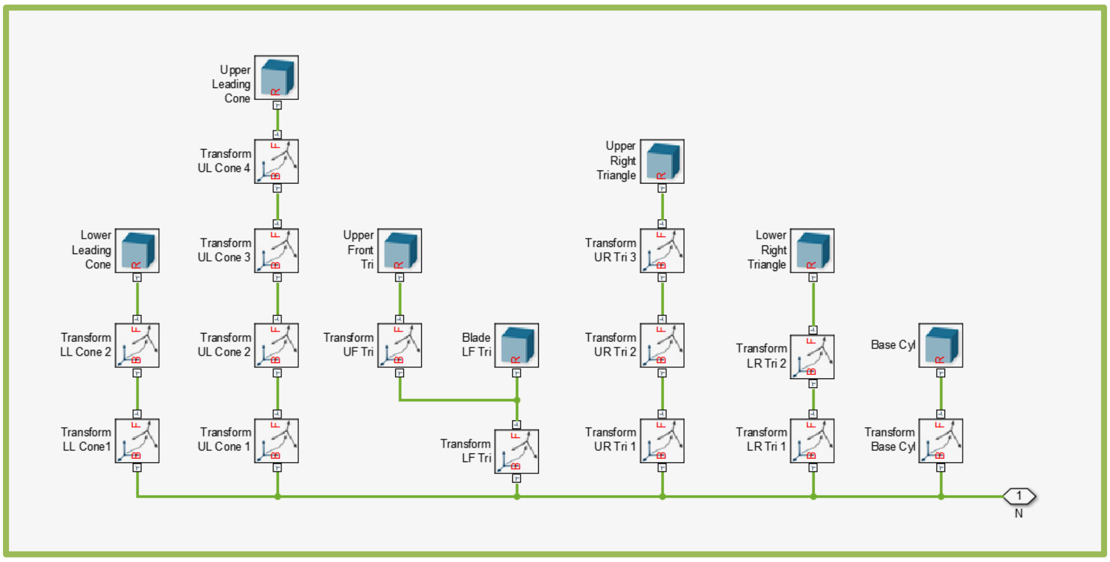


Figure 13: Elements of Blade Model

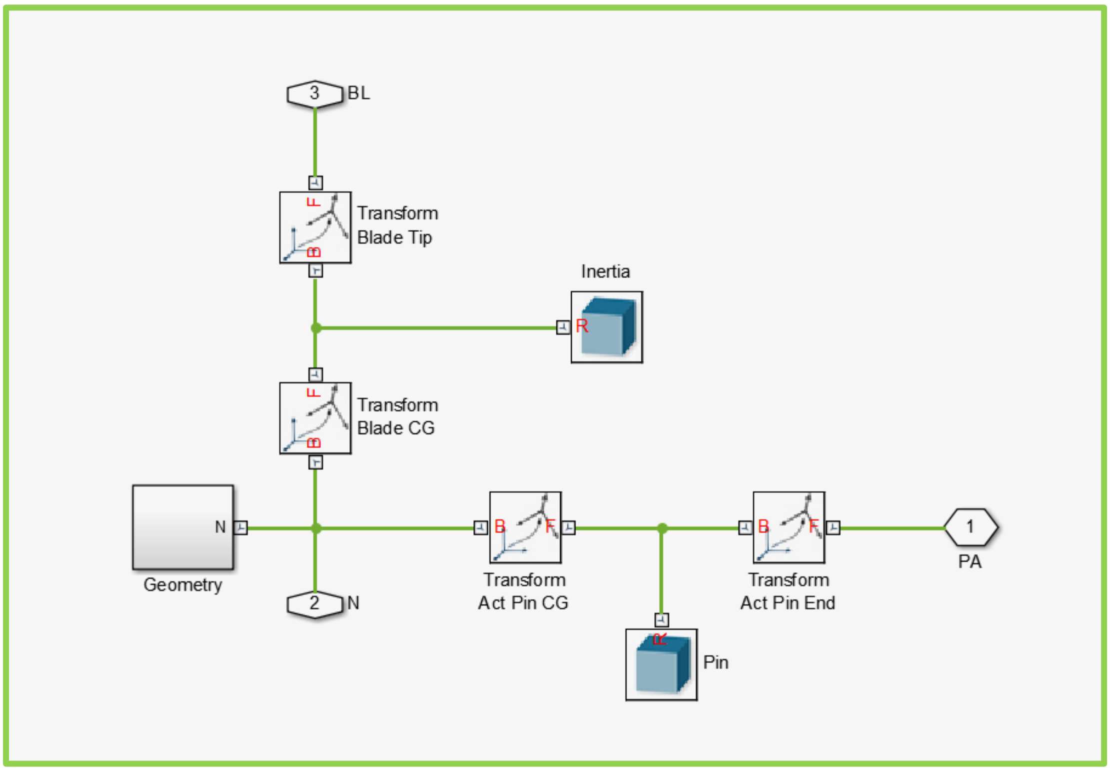


Figure 14: The Geometry of Blade Model

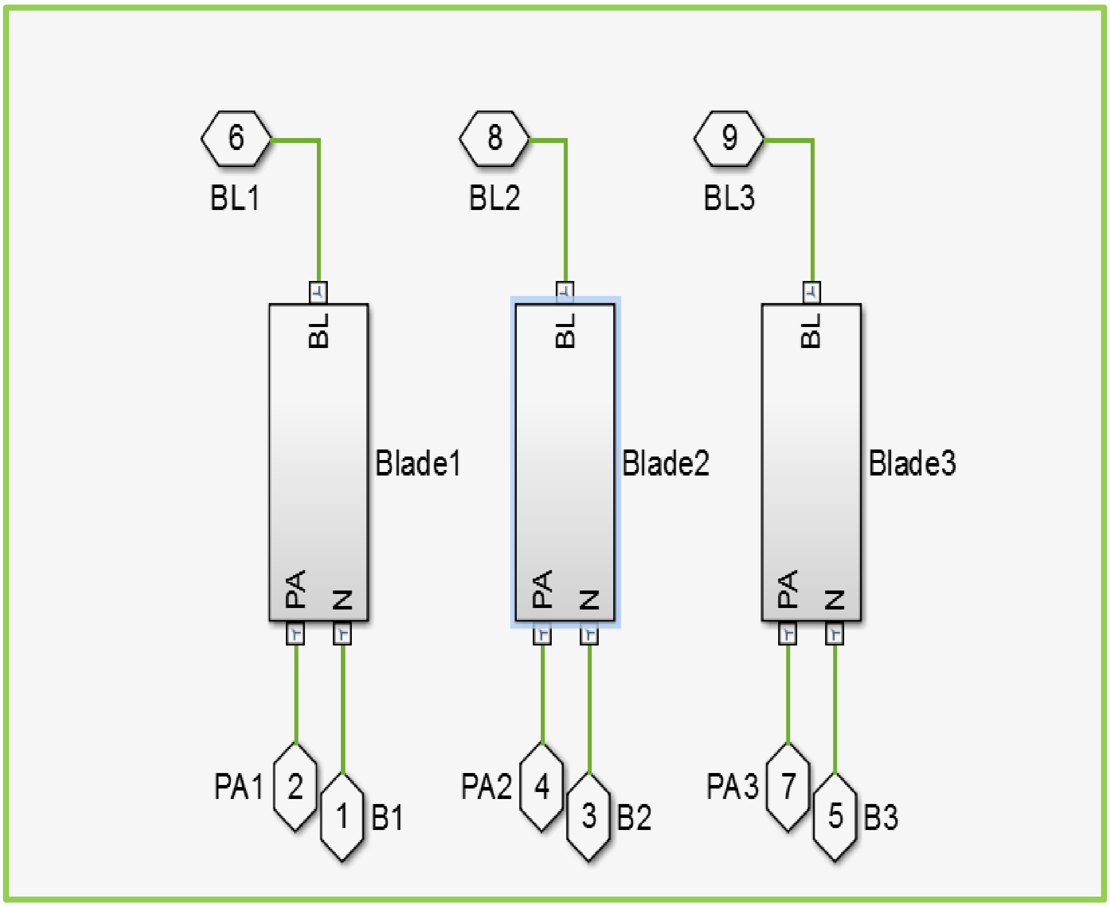


Figure 15: Blade Model

Blade Load (Blade Element Momentum Theory)

Physical modeling blocks for blade load is modelled based on the blade element momentum theory. The physical blocks is created from the derivation of drag and lift forces acting on the blade.

