# Aeroelastic Simulation of Small Wind Turbine using HAWC2

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2013

**Abstract: Horizontal axis wind turbines are subjected to various static and dynamic loads under different load situations. Aeroelastic modelling is used in wind turbines to couple the aerodynamic and structural loads acting on the turbine and to analyse the aeroelastic response. The small wind turbine Nimbus 1.6 KW has been modelled in the Aeroelastic code HAWC2 which uses Multibody dynamics for the structural modelling and BEM theory for the aerodynamic part. The natural frequency and different modes of the turbine has been calculated after the complete modelling in HAWC2.**

**Keywords: HAWT, Aeroelastic modelling, Multibody dynamics, HAWC2, BECAS.**

# Acknowledgements

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**Appendices**

A  HAWC2 structural input file, fixed rotor.

B  Parameter File airfoil2BECAS, rotor blade section 3.

C  Wind Turbulence box, HAWC2.

# 1   Notation

| | |
|---|---|
| $A$ | Area |
| $a$ | Axial induction factor |
| $a'$ | Tangential induction factor |
| $C_d$ | Coefficient of drag |
| $C_l$ | Coefficient of lift |
| $c$ | Chord length |
| $c(r)$ | Chord length at radius 'r' |
| $E$ | Young's modulus |
| $F_N$ | Force in the normal direction of the rotor plane |
| $F_T$ | Force in the tangential direction of the rotor plane |
| $G$ | Shear modulus |
| $g$ | Acceleration of gravity |
| $J$ | Mass moment of inertia |
| $k$ | Spring coefficient |
| $M$ | Bending Moment |
| $m$ | Mass |
| $N$ | Number of blades |
| $r$ | Radius |
| $Re$ | Reynolds number |
| $t$ | Time |
| $U$ | Free stream velocity |
| $u$ | Velocity in x coordinate |
| $v$ | Velocity in the y direction |
| $V_{rel}$ | Relative velocity of wind |
| $V_{hub}$ | Velocity of wind at hub height |
| | Angle of attack |

| | |
|---|---|
| ς | Pitch angle |
| ν | Strain |
| ″ | Twist angle of the rotor blade |
| ~ | Kinematic viscosity |
| ω | Wind angle |
| Š | Angular frequency |

**Abbreviations**

| | |
|---|---|
| BECAS | BEam Cross section Analysis Software |
| BEM | Blade Element Momentum |
| DLL | Dynamic Link Library |
| DTU | Danish Technical University |
| FEM | Finite Element Method |
| HAWT | Horizontal Axis Wind Turbine |
| IEC | International Electro technical Commission |
| NREL | National Renewable Energy Laboratory |
| PET | Poly Ethylene Terephthalate |

# 2   Introduction

Aeroelasticity of wind turbines is the most important characteristic under research concerning wind turbines. The combination of aerodynamic, elastic and inertial forces acting on the wind turbine is very important in determining the efficiency and safety of wind turbines. Aeroelastic simulation is tool which helps to investigate the static and dynamic response of a wind turbine under various forces of excitation from different wind conditions. A clear understanding about the aerodynamics, structural dynamics and the interaction between these two enable the development engineers to design light weight highly efficient wind turbines. International Electro technical commission (IEC) has structured rules and standards which should be used to design and certify small and large wind turbines. IEC has also recognized Aeroelastic simulation as a tool which can be used to evaluate the forces acting on the turbine. This reduces the economic and time resources required for evaluation through experimental testing of wind turbines considerably.

According to IEC 61400-2, small wind turbines can be modeled either using a simplified model or with aeroelastic simulation model. The safety factor used in the simplified model is 3.3, which accounts for the turbine to be modeled for 3.3 times the maximum load acting in the worst case scenario. With a suitable aeroelastic model the safety factor can be as small as 1.1. This can highly influence the size and costs per kilowatt energy produced by the wind turbine which make the wind energy cheaper and affordable. The scope of the thesis is to set up a full aeroelastic model of the wind turbine and to do the natural frequency analysis. The aeroelastic simulation model is further used in aerodynamic analysis and load calculation studies of the same wind turbine.

The research in the field of Aeroelasticity in the field of wind turbines started in Europe with Friedmann who derived a set of equations for wind turbine coupled flag-lag torsional equations of motion [1]. These equations are written for single wind turbine blade to investigate the aeroelastic stability.

Risø-DTU is the leading research institute in the field of developing aeroelastic codes in Europe. The software HAWC2 is one of the most advanced softwares for analyzing both offshore and onshore wind turbines. HAWC2 uses Blade Element Momentum (BEM) method for the aerodynamic model, Multibody dynamics is used in the Structural dynamic model and wind simulation is done with the help of Wasp engineering. Matlab or Python is used for the post processing of the data [2].

FAST from National Renewable Energy Laboratory, USA is a free aeroelastic software which is based on Multibody dynamics. It's used extensively by wind turbine manufacturers and researchers in USA for aeroelastic research. Fast is based in the software interface Pearl, which uses BEM as the Aerodynamic model and a Model approach is used in determining the structural dynamics approaches of the wind turbine [3].

Bladed GH is an industry leading aeroelastic tool software from Garrad Hassan which is certified by Germanischer Lloyd for the certification and design of wind turbines. The tool is quite accurate with a simple Graphical user interface which uses BEM method for the aerodynamic model and Multibody dynamics for the structural dynamic model. Bladed is commercial software from Garrad Hassan which is used by various wind turbine manufacturers around the globe for the design and optimization of wind turbines. The software comes with various modules which provide complete modeling of offshore and onshore wind turbines. The modules include options for Static analysis, analysis of loads and energy capture and interaction with the electrical network [4].

The other similar aeroelastic codes dealing with wind energy are ADAMS/WT which is a Fortran based software using MSc Adams for the multibody dynamics part. The software is developed as a contract for NREL. YawDyn has been developed in University of Utah in association with NREL which focuses on the stabilization of yaw using the Adams for the structural dynamics parts and classical BEM theory for the aerodynamics part [5]. HAWC is an earlier version of HAWC2 from Danish Technical University using Finite element method instead of multibody dynamics. VIDYN is the aeroelastic code developed by Teknikgruppen AB in Sweden which uses BEM for aerodynamic model and Model analysis for the evaluation of structural stability. PHATAS is an

aeroelastic code from ECN which uses frequency domain calculations for integrated pitch and yaw control.

The aeroelastic research in wind turbines a new and gradually evolving field. National Renewable Energy Laboratory, USA and Danish wind energy institute are the top two research institutes working on the aeroelasticity of wind turbines. The other major players in this field include ECN, Netherlands and Garrad Hassan UK. The published papers on aeroelasticity in different countries around the world retrieved from the engineering index are shown in the figure 1.1 [6].