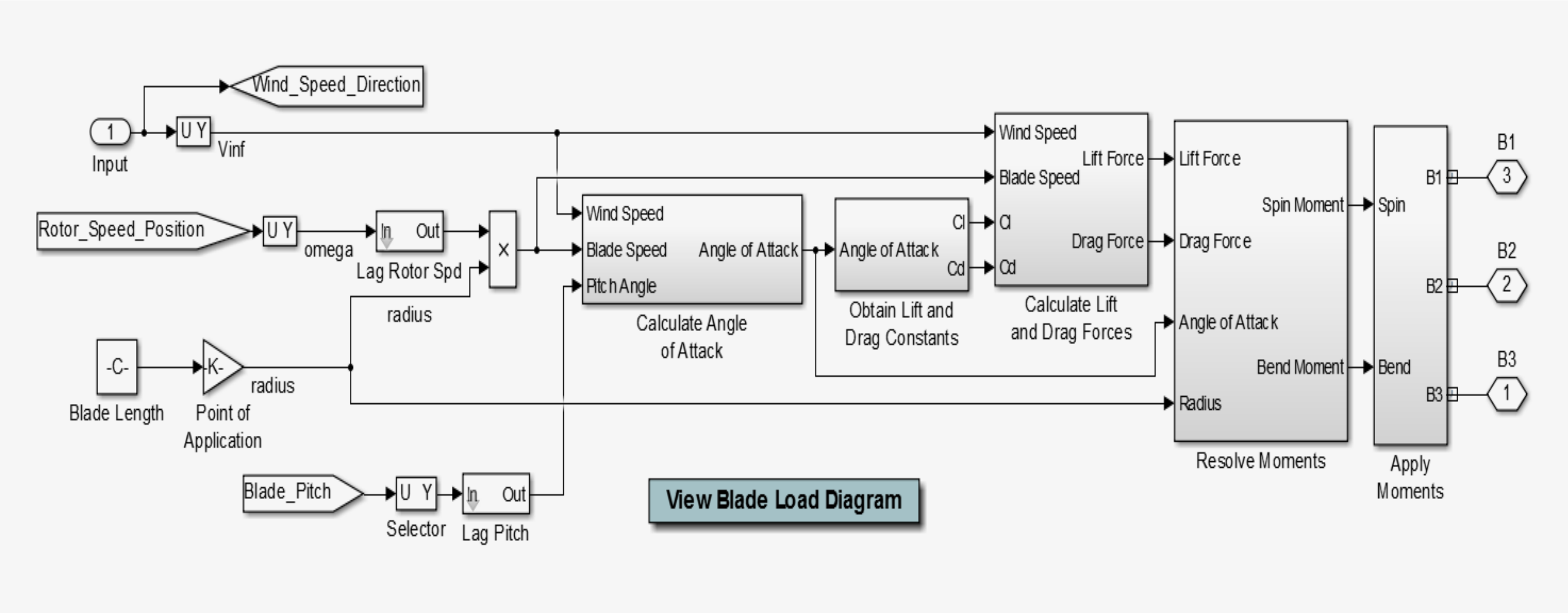


Figure 16: Blade Load Model

Tower Model

The tower is model as fixed structure. The connection between the tower and the foundation is considered as fixed using revolute joints.

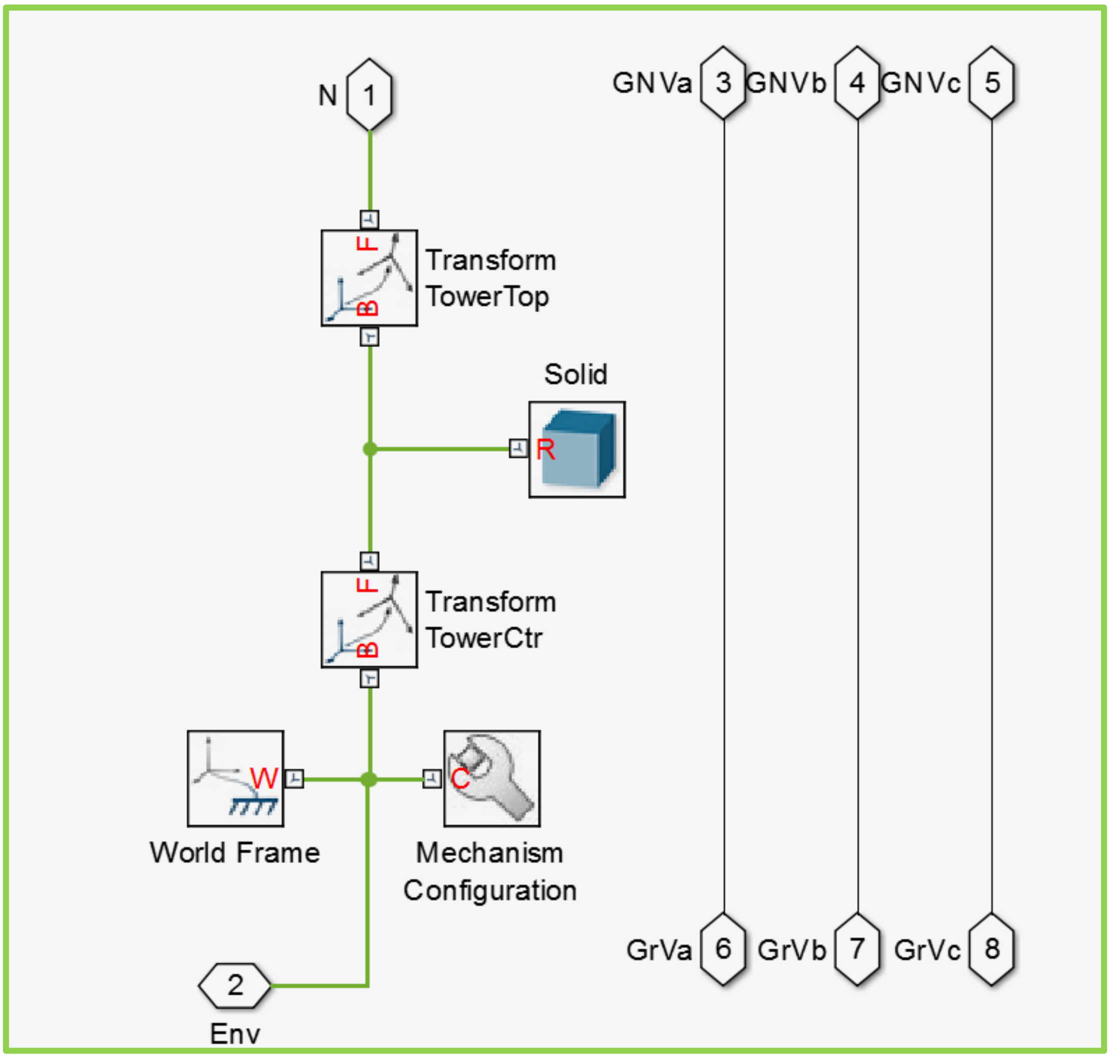


Figure 17: Tower Model

Foundation Model

For the foundation model, the joints between elements is very important and the chosen of the joint element must be correct to allow the movement of the tower hence to see the effect on the foundation.