Denmark(65)     United States(53)
China(37)     Greece(25)
Netherlands(18)     Germany(16)
France(15)     United Kingdom(12)
Sweden(8)     Italy(7)
Australia(6)     Canada(5)
Belgium(5)     Spain(5)
New Zealand(4)     India(3)
Romania(3)     Japan(2)
Republic of Korea(2)     South Africa(2)
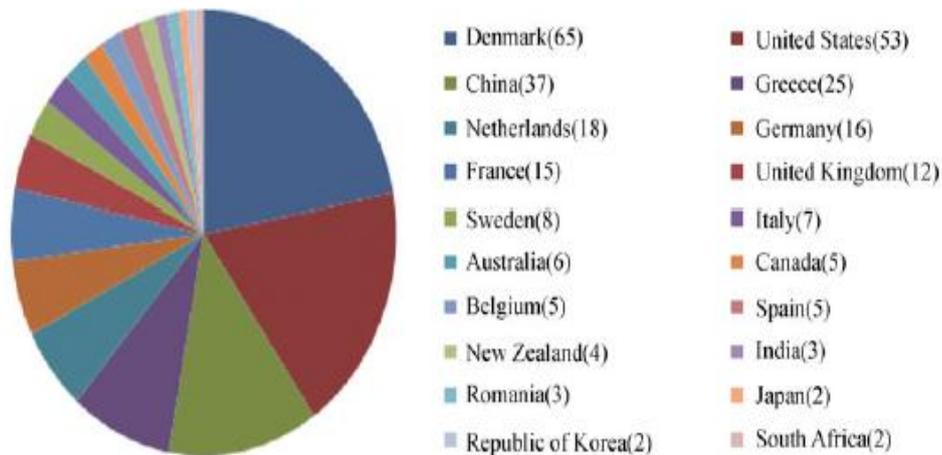
*Figure 1.1. Distribution of Research papers on Aeroelasticity in different countries published in Engineering index.*

Out of these various softwares available for aeroelastic simulations three of them are shortlisted for the final evaluation. FAST, BLADED and HAWC2 are analyzed in detail to choose the optimum software based on the following parameters.

- Validated software with extensive usage in research and Industry.
- Availability of the software.
- Availability of documentation and services.

- Ease to use.

FAST, BLADED and HAWC2 are analyzed in detail to choose the optimum analysis tool for our case.

# 3    Aeroelastic Modelling of Nimbus 1.6 KW HAWT in HAWC2

Aeroelasticity is the combination of analysis of different forces like aerodynamic forces, inertial and elastic forces interacting with each other, aeroelastic softwares are platforms where these three approaches interact with one another to determine the resultant loads in the turbine. Different softwares or codes use different approaches to analyze each of these parameters.

HAWC2 has been used in the research process for aeroelastic modeling. The software has been validated and extensively used in researches and industries all over the world. The software doesn't have a well defined user interface, the user is expected to know the coding structure of the program and can make sufficient changes in the htc files which is the interface to the HAWC2 solver. This makes the software extremely flexible which enables the user in simulation modelling and creating user defined equations which can be then solved using the software. The free student research license of the software from the developers from RISOE, Denmark is used for the aeroelastic modeling in this project.

The code is capable of modelling both onshore and offshore wind turbines with one or multiple blades. The code is capable of modelling the control systems in wind turbines. The pitch controlled wind turbine can be modeled and the code can be incorporated with the real active pitch control system used in the wind turbine with a suitable DLL. This DLL is then connected to the HAWC2 interface. It can be also used to model traditional stall controlled wind turbines as well. The code has well defined structure which enables the user to model the foundation characteristics like guyed support structures, the monopoles, tripods and jackets for offshore wind turbines. The soil module helps to design the soil and the foundation in a more realistic way. The code has the capability to simulate multiple rotors in one simulation and also to simulate the floating turbines and mooring lines.

The aerodynamic part of the code contains extension of the BEM theory with three dynamic stall models. These include, Stig Oye model, Active trailing edge flap model and also a model of modified Beddoes Leishmann model. The software is capable of taking into account the skew inflow, the tip loss correction method or Prandtl's correction method, dynamic inflow and the wind shear characteristics that usually occur in the real environments [6].
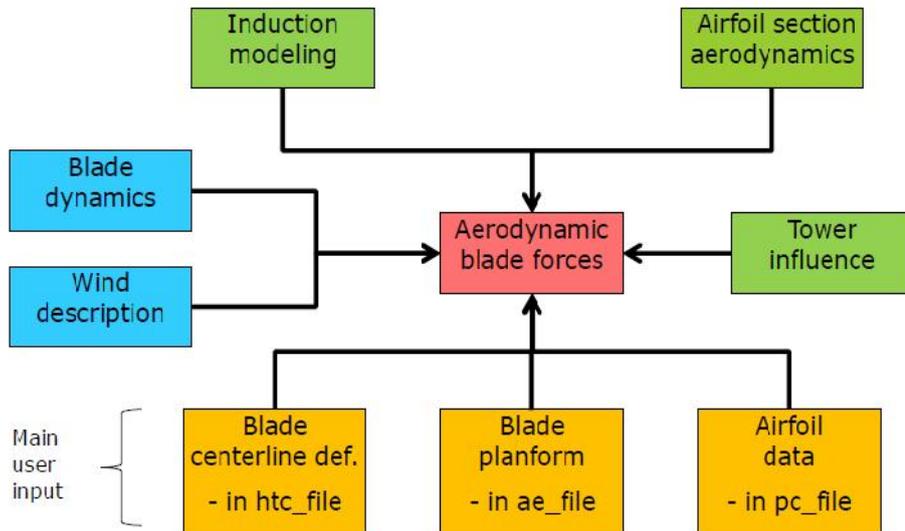


*Figure 3. 1 Aerodynamic modelling phases in HAWC2 [6].*

The control of the turbine is basically done by using a Dynamic Link Library. This control program is linked to the HAWC2 interface during the simulations. As explained before, HAWC2 is able to model both stall regulated and pitch regulated wind turbines. A pitch controlled variable speed controller developed by DTU has been given as default DLL. This will be further used in the project for the simulations. An in-house DLL has to be developed according to the passive pitch control system for Enbreeze in future.

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## 3.1  Nimbus 5.2 1.6 KW wind turbine

Nimbus 5.2 is the second generation Prototype from Enbreeze Gmbh, specialized in the field of small wind turbines based in Germany. The wind turbine uses Pitch control system with an innovative mechanism which automatically turns the rotor blades away from the wind with increasing wind speeds. The patented pitch control system designed by enbreeze is purely mechanical and is designed such that the rotor blade pitches out the wind with increasing wind speeds and constant power is delivered in all wind speeds. The second generation prototype installed in the test field at Nattermannalle, Koln is shown in Figure 3.1.2. This turbine is used for study under the project.



*Figure 3.2 Nimbus 5.2 1.6 KW prototype.*

The turbine is developed by the Research and development team of Enbreeze GmbH and has been installed in December 2012 for testing and validation.