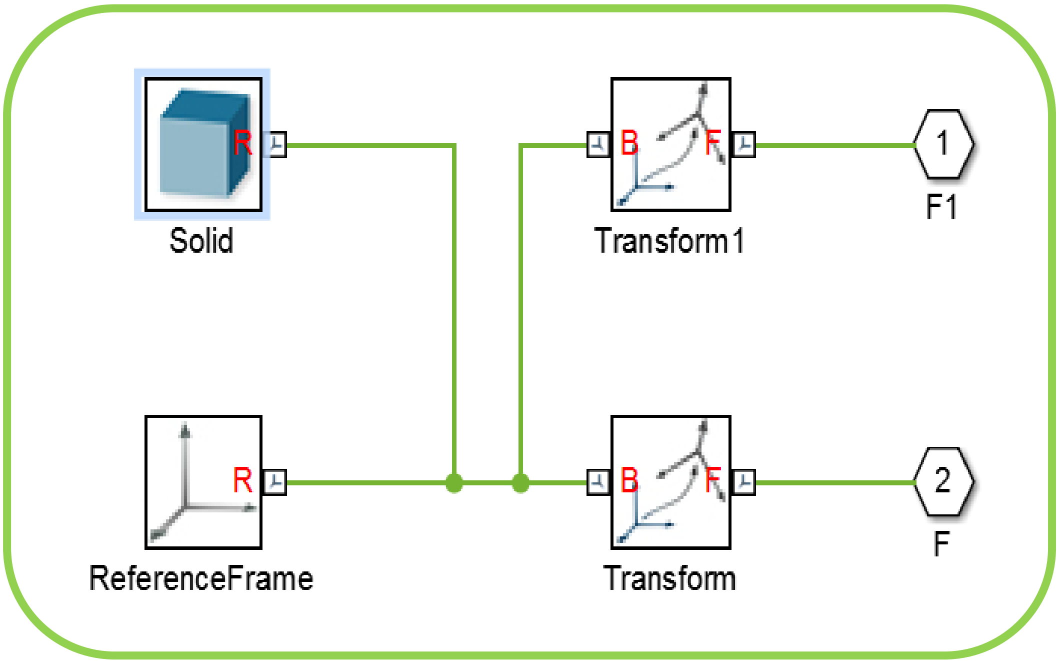


Figure 18: Simmechanics Blocks for the Foundation Model

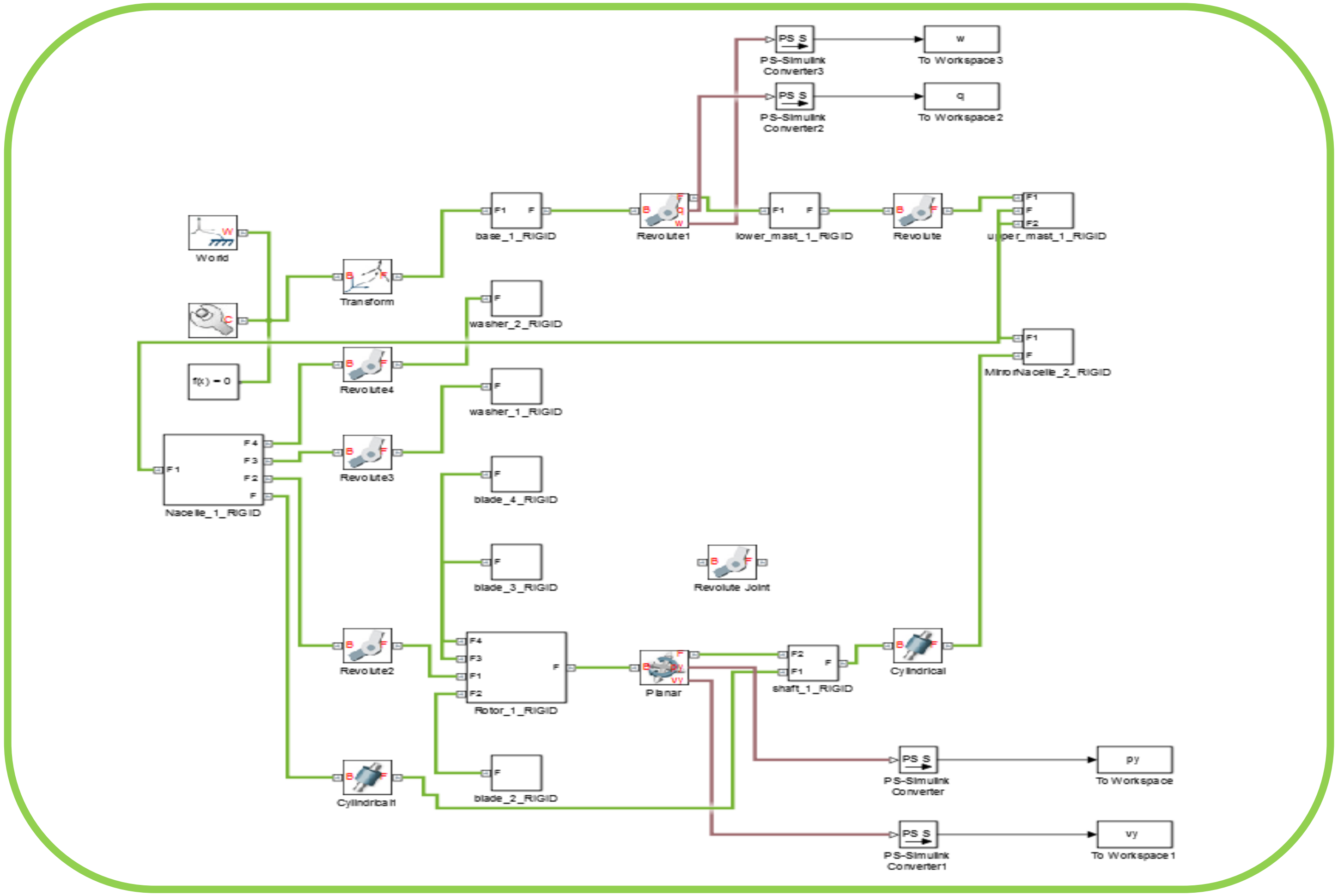


Figure 19: Physical Model of Wind Turbine in Simmechanics Blocks

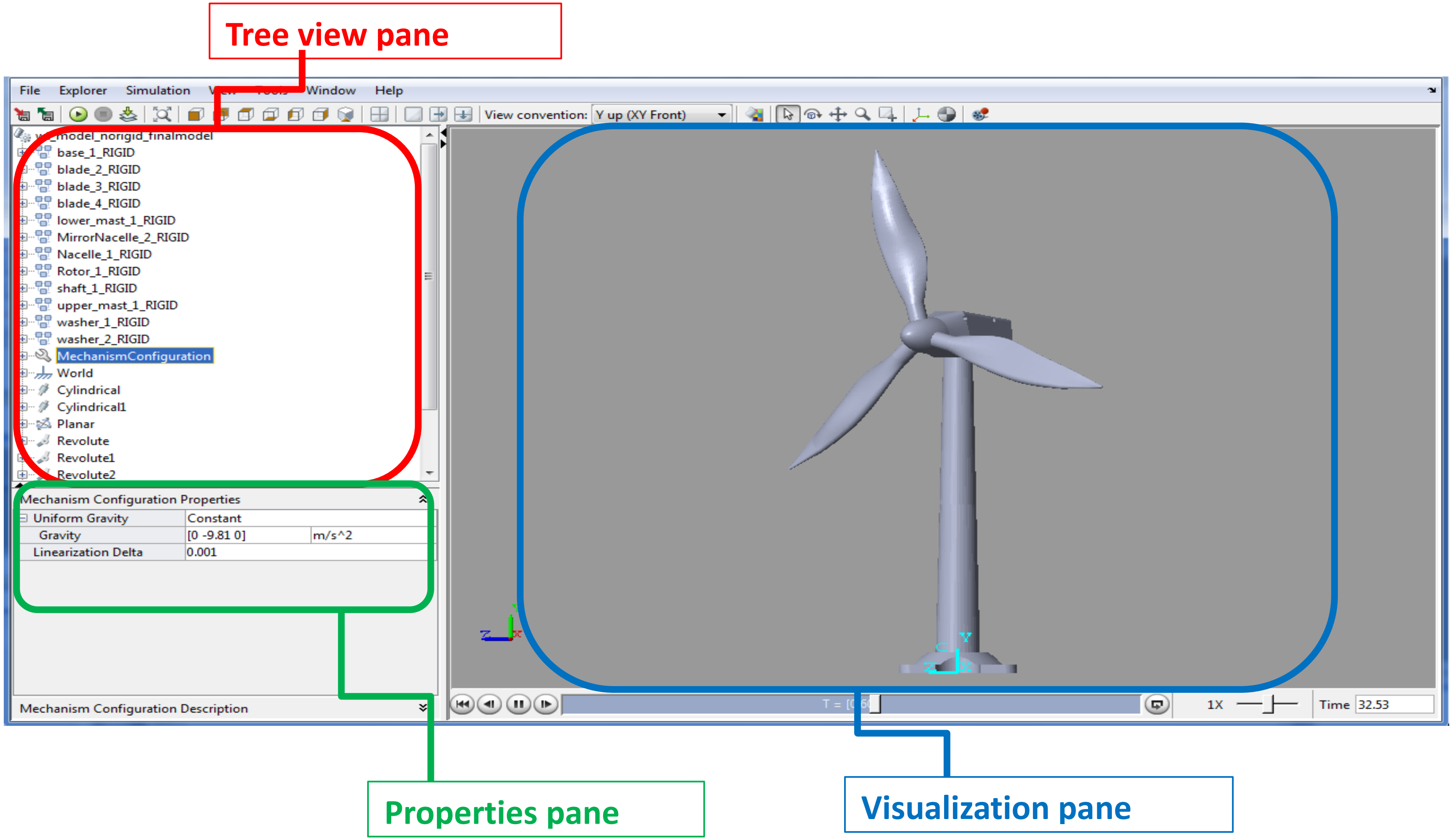


Figure 20: Visualization of Wind Turbine Model in Mechanics Explorer during Simulation

Figure 20 above shows the 3D visualization of the wind turbine model from the simmechanic blocks model. The mechanics explorer tool is used to visualize and explore the multibody model. The tool comprises a visualization pane to view the model, a tree view pane to explore the model hierarchy, and a properties pane to examine the individual component parameters.

3.9. Gantt chart

Table 1 below shows the Gantt chart of this project for FYP 1.