The specifications of the turbine are shown in the Table 3.1 below

*Table 3.1 Specifications of Nimbus 5.2.*

| Properties | Nimbus 5.2 Enbreeze |
|---|---|
| Rated Power | 1.6 KW |
| Rated speed | 7 m/s |
| Cut in wind speed | 3 m/s |
| Design wind class | II (DIN EN 61400-2) |
| Rotor diameter | 5 m |
| Rotor type | Down wind |
| Blade Material | PET |
| Control | Mechanical Pitch control |
| Rotor swept area | 20 m$^2$ |
| Direction of rotation | Clockwise in the down wind direction |
| Number of blades | 3 |
| Pitch angle | Variable |
| Yaw system | Passive |
| Nacelle Tilt | 0 degree |
| Teetering in rotor | Non teetered type. |
| Coning angle | 0 degree |
| Generator | Permanent magnet generator |
| Tower height | 6 m |
| Tower top mass | 151.2 kg |
| Tower base diameter | 152.4 mm |

The control of the wind turbine is passive mechanical pitch control. The Autodesk inventor representation of the mechanical pitch control system has been shown in the figure 3.3. The rotor blades are connected to a central cam disc called with three roller arms. There are two dead weights attached to each rotor blades shaft. The dead weights assist the rotor blades to turn back to the wind when there is a decrease in wind speed. A direct drive permanent magnet generator has been used for generating electricity. The generator torque is controlled by inbuilt software program developed by Enbreeze. The cut in speed of the turbine is as low as 3 m/s and the wind turbine blades are designed to produce 1.6 KW at a rated wind speed of 7 m/s at an optimal tip speed ratio of 6.1. The turbine is equipped with a passive yaw system. The rotor blades are placed without a coning angle or nacelle tilt with respect to the horizontal plane. The center of mass of the nacelle coincides with the center of axis of the tower. The mass of the nacelle and the rotor is 151.2 kg. The inertia of the rotating parts of the generator is 0.66 kgm$^2$
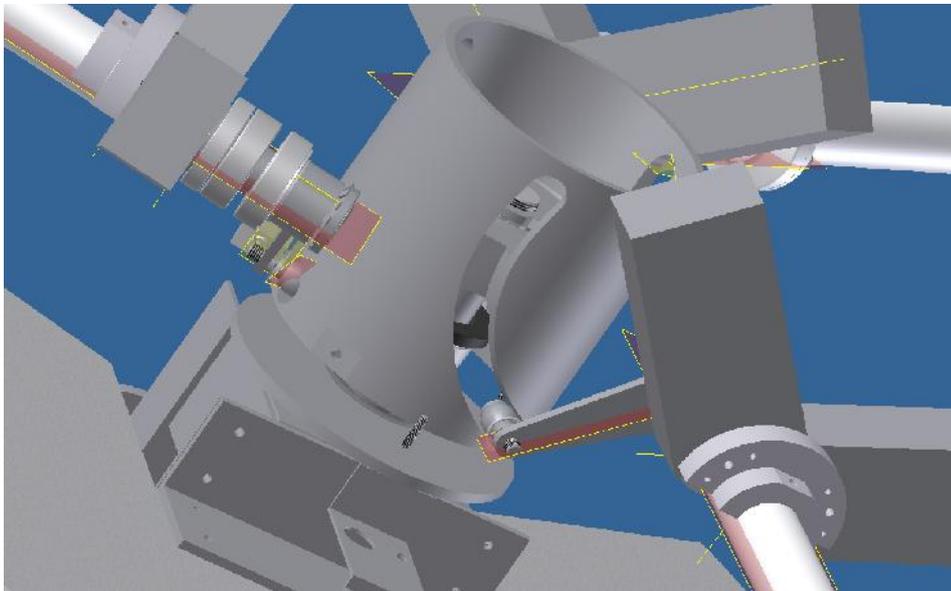


*Figure 3.3 Passive pitch control mechanism in Nimbus 5.2.*

## 3.2 Aerodynamic Modelling

Aerodynamic models are implemented using different aerodynamic theories in fluid mechanics such as

- Blade Element Momentum theory
- Free wake panel method

Among these two, Blade element theory is most widely used because of its computational easiness and accurate results with less input. The BEM theory is discussed below.

### 3.2.1 Blade Element Momentum Theory

The blade element theory can be used in the aerodynamic modeling of the rotor blades. The blade is divided into a number of cross sections along the length of the blade and the each 2D element is analyzed. The lift and drag in each section along with the thrust and the torque is balanced. Besides the force balance, the equilibrium of momentum is also considered. Both axial momentum and angular momentum are applied. The balance of rate of change of fluid momentum with the blade forces is established for each annular area [7].

The lift acting on the wind turbine is given by the equation,

$$L = \frac{1}{2} \ldots V^2{}_{hub} c C_L \qquad\qquad (3.1)$$

The drag force can be found out from the equation,

$$D = L = \frac{1}{2} \dots V^2{}_{hub} c C_D \qquad (3.2)$$

The rotor blade profiles starts stalling at an angle of attack of 12-15 degree depends upon the aerodynamic profile and the position of the profile in the span of the rotor blade. This is due to the increase in turbulence in the upper part of the blade which decreases lift and increases drag. The force balance on an airfoil according to the BEM theory is shown in Figure 3.4
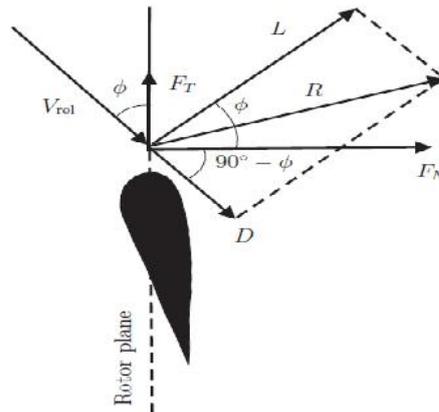


*Figure 3.4 Force balance on an aerofoil according to BEM [7].*
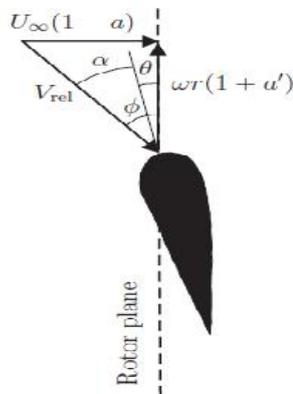


*Figure 3.5 Velocity triangle at the aerofoil section [7].*

The fraction of annular area covered by the control volume is

$$\sigma = \frac{c(r)N}{2\pi r} \tag{3.3}$$

where c(r) is the chord length at the radius r, N, number of blades

r, the radius of the rotor blades.

The Thrust and Torque on the control volume is given by

$$dT = NF_N \, dr = \frac{1}{2}\rho N \frac{U_\infty(1-a)^2 cC_N dr}{\sin\phi^2} \tag{3.4}$$

where dT is the is the thrust in N ,$U_\infty$ is the free stream velocity in m/s, N is the number of blades, a is the tangential induction factor

$F_N$ and $F_T$ are the forces per unit length in N/m

$$dQ = rNF_T \, dr = \frac{1}{2}\rho \frac{U_\infty(1-a)r\Omega(1+a)cC_T r dr}{\sin\phi \cos\phi} \tag{3.5}$$

The two induction factors are defined as

$$a = \frac{1}{\dfrac{4(\sin\phi)(\sin\phi)}{\sigma C_N}+1} \tag{3.6}$$

$$a' = \frac{1}{\dfrac{4(\sin\phi)(\cos\phi)}{\sigma C_T}+1} \tag{3.7}$$

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$$\tan \phi = \frac{U_\infty (1-a)}{r\Omega(1+a)} \tag{3.8}$$

These set of non linear equations are solved numerically. The blade element theory provides accurate results in comparison to the cost of time spent on computation. Each control volumes are assumed to be independent and each strip is computed for the results before starting the computation of the next radius.

### 3.2.2   Free wake panel method.

Free wake panel method is another method used for aerodynamic modeling. Free wake modeling is used when the flow is subsonic and viscous effects are negligible. The method is generally used in aerospace industry for conceptual analysis because of its easiness and less time required for the results.

Panel method can be used to predict the lift and form drag. It cannot model viscous effects like boundary layers and flow separation. The Skin Friction drag cannot be calculated by this method. A wake is generated on the trailing edge of the aerofoil for the calculation of lift and drag, The method is incapable of calculating the lift and the form drag without the wake due to its inviscid modeling nature.