No.	Progress / Week Number	FYP 1													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Research & Information Gathering														
	Project Research														
	Background of Study														
	Literature Review														
	Milestone: Completion of Extended Proposal						●								
2	Identify the Design Parameters														
	Type of Loads														
	Parametric Study of the Foundation/Prototype if Wind Turbine														
3	Familiarization of SIMSCAPE MULTIBODY software														
	Milestone: Completion of Proposal Defense									●					
4	Development of WindTurbine Model														
5	Simulation Model Development														
	Milestone: Completion of Interim Report Draft													●	
6	Model Simulation (Working Prototype)														
	Milestone: Completion of Final Interim Report														●

●	Suggested Milestone
	Process

Table 1: Gantt chart for FYP 1

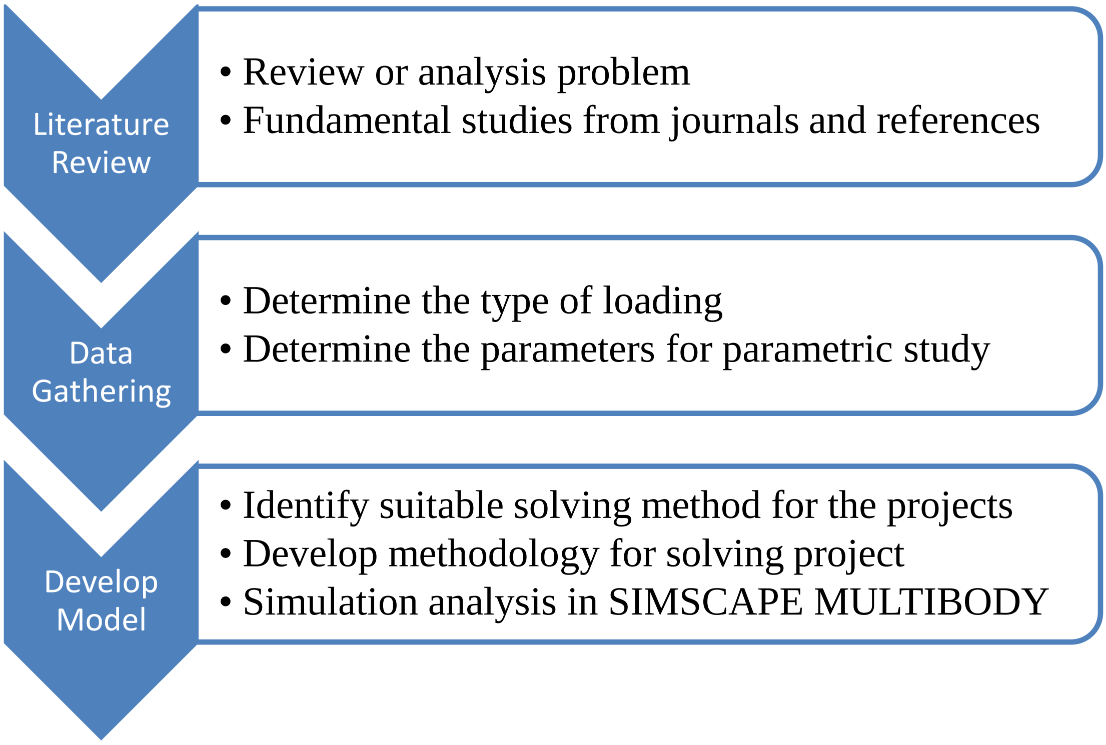
Table 2 shows the Gantt chart of this project for FYP 2.

No.	Progress / Week Number	FYP 2														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Analysis of Wind Turbine Model															
	Model Simulation (Working Prototype)															
	Provide Model Simulation															
	Milestone: Completion of Progress Report							●								
2	Perform the Parametric Study															
	Provide Time - Series Analysis															
	Identify the Contribution of Soil on Foundation															
	Milestone: Completion of Pre-SEDEX										●					
4	Analysis the Effect of Stiffnes on Foundation Depth/Length															
5	Analysis the Effect of Stiffnes on Single Pile (Monopile)															
	Milestone: Completion of Draft Final Report											●				
6	Preparation of Final Report															
	Milestone: Submission of Dissertation (soft bound)												●			
7	Milestone: Submission of Technical Paper												●			
8	Milestone: Viva													●		
9	Milestone: Submission of Project Dissertation (hard bound)															●

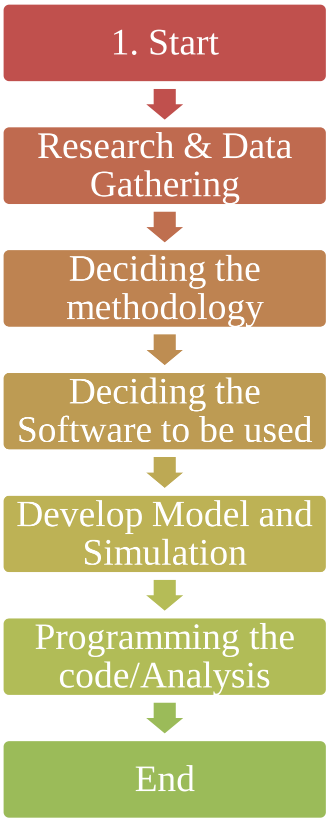
●	Suggested Milestone
	Process

Table 2: Gantt chart for FYP 2

3.10. Project Milestone



3.11. Flowchart



CHAPTER 4

RESULT & DISCUSSION

The output of the results can be obtained by applying the sensing motions and forces. The sensor blocks are able to measure the body motions, joint motions, and constraint reaction forces. The figures below shows the dynamic behavior of the wind turbine due to pitching and yawing motions.

4.1.Dynamical Behavior of the Wind Turbine

Wind Speed Set Up for Simulation

The wind speed is set up varying to the time for the simulation. This reason is to develop a stochastic simulation procedure in order to provide time-series of the displacement of the tower and the power output. So the Figure 21 below shows the wind speed varying to the time for 80 seconds during the simulation.