### 3.2.3   Aerodynamic modeling in HAWC2

Aerodynamic modeling in HAWC2 uses the classic Blade Element Momentum theory approach to model the aerodynamic forces acting on the blade. The aerodynamic forces acting on the structure includes the forces acting on the blades as well the aerodynamic drag forces acting on the

tower and the nacelle. The forces are the transferred to the structural model to calculate the aeroelastic response. The aerodynamic input to HAWC2 is distributed in 3 main files.

- Center line definition of the blade in .htc file

- The Profile coefficients (Polars) of the rotor blades sections in the .pc file

- The data of the blade Plane form in the .ae file.

The profile coefficients of the blades are obtained by a 2D CFD simulation of the rotor blades. The center line of the blades is defined with respect to the global coordinates the structural file. The thickness to chord length ration along the span of the blade is calculated for respective sections and is written inside the .ae file.

The aerodynamic modeling in HAWC2 is able to predict the dynamic inflow which occurs when the wind load changes are faster than the time needed for the inflow velocity to be in equilibrium with the aerodynamic loads. The design for the skew inflow will take care of the real cases with a yaw misalignment such that the flow is not always axisymmetric. The shear effects on the blade due to different wind speeds with respect to blade section height from the ground are taken care into account using a polar grid induction model. When there is very large displacement of the end of the rotor blades such that the rotor blades are not perfectly rotating in the rotor plane, the thrust on the rotor blades changes and so the induced velocities. This effect is considerable in modeling very large wind turbine blades. Prandtl's tip correction model has to overcome BEM theory's assumption of having infinite number of blades. Glauert's yaw correction formula is used to derive the resultant induction factors in different yaw misalignment cases [6].

The BEM procedure used in HAWC2 is implemented by discretizing the rotor plane into independent concentric annular elements and azimuthal variation of loading.

- The local wind speed is obtained at each point of the polar grid and the local induced wind speed from the previous iteration is used for the calculation.

- The local coefficient of thrust is calculated at two neighboring blades which has the local wind speed and the local induction used.

- The Prandtl's tip loss factor which take care of the assumption of infinite number of blades in BEM theory has been rectified

- The local CT is obtained by interpolating the CT based on 2 blades and the azimuthal distance between the wind speeds.

- The local induction factor 'a' is obtained at the point.

- The correction for skew inflow angle is added to the induction factor

- The tangential induction factor is then calculated

- The axial and tangential induction factors are then calculated.

- In accordance with the skew inflow angle and axial induction influence, a correction is made for the azimuthal variations of axial induction.

- The tangential u and axial u are updated based on two first order low pass filters. This is done such that both near and far wake [8].

These steps are done for each point in the polar grid, after this for each point in the blade the induced velocities are calculated at a radius by azimuthal interpolation of two closest grid points.

### 3.2.4  Determination of Polars of rotor blade airfoil Profiles

The Aerodynamic part of HAWC2 works on BEM theory. The blade is defined as different sections starting from the tip of the blade to the rotor centre. The structural properties, the aerodynamic coefficients and the aerodynamic layout are defined in 3 different data sheets and are linked to the HAWC2 program.

The aerodynamic layout file contains the data for defining the rotor blade profile with respect to the Z axis which starts the last node of the hub. The

position of the aerodynamic centre is kept at $C_{1/4}$ of the Chord, where C is the chord length with calculated velocities in $C_{3/4}$ as shown in figure 3.6 and in Figure 3.7.
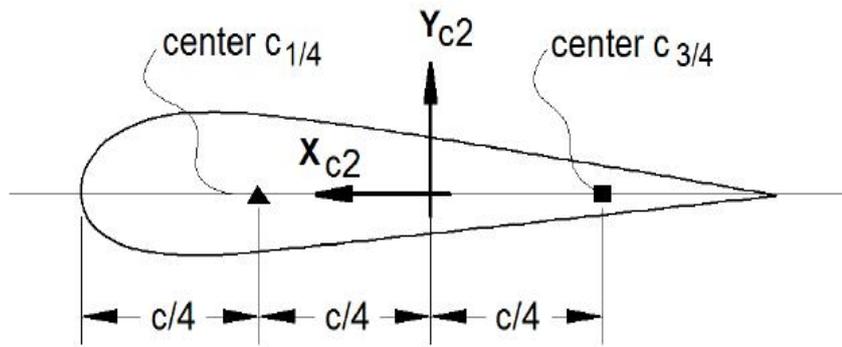


*Figure 3.6 Definition of aerodynamic centre on aerofoil section [6].*
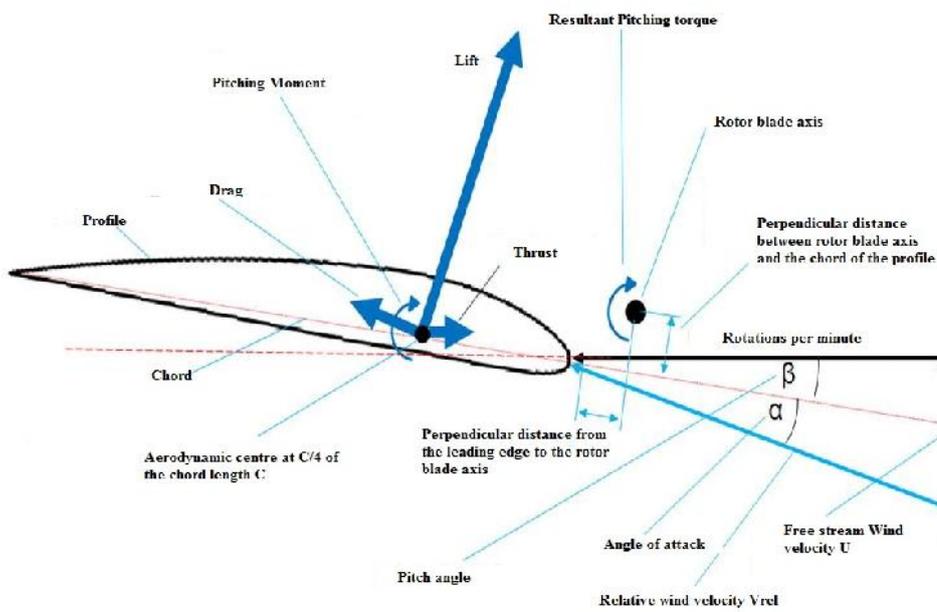


*Figure 3.7 Forces and angle velocity on the rotor blades.*

### 3.2.5 Enbreeze Rotor blades

The rotor blades used in the wind turbine has been developed by the company named Aerodesign works. It of 2.5 m in diameter and is fabricated with PET. The rotor blades are designed for a rated Power of 1.6 KW at 7 m/s. The HAWC2 aerodynamic input requires the Polars of the rotor blade from angles of attack range from -180° to +180 ° degrees. The lift and drag coefficients of the rotor blades at different angle of attack are found out using Solid works flow simulation student version. Various 2D aerofoil analysis softwares likes Java foil, Aerofoilengineering, X foil, and Qblade where used to for the same and the results have been tested for the lift and drag coefficients available and it is found that Solidworks flow simulation has more stability and better results especially near the stall region. The simulation setup has been validated for a NACA airfoil and the results were obtained with an error of ±5 %.

Five Profile sections along the length is selected as shown in the Figure 3.8.
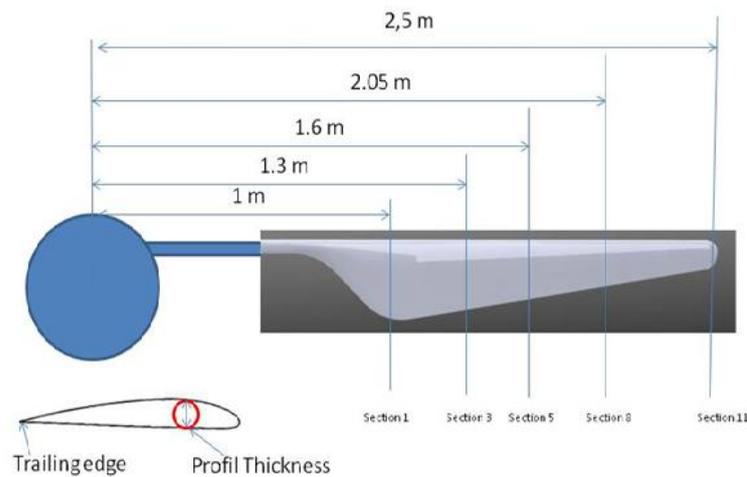


*Figure 3.8 Aerofoil sections under analysis at different parts of the blades.*

An initial computational mesh of 400*300 is created. A local mesh is created in the interface where solid and fluid cells interact. A very high mesh refinement level is given to capture the change in properties where the solid and fluid interact as shown in Figure 3.9.
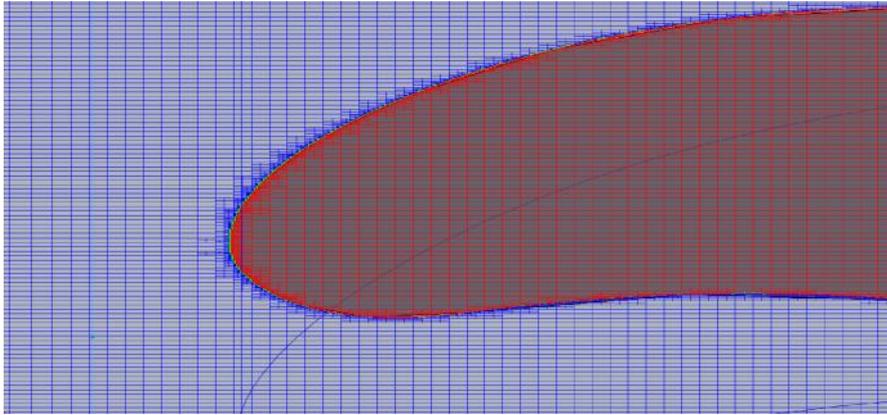


*Figure 3.9 Refined partial cells at solid fluid interface.*

Symmetric boundary conditions are given at both ends of the Z axis which is necessary for 2 D flow. The inlet velocity for each section is calculated based on a constant Reynolds number. The Reynolds number selected for the flow is Re=300,000. The inlet velocities for each section are calculated from the formula

$$\text{Re} = \frac{...vL}{\sim} \tag{3.9}$$

where Re is the Reynolds number

v is the velocity in m/s

l is the length in m

μ is the kinematic viscosity in Ns/m$^2$

The inlet velocities are defined such that the flow is towards the positive x direction, and the solid fluid interaction begins at the leading edge and

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leaves the rotor blade at the trailing edge. A turbulence intensity of 0.1 % and turbulence length of 10 micro meters are selected. The resultant forces on the x direction are equal to the Drag force of the profile and the force in the y direction is equal to the Lift force. The coefficient of lift and drag are calculated from the following equations written below. 5 Sets of Batch simulations were done for different angle of attack starting from 0 to 90 degrees. Each batch simulations included 20 simulations. The coefficient of lift versus angle of attack is shown in Figure 3.10 below. It can be seen that the most of the rotor blade sections stall at an angle of attack of 18 -20 degrees.
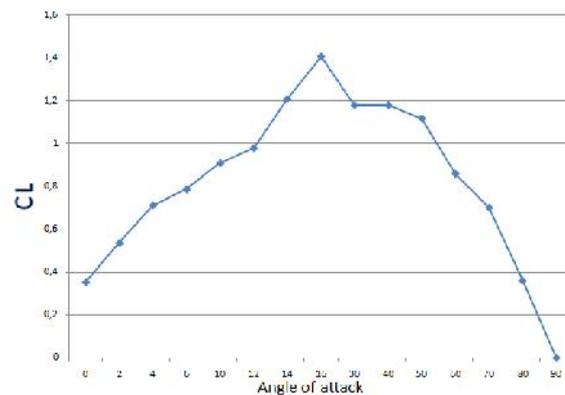


*Figure 3.10. $C_L$ versus angle of attack, section 11*

## 3.3   Structural Definition

Aeroelastic simulation includes aerodynamic and structural simulations. The dynamics of the operation of wind turbine can be understood by the structural modelling of the HAWT in Multibody dynamics. It can be also understood as floating frame approach. The wind turbine structure is divided to a number of elements. Each element is considered as a Timoshenko beam element which accounts for both shear and bending deformation. Each body has its own coordinate system. The calculation of inertial loads is based on this coordinate system when the body is moved in space. This gives the advantage of accommodating for large deflections and rotations which is hard to be visualised in FEM method [9].

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Each element interacts with the neighbouring elements with joints. The constraints are imposed in these joints and are implemented as algebraic equations. The HAWC2 is designed such that external loads are applied on the deformed state and this is very useful in analysing pitch loads and twist of the blades [9]. When the elements are divided accordingly, HAWC2 will be able to simulate large rotations and also the wind turbine with highly flexible structures.

## 3.4   Definition of Tower and Nacelle Components

The main structural components such as Tower, the connection between the tower and the Nacelle, the Yaw bearing, the main rotating shaft and the hub, pitch bearing between the hub and the rotor blades and the rotor blades has to be modelled for the aeroelastic analysis of the turbine. The HAWC2 models the structural components as Timoshenko beam elements with defined Centre line of the each components with reference to the local and global coordinate system. The definition of the centre line is the first and foremost part of the structural definition. Each structural part is defined as Timoshenko beam element with 19 Structural properties shown in the table 3.2. The representation of elements and nodes used in my model is shown in Figure 3.11.

All bodies are modelled as Timoshenko beam elements with 6 Degrees of Freedom. These 19 parameters define the Timoshenko beam input parameters for the calculations and these have to be calculated with respect to each node in the each structural body. The structural and material damping for these beam elements are also given in the .htc files. The orientation of each node is also given as input with corresponding constraints for motion.