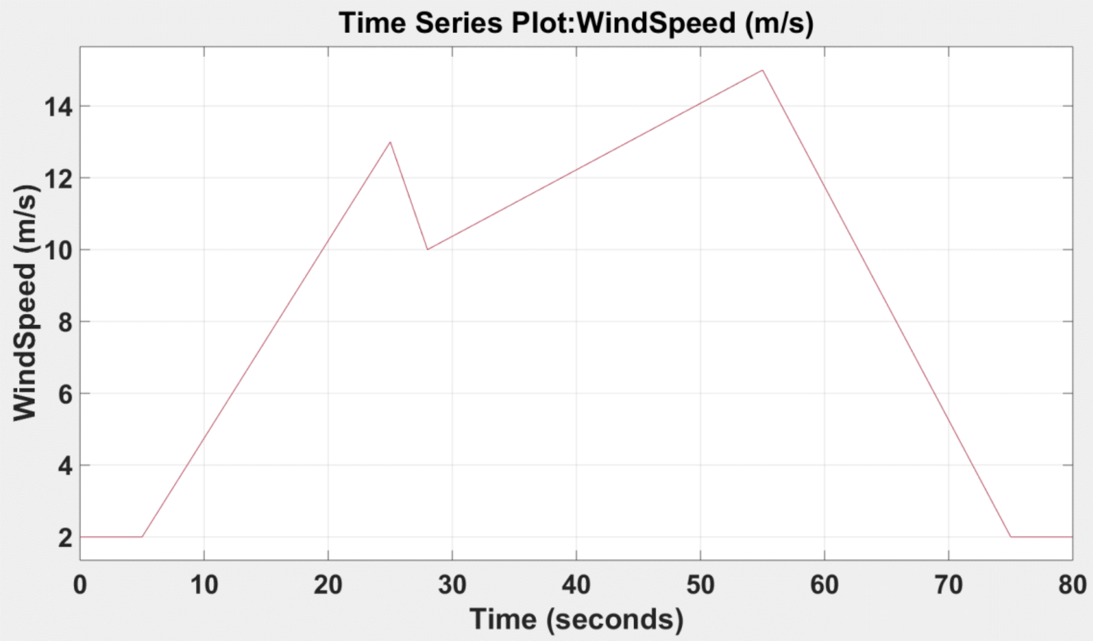


Figure 21: Graph of Wind Speed vs. Time

Pitching Motions of the Wind Turbine

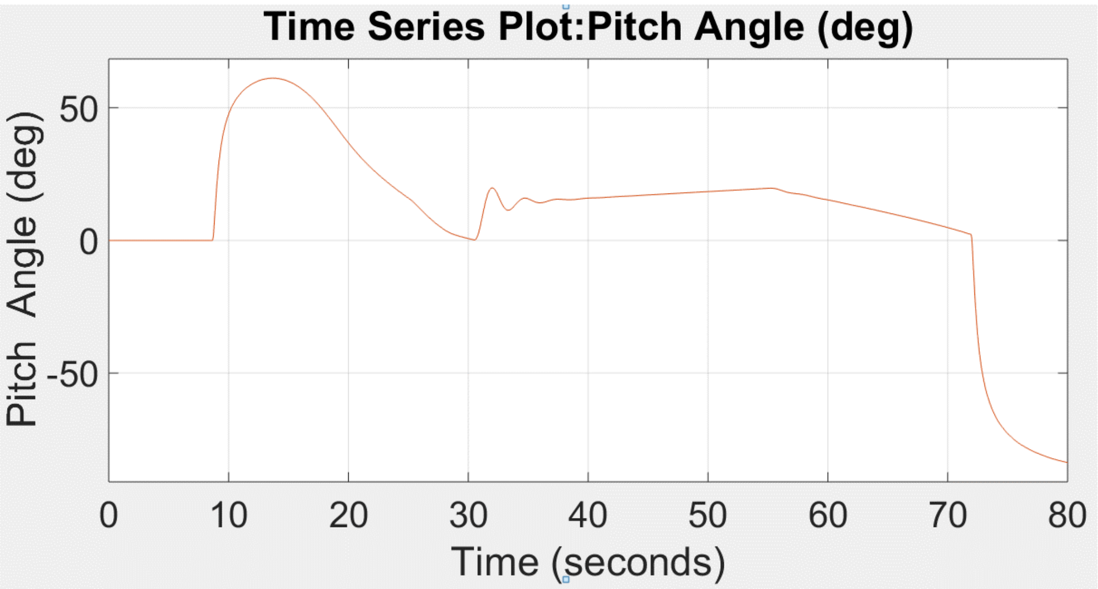


Figure 22: Graph of Pitch Angle vs. Time

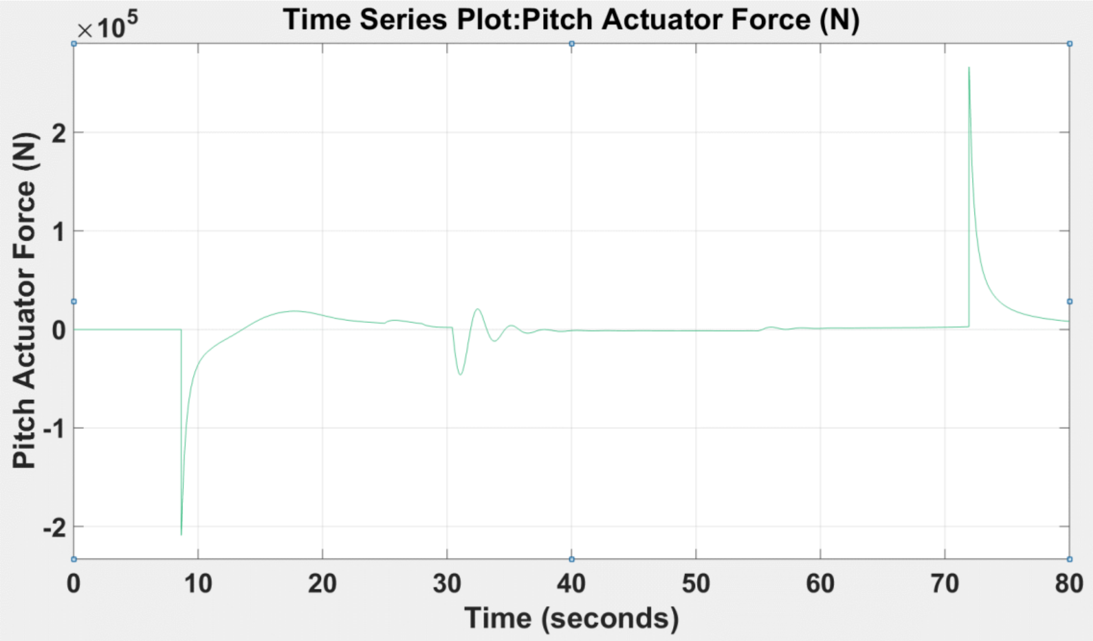


Figure 23: Graph of Pitch Actuator Force vs. Time

Yawing Motions of the Wind Turbine

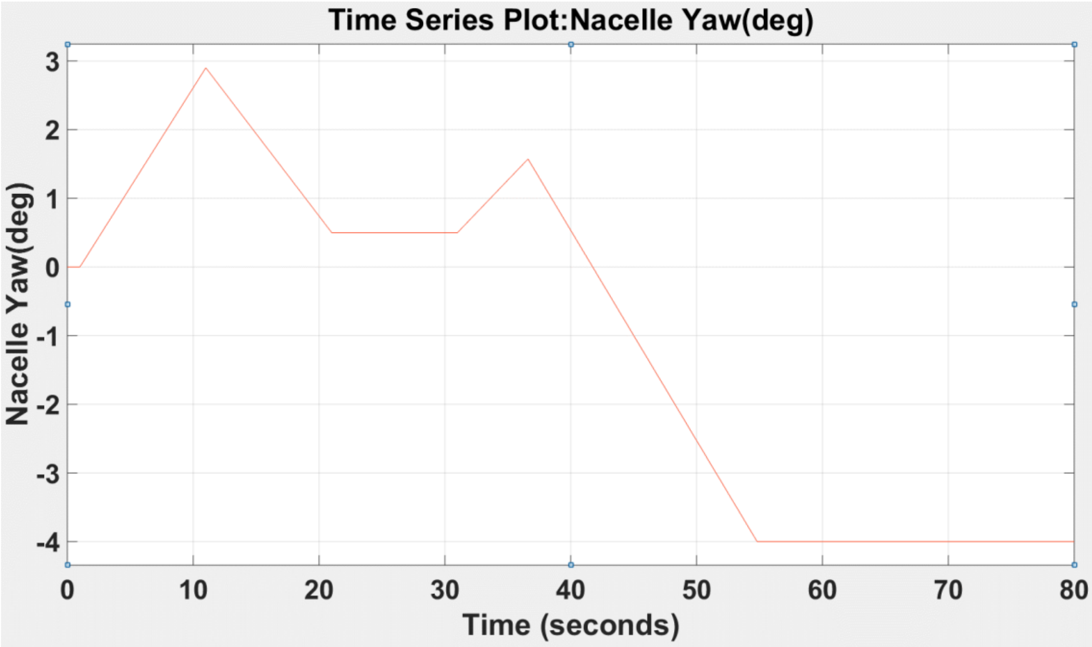


Figure 24: Graph of Nacelle Yaw vs. Time

Figure 25: Graph of Nacelle Yaw Angle vs. Time

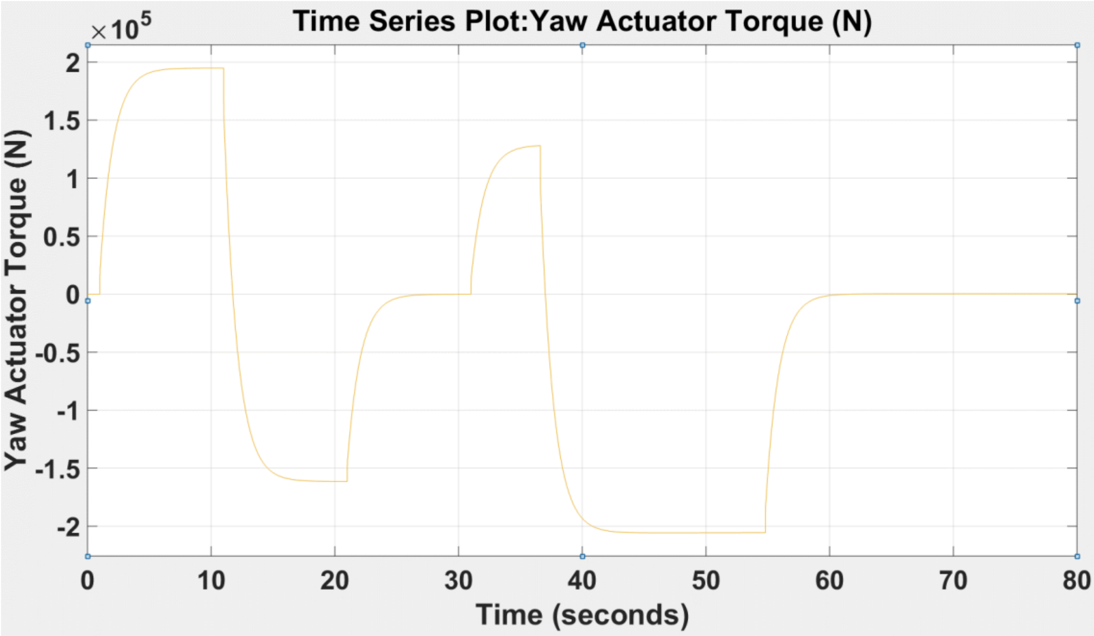


Figure 26: Graph of Yaw Actuator Torque vs. Time

To describe the motions of the wind turbine, the dynamical behavior of the wind turbine has been observed. The dynamic load due to the wind speed causes the wind turbine to pitch and yaw. Pitching motions causes the wind turbine moving laterally and the yawing motions causes the rotation of the nacelle. The pitch angle is very significant to the performance of the power output of a wind turbine. From the Figure 22, the pitch angle of the blade is sudden drop due to the high angle of attack at the upwind area that can cause dynamic stall. The hydraulic actuator is designed to collective the pitch. From the Figure 23, the pitch actuator force of the wind turbine is inversely to the pitching motions or the angle of pitching in order to control the movement. While for the yawing motions, the rotation of the wind turbine blade can causes the nacelle rotating. From the Figure 24 and Figure 25, the nacelle yaw angle also occurring sudden drop due to stall on the blade at the upwind area. This is because the upwind area of the blade has high angle of attack.

4.2.Parametric Study

The analysis were done on a single pile. For the analysis, the length and area of pile are varies. The length of the pile chosen are 3m, 6m, 9m, and 12m. while the area of pile chosen are, 200 x 200 mm^2, 250 x 250 mm^2, 300 x 300 mm^2, and 350 x 350 mm^2. The Modulus Elasticity of concrete is 50 GPa. For different pile length the maximum area is chosen and for the area of pile the maximum length of pile is selected as mentioned in the data below.

The details of the pile parameters is presented in Table 3 and Table 4 below.

Area of Pile	=	350 x 350	mm^2
Length of Pile	=	3	m
		6	
		9	
		12	
$E_{concrete}$	=	50	GPa

Table 3: Different Length if Pile Foundation

Length of Pile	=	12	m
Area of Pile	=	200 x 200	mm^2
		250 x 250	
		300 x 300	
		350 x 350	
$E_{concrete}$	=	50	GPa

Table 4: Different Area of Pile

From the graph below, the displacement of the pile is linearly move based on the load acting on the pile. This is because the pile is represented by a linear spring. The graph shows that the higher the load, the higher the displacement of the pile.

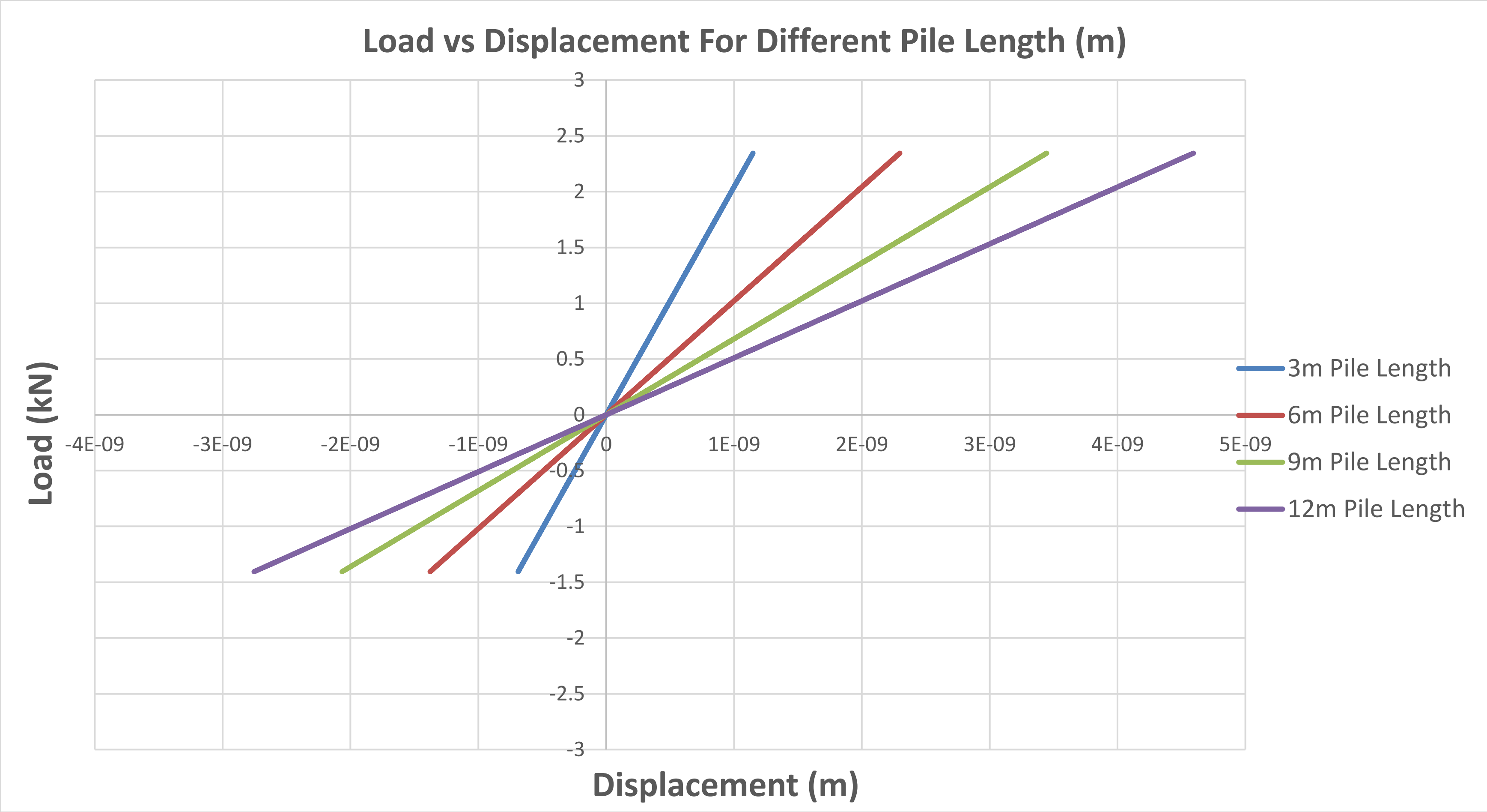


Figure 27: Load vs. Displacement for Different Pile Length

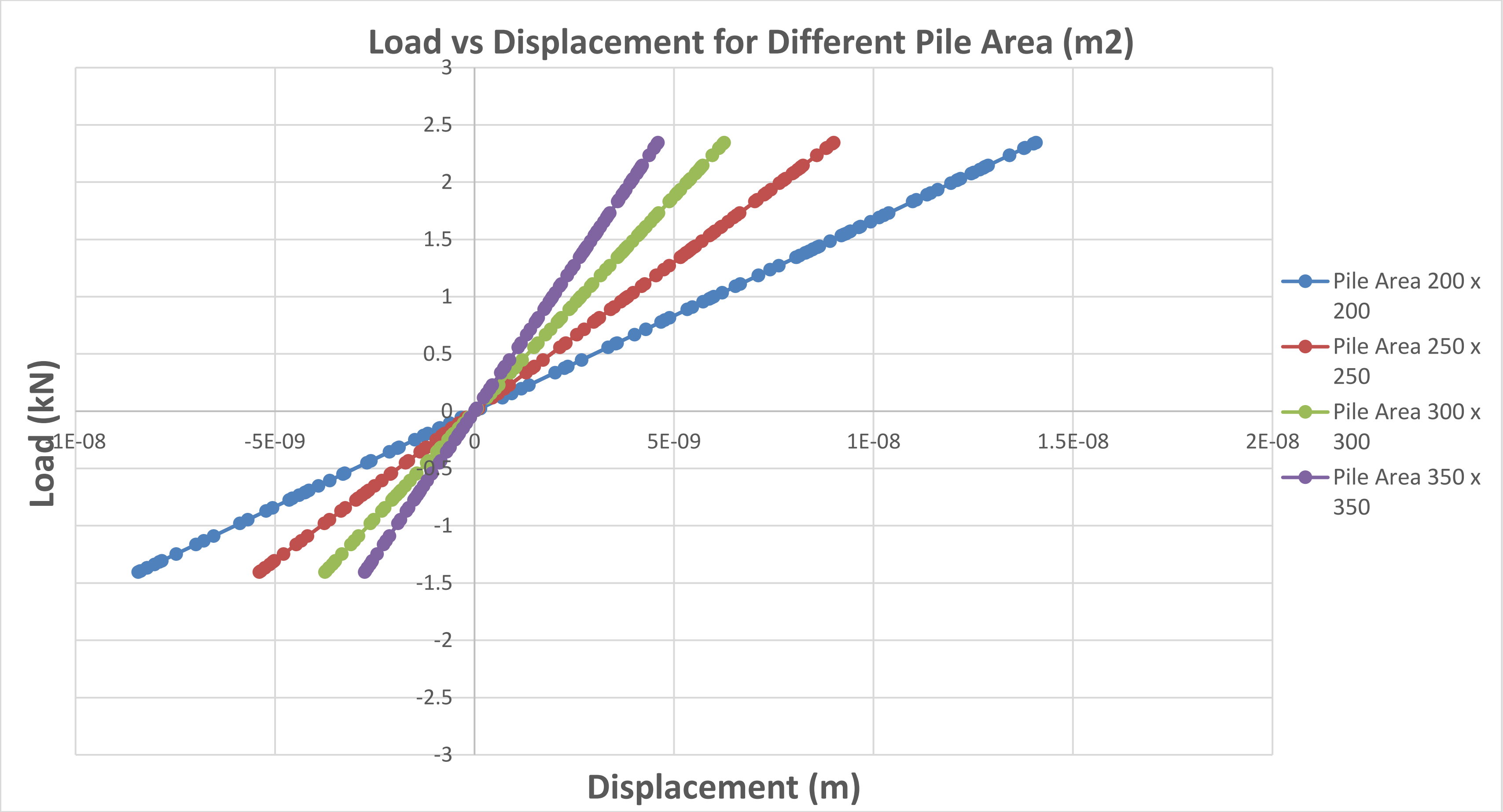


Figure 28: Load vs. Displacement for Different Area of Pile

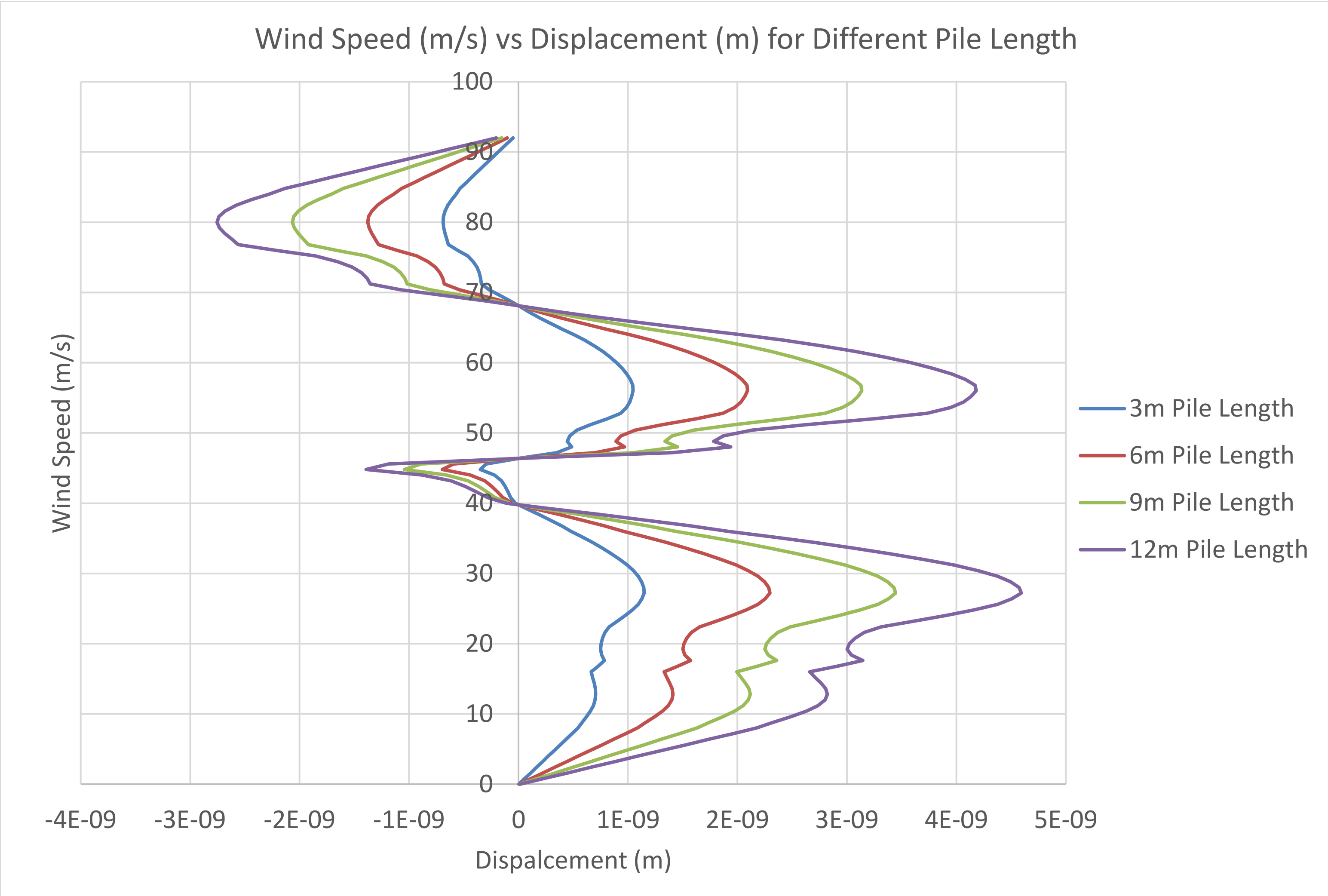


Figure 29: Wind Speed vs. Displacement for Different Pile Length

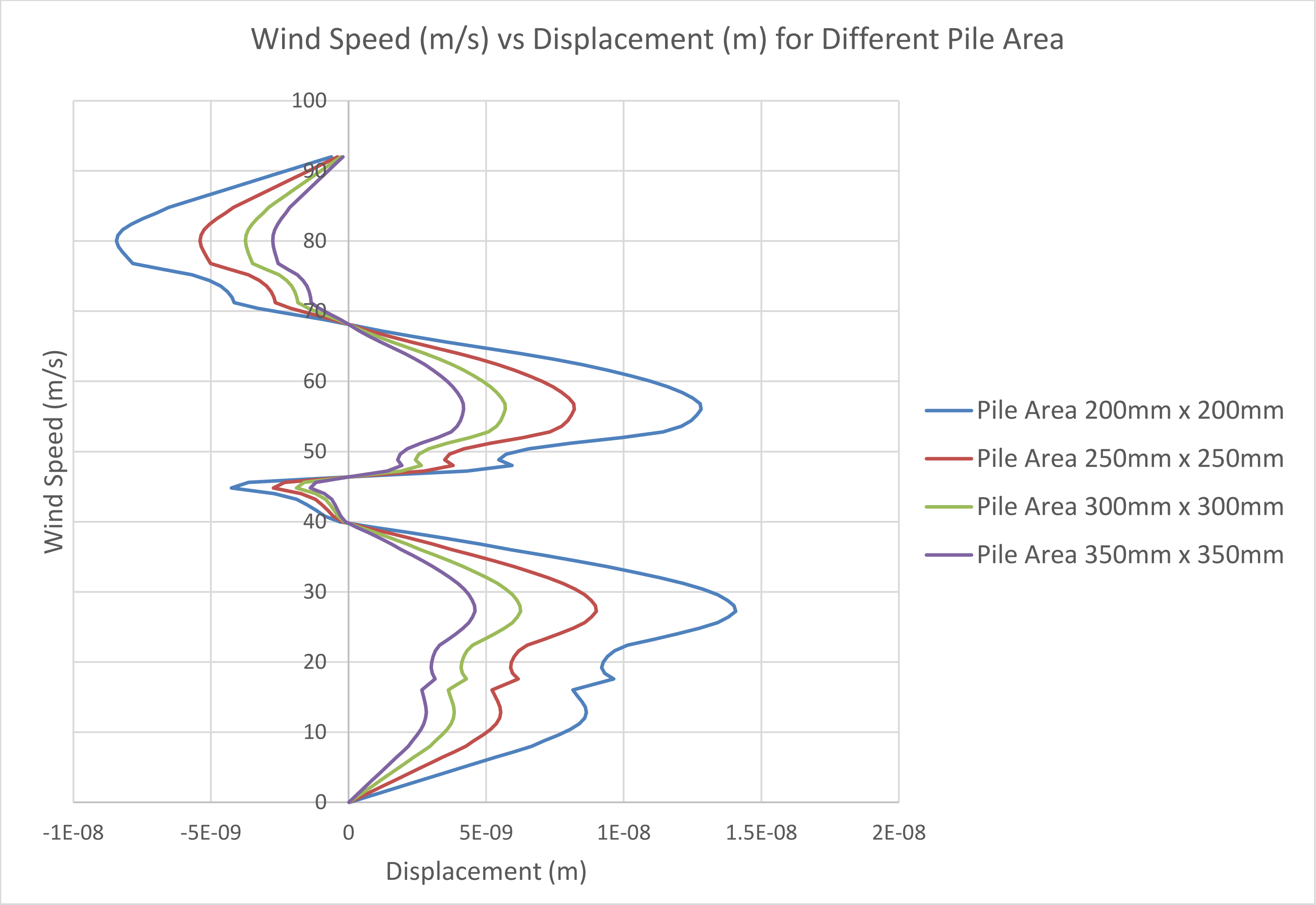


Figure 30: Wind Speed vs. Displacement for Different Area of Pile

From the Figure 27 and Figure 28 above, it shows the displacements of the pile foundation is linear to the load. This is because, the pile foundation of the wind turbine is modeled as a linear spring. However, the effect of the displacement of the pile foundation is very small but the effect will cause the soil around the pile foundation will be loose due to the cyclic loading acting laterally on the wind turbine tower. Form the Figure 29 and Figure 30, the displacement of the pile foundation can be observed within different wind speed. The graph shows that the displacement of the pile foundation is oscillated with the dynamic response that are applied to the blades which is the wind speed that causes the blade rotating. The graph is plotted against time in seconds since the dynamic force acting on the blade is changing with time.

CHAPTER 5

CONCLUSON & RECOMMENDATION

As the conclusion, the preliminary study about the wind turbine has been performed using multi-body system. The wind speed produce the pitching motions effects in increasing the angle of vortex causes the dynamic stall. The dynamic loads acting on the blade causes the blade to pitch omitting the effects on the tower to the foundation