Multibody dynamics is used in the structural modelling which uses the floating frame approach of the reference point. Large deflections (translations) and rotations are calculated on the points where the nodes of the main body structures interact while small deflection is calculated within each main body nodes [9]. The joints for each main body structure have coupled with each other using algebraic equations. This helps to model non linearity like large deflection and rotations being passed from one main

body to an another body. The floating frame approach can be visualised in Figure 3.12
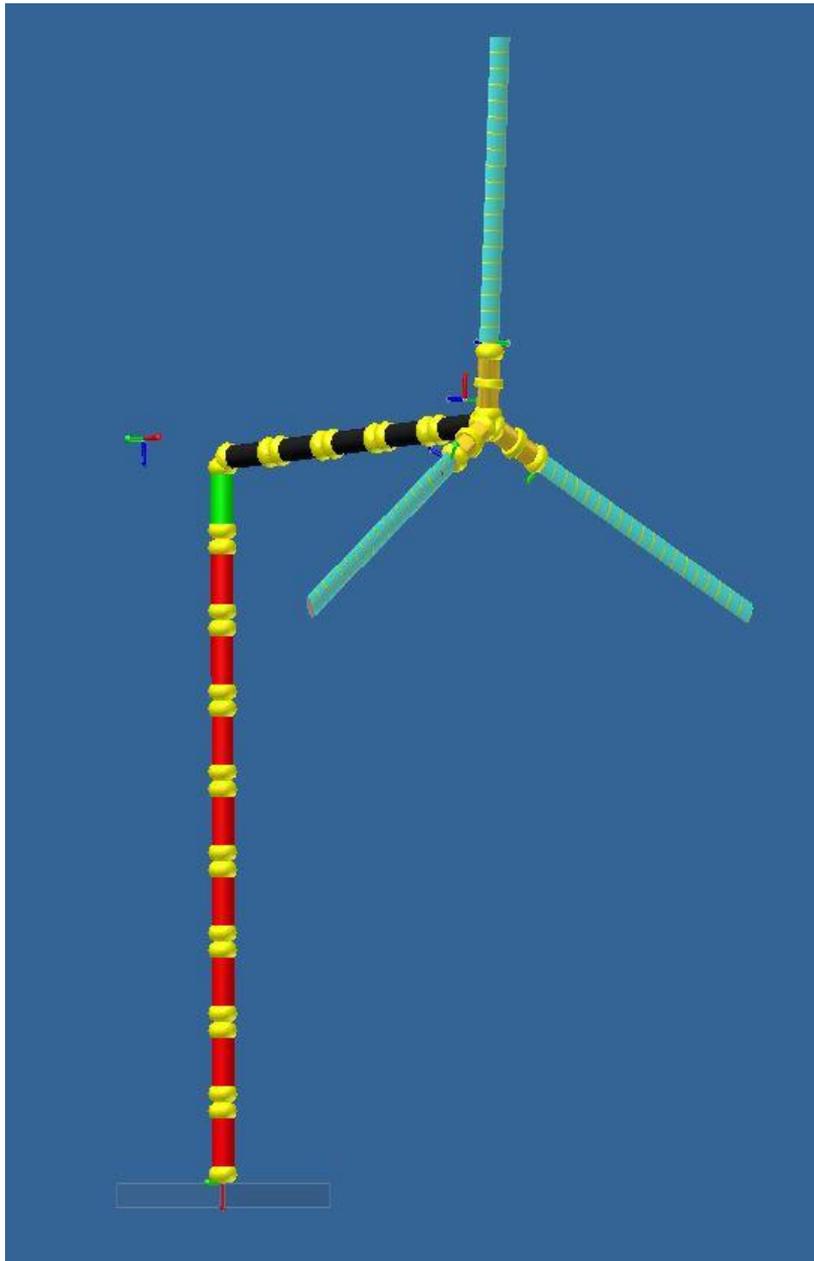


*3.11. Multibody formulations, elements and nodes in the structure.*

*Table 3.2.1 Structural input for HAWC2.*

|         | **Value**                                                                 |
|---------|---------------------------------------------------------------------------|
| *r*     | Curved length distance from the main_body node 1[m].                      |
| *m*     | Mass per unit length kg/m                                                 |
| *xm, ym* | xc2 and yc2 coordinate from C1/2 to mass centre [m].                     |
| *rix*   | Radius of inertial related to elastic centre.                            |
| *riy*   | Radius of inertial related to elastic centre.                            |
| *xs, ys* | xc2 and yc2 coordinate from C/2 to shear centre[m].                     |
| *E*     | Modulus of elasticity, N/m$^2$.                                           |
| *G*     | Shear modulus of elasticity, N/m$^2$.                                     |
| *Ix*    | Area moment of inertia with respect to the principal bending xe axis [m$^4$]. |
| *Iy*    | Area moment of inertia with respect to the principal bending ye axis.    |
| *K*     | Torsional stiffness constant with respect to the ze axis at the shear centre.[m$^4$/rad]. |
| *kx*    | Shear factor for force in principal bending xe direction.                |
| *ky*    | shear factor for force in principal bending ye direction                 |
| *A*     | cross sectional area[m$^2$]                                               |
| *s*     | Structural pitch with respect to zc2 axis.                               |
| *xe, ye* | xc2, yc2coordinate from C1/2 to centre of elasticity[m].                |

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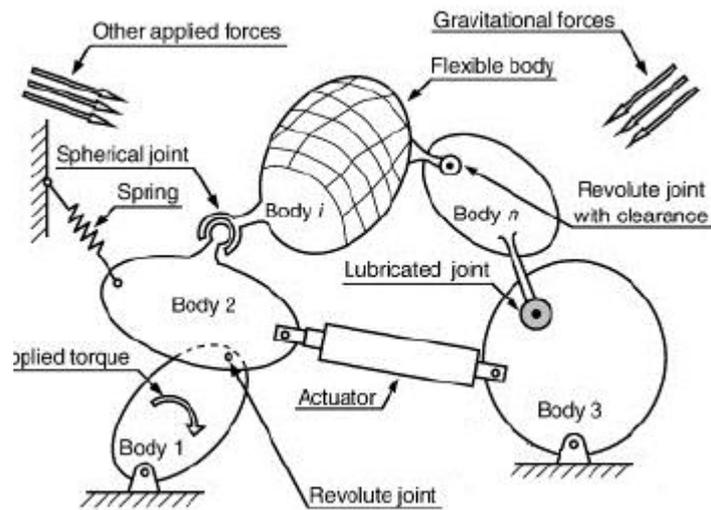
*Fig. 3.2.2.1 Multibody dynamics approach.*

Modelling of the wind turbine is done by breaking down the wind turbine to main bodies and sub structures. The main bodies in the enbreeze Nimbus 5.2 include

- Tower.

- Connection between tower and Nacelle.

- Main rotor shaft.

- Hub.

- Connection between hub and the rotor blades.

- Rotor blades.

Each main body can be divided into a number of sub bodies or sub structures. Main bodies are linked to each other with joints.