of the wind turbine. Thus, the method on how to conduct this project is presented in the methodology on how the model is created and the implementation of Blade Element Momentum Theory. Moreover, the effect of the load and the wind speed on the pile displacement have been studied as well as the dynamic behavior of the wind turbine. The displacement of the pile foundation is linear to the load as the pile is modeled as a linear spring. The effect of the displacement is increasing when higher load acting laterally to the pile. The effect of the pile displacement also has been observed, and the effect is oscillating to the wind speed. Due to the pitching motions, the movement of the tower towards and backwards cause the displacement of the pile oscillated when the wind speed is changing.

REFERENCES

Adhikari, S., & Bhattacharya, S. (2011). Vibrations of wind-turbines considering soil-structure interaction. *Wind and Structures*, *14*(2), 85.

Arany, L., Bhattacharya, S., Hogan, S. J., & Macdonald, J. (2014). Dynamic soil-structure interaction issues of offshore wind turbines. In *Proceedings of the 9th international conference on structural dynamics*, *EURODYN* (pp. 3611-3618).

Currie, M., Saafi, M., Tachtatzis, C., & Quail, F. (2015). Structural integrity monitoring of onshore wind turbine concrete foundations. *Renewable Energy*, *83*, 1131-1138.

Ingram, G. (2005). Wind turbine blade analysis using the blade element momentum method. version 1.0. *School of Engineering, Durham University, UK*.

Naghavi, N., & Baziar, M. H. (2008). Parametric Study of the Response of Single Pile under Lateral Loading at the Pile Head.