*Figure. 3.13. Definition of beam element nodes*

The properties of the main bodies are first defined with respect to its own coordinate system. Each bodies has its own coordinte systems. These coordinate systems have its own orientation with respect to the global coordinate system.
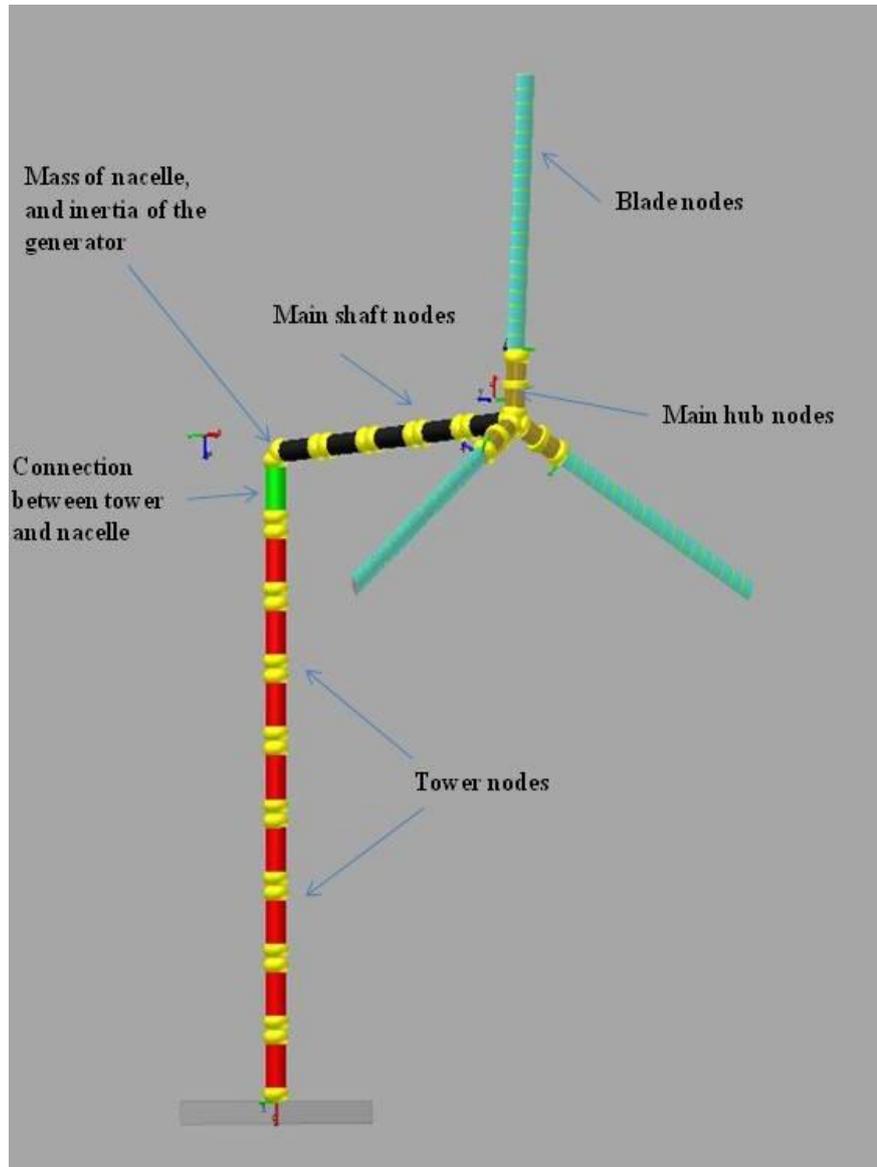
31

The tower of enbreeze Nimbus 5.2 is 6 m long in length. The tower is modeled with 8 elements with the first node of the first element being fixed to the ground and the last element of the 8th node which is connected to the connection element between the tower and the nacelle. The base node or the first node of the tower is fixed and attached to the ground using fix 0 constraint in HAWC2 which restricts both translation and rotation at node 1. The global coordinate system is kept such that negative x is pointing towards the increasing tower height and negative y in the direction of wind in our down wind case. The structural properties above mentioned in Table 3.2 has been calculated for each section and has been updated in the .st file in the HAWC2 data section.

The connection between the tower top and the nacelle is defined with one element consisting of the first node attached to the tower top and the second one at the beginning of the rotating shaft. The Nimbus 5.2 consists of a rotary flange with the bearing block which consists of the yaw bearing and suitable structures for accommodating the slip rings and the other components for instrumentation. The connecting structure is modeled as a single structure with one beam element. The connecting block is 200 m long and has the same direction of xyz coordinates as the global case and the node connecting the tower, but rotated along the x axis with an angle of -90 degrees and the rotated at an angle of 180 degrees on the y axis on the node connecting to the shaft. The change in orientation at different nodal points can be seen in the figure 3.15 below. The second node of this beam element where the first node of the shaft is attached is the place where the mass of the nacelle and inertia of the nacelle is given. The inertia of the structure is calculated using Autodesk Inventor with respect to corresponding orgin from the CAD files used in the design and production process.

The main body, the rotor shaft of the wind turbine which connects the rotating rotor blade hub to the generator is modeled as a Timoshenko beam with 5 elements. The shaft is 0.5 m long in our case. The first node of the beam element of the shaft which links the connection between the shaft and the tower intermediate structure has given the generator inertia and the last node of the 5 beam element has given the mass of the rotating parts which include the hub, the rotor blades, 3 in our case and the dead weights which are used to assist the rotor blades in the control system when the wind speed decreases so that the rotor blades pitches back to the wind. There are

2 bearing in our case, the main rotating shaft bearing and also a bearing in the middle of the shaft for better stability and also connecting components like flexible couplings attaching the rotor shaft and the generator shaft. These components are not directly modelled in our case, but added with the generator mass and inertia to consider the effects of the extra mass and inertia of these components. The orientation of the coordinate system is changed at the last node of the shaft to model the rotor plane. The coordinates from the tower top is rotated 90 degrees in the anticlockwise direction with respect to x axis and then rotated 180 degrees clock wise.

The hub of the enbreeze wind turbine consists of the innovative pitch control system and suitable connection mechanism to connect the rotor blades to the hub. The control of the wind turbine is mechanical pitching of the rotor blades in a cam disc. The control of the system has to modelled in a suitable program like C++ or Python and to be linked to the HAWC2 program. This has not been done due to the time and economic constraints at the moment. In the HAWC2 structural input the hub is defined as a main body. Three hubs are defined for a 3 bladed wind turbine as a main bodies, with one beam element each. The first node of each hub element is attached to the last node of the shaft and the second node to the rotor blades.

The coordinates from the tower top is rotated 90 degrees in the anticlockwise direction with respect to x axis and then rotated 180 degrees clock wise for the first hub. For the second and third hub the coordinates systems from the tower top are then rotated 90 degrees in anticlockwise direction with respect to y axis and then rotated 60 degree anticlockwise with respect to the y axis to accommodate 120 degree angle between the 3 rotor blade axes. The hub is made of aluminum. The beam element representation of the whole structural representation can be seen in the Figure 3.13. The eccentricity of the position of rotor blades in coinciding to the central point in the rotor axis is shown by the Figure 3.14. This feature helps to reduce the flap wise bending moment in the rotor blades.

The pitching axis of the wind turbine rotor blades are designed such they usually coincide at the centre of the rotating axis. In our case the axis of each rotor blades are kept at an eccentricity of 0.1 m from this axis. This feature has been modeled using suitable function in the HAWC2.
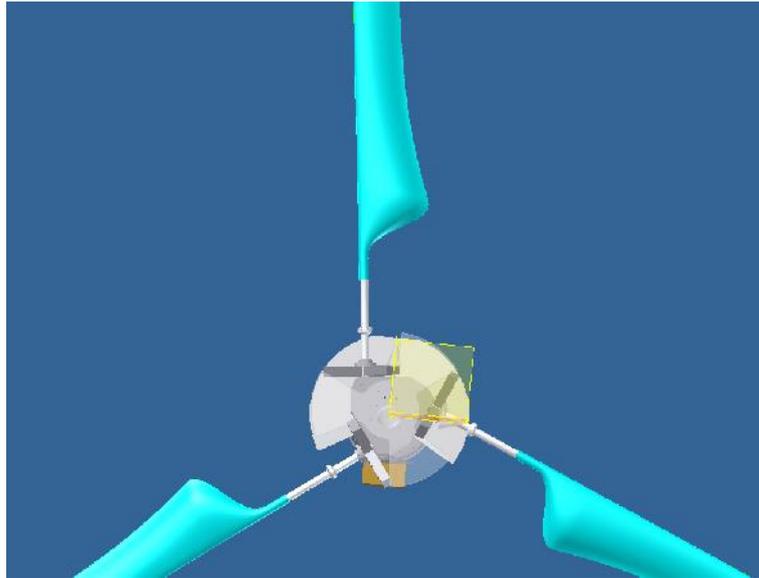
33

*Figure 3.14 Hub, Nimbus 1.6 KW Autodesk inventor view.*

The rotor blades are attached to the hub. The main body rotor blades are designed with 7 beam elements across the length of the rotor blades. The blades are 2.5 m in length and which consists of cylindrical structure with all the necessary components like flying weights and suitable connection mechanisms till 1 m and then 1m to 2.5 m composes blade profiles. The blades are designed for very small wind speeds with an optimal tip speed ratio of 6.1. The cut in speed of the rotor blades are as slow as 3 m/s and the optimal wind speed is 7 m/s, producing a power of 1.6 KW.