Wang, S., Huang, Y., Li, L., Liu, C., & Zhang, D. (2017). Dynamic analysis of wind turbines including nacelle–tower–foundation interaction for condition of incomplete structural parameters. *Advances in Mechanical Engineering*, *9*(3), 1687814017692940.

Wood, D. (2011). Small wind turbines. In *Advances in wind energy conversion technology* (pp. 195-211). Springer Berlin Heidelberg.

APPENDICES

Matlab Script Code

The matlab code below is used to calculate the lift and drag coefficient. The code is obtained from Chapter 3: Blade Element Momentum Theory book of Small Wind Turbine by David Wood, 2011

Calculation of Lift and Drag Coefficient, Cl and Cd

```
function [Cl, Cd] = LandD_0012(aoa, Re)
% Function to calculate the lift, Cl, and drag, Cd, coefficient of
% a NACA0012 aerofoil using the correlations of McCroskey, NASA
% TM 100019 (1987).
    if aoa > 12.0, aoa = 12.0; end
    if aoa < -12.0 aoa = -12.0; end
% Equn (4.3) for Cl is only valid for aoa < |12 deg|.
    Cl = aoa*(0.1025 + 0.00485*log10(Re/10^6));
% Equn (4.4) for minimum Cd.
    Cd0 = 0.0044 + 0.018*Re^(-0.15);
% A data fit to obtain Cd at other angles.
    delCd = (Cl/1.2)^2*0.009;
    Cd = Cd0 + delCd;
return
```

Calculation of blade pitch angle, radius of tip, radius of hub, chord of blade element, and twist of blade element.

```
function tcdist(nbes, pitch, r_tip, r_hub_in)
% M-file to give chord and twist distribution of the blade used by
% M. B. Anderson et al. Performance and wake measurements on a 3 m
% diameter HAWT, 4th Intl Symp. Wind Energy Systems 1982.
% The output is written to rad_ch_tw.dat where r_tip is in m
% radius is normalized by tip radius and angles are in degrees.

% Variables are:

%   nbes - number of blade elements
%   pitch   - blade pitch or setting angle in degrees
%   r_tip   - radius of tip (m)
%   r_hub   - radius of hub (m)
%   rad(i) - radius of the centre of element i
%   chord(i) - chord of blade element i
%   twist(i) - twist of blade element i

r_hub = r_hub_in/r_tip;
delr = ( 1.0 - r_hub)/nbes;
for i = 1:nbes
    if (i == 1)
        rad(1) = r_hub + delr/2;
    else
        rad(i) = rad(i-1) + delr;
    end
    chord(i) = chd(rad(i));
    twist(i) = t1(rad(i)) + pitch;
end
data_out =[rad' chord' twist'];

% Make the first line of the data contain nbes r_tip and r_hub
data_out =[nbes r_tip r_hub_in;data_out];
save('rad_ch_tw.dat','data_out','-ascii')

function out = t1(x)
% Twist distribution. Fit is 4th order poly to r/R = 0.7, then linear
if (x <= 0.7)
    out = 54.16632 - x*(307.42939 -x*(719.549614 - x*(785.971096- ...
            x*326.673372)));
else
    out = 5.318999 - 7.059999*x;
end
return

function out = chd(x)
% Chord distribution - 4th order poly fit
out =   5*(0.16165732 - x*(0.5847727 - x*(1.0327255 - x*(0.8756711 -
...
        x*0.2844545))))/3;
return
```

Calculation of power output.

```
function simple_power_calc(Numb)

% Program to implement blade element/one-dimensional wake analysis
for
% a horizontal-axis wind turbine with any number of blades of any
length.
% Unless otherwise specified, all length are normalised by the
% tip radius (r_tip) and all velocities by the wind speed, U0.  In
this
% version the blade element width (delr) is equal for all blade
elements.

% Function argument is:
%   Numb - number of blades

% Main variables are:
%   a - axial interference factor
%   adash - rotational interference factor
%   aoa - angle of attack of blade element
%   chord - chord of blade elment
%   C_a - factor for elemental thrust
%   C_adash - factor for elemental torque
%   Cd - drag coefficient
%   Cl - lift coefficient
%   Cp - power coefficient
%   Ct - thrust coefficient
%   delr - radial width of blade element
%   delthr - thrust on blade element
%   deltor - torque on blade element
%   lambda - tip speed ratio (TSR)
%   lamr - local speed ratio of blade element = X in Equn (3.7b)
%   gam - circulation of blade element
%   nbes - number of blade elements
%   phi - inflow angle between Ut and plane of rotation
%   Re - blade element Reynolds number
%   r_hub - radius of hub
%   r_tip - radius of tip (m)
%   rad - radius of midpoint of blade element
%   sigma - local solidity, Equn (3.15)
%   twist - angle between chord line and plane of rotation
%   Ut - effective velocity at blade element, Equn (3.7a)
%   U0 - wind speed (m/s)

visc = 1.5e-5; % Kinematic viscosity of air (m^2/s)
rho = 1.2;     % Density of air (kg/m^3)
tol = 1.e-4;   % Convergence tolerance for BE analysis
in = load('rad_ch_tw.dat'); % Read data file with radius, chord, and
twist
rad=in(:,1);      % Recover the radius of the blade elements
nbes = rad(1);    % First entry is nbes
rad(1) = [];      % Remove from array for radius
chord=in(:,2);    % recover the chord of the blade elements
r_tip= chord(1); % First entry is r_tip
chord(1) = [];
twist=in(:,3);    % Recover the twist of the blade elements
r_hub = twist(1);% First entry is r_hub
twist(1) = [];
delr=rad(2)-rad(1); % Determine width of blade elements
```

```
out_format='  %7.4f %3d  %7.2f  %7.3f  %7.3f  %8.5f  %8.5f  %8.3e \n';

U0 = 100.0;
while U0 > 0.0
   U0 = input(' Enter the wind speed in m/s: end with -ve: ');
   if U0 < 0.0, break; end
       while U0 > 0.0
            lambda = input(' Enter TSR: end with -ve: ');
            if lambda < 0.0, break; end
            thrust = 0.0; torque = 0.0;
            fprintf('\n')
            fprintf('   Radius  iter.  aoa       a       Cl       Cd')
            fprintf('      deltor      Re \n')
            a = 0.3; % Initialise a
            for i = 1: nbes % Loop over each blade element
                adash = 0.0; deltor = 0.0;
                lamr  =  lambda*rad(i);    %  Local  speed  ratio,  Equn
(3.7b)
                sigma   =   0.5*Numb*chord(i)/pi/rad(i);     %   Local
solidity, (3.14)
                diffa = 200*tol*a;
                j=1; % Misisng from program listing in book
                while diffa > tol*a
                     j=j+1; % Misisng from program listing in book
                     phi   =  atan((1   -   a)/(1   +   adash)/lamr)   ;   %
Eq.(3.12)
                     cosphi = cos(phi);
                     sinphi = sin(phi);
                     aoa = phi*180.0/pi - twist(i); % Eq. (3.8)
                     Ut  =  sqrt((1-a)*(1-a)  +  (lamr*(1 + adash))^2);
%Eq. (3.7a)
                     Re   =   Ut*U0*chord(i)*r_tip/visc   ;   %   Reynolds
number
                     [Cl, Cd] = LandD_0012(aoa, Re); % Find Cl and Cd
                     C_a = Cl*cosphi + Cd*sinphi; % For axial force
                     C_adash = Cl*sinphi - Cd*cosphi;% For tangential
force
% Balance wake axial momentum and blade thrust, Eq. (3.13), to find
new a
                     faca = Ut*Ut*sigma*C_a;
% Use Glauert's empirical correction when a > 0.5, Equn (2.20).
                     if faca > 1.0
                         newa = (1 + sqrt( faca - 1))/2;
                     else
                         newa = (1 - sqrt(1 - faca))/2;
                     end
                     diffa = abs(a - newa);
                     a = 0.5*(a + newa); % Average old and new a
                     adash = a*C_adash/(C_a*lamr); % Eq. (3.15)
                end
                Ngam = 0.5*Numb*Ut*Ut*chord(i)*C_adash/(1 - a);
                delthr = Numb*Ut*Ut*chord(i)*delr/pi;  % Eq. (3.10)
                deltor = delthr*rad(i)*C_adash;    % Eq. (3.11)
                delthr = delthr*C_a; % Complete Eq. (3.10)
                thrust = thrust + delthr; % Sum the rotor thrust
                torque = torque + deltor;    % Sum the rotor torque
                fprintf(out_format, rad(i), j, aoa, a, Cl, Cd, deltor,
Re)
            end
            cp = torque*lambda; % Find the power coefficient
```

```
            fprintf(' \n')
            fprintf(' Cp = %5f,    Ct = %5f  \n', cp, thrust)
            power = 0.5*cp*rho*U0^3*pi*r_tip^2; % Find Power in Watts
            thrust = 0.5*thrust*rho*U0^2*pi*r_tip^2; % Find Thrust in
N
            fprintf(' Power = %5e Watts,   Thrust = %5e Newtons \n',...
                power, thrust)
            fprintf(' \n')
        end
end
```