The orientation of the coordinates of the rotor blades are similar to the last node of the respective hubs they are connected with. The rotor blades of the down wind turbines are usually provided with a coning angle. The coning angle is the angle between the pithing axis of the rotor blade with respect to the rotor plane. Studies has showed that coning angle helps the down wind turbine to align better with the wind when the wind changes it direction. The coning angle is given 0 degree in our case for preliminary analysis and the wind turbine nacelle is at 0 degree tilt with respect to the horizontal plane. The structural properties of rotor blades are accurately obtained

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using a Beam Cross Section Analysis Software called BECAS from Danish Technical Institute.
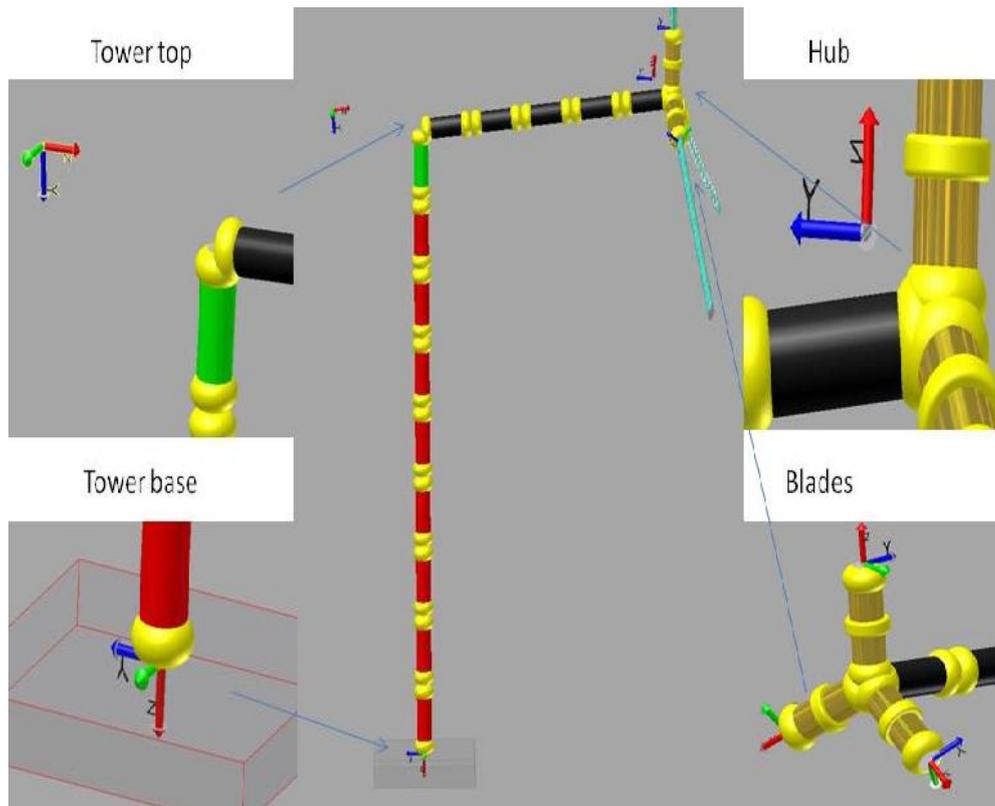


*Fig. 3.15. Local coordinate system and orientation of main bodies.*

The structural properties of each and every body with respect to its local coordinates and global coordinates have been calculated. As discussed before, BECAS is used for complex structures like rotor blades, but for rest of the parts it is calculated using basic equations. The orientation of the local coordinates at different main bodies is shown in the Figure 3.15. The calculation of structural properties of shaft is shown below

$$D = 152.4 mm \tag{3.10}$$

$$R = 0.0762 \text{ m} \tag{3.11}$$

$$t = 6.3 \text{ mm} \tag{3.12}$$

$$r = R - t = 0.0699 \text{ mm} \tag{3.12}$$

$$... = 7850 \frac{kg}{m^3} \tag{3.13}$$

$$E = 2.10E11 \frac{N}{m^2} \tag{3.14}$$

$$G = 8.8E10 \frac{N}{m^2} \tag{3.15}$$

$$A = 0.0028916 m^2 \tag{3.16}$$

$$m = ...A = 22.6991886 \frac{kg}{m} \tag{3.17}$$

$$I_x = \frac{f}{4}(R^4 - r^4) = 0.0000077 m^4 \tag{3.18}$$

$$I_y = I_x \tag{3.19}$$

$$R_{ix} = \sqrt[2]{\frac{I_x}{A}} = 0.0000077 m^4 \tag{3.20}$$

$$R_{iy} = \sqrt[2]{\frac{I_x}{A}} = 0.0000077m^4 \qquad (3.21)$$

$$k_y = k_x = 0.5 \qquad (3.22)$$

$$K = \frac{f}{2}(D^4 - d^4) = 0.0000155m^4 \qquad (3.23)$$

Similarly the structural properties are calculated for 8 sections of Tower, one section of tower top, 5 sections of the shaft, 2 sections of each hub. BECAS has been used to find the structural properties of the blades.
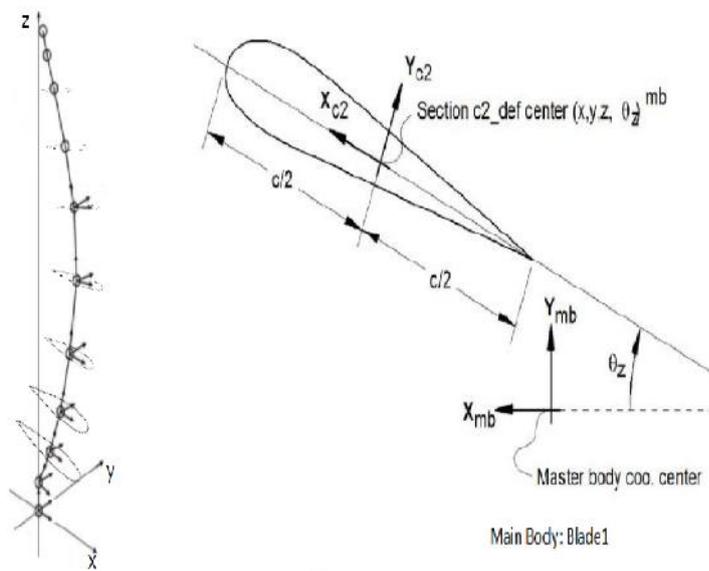


*Figure 3.16 Definition of blade center lines [6].*

### 3.4.1 BECAS

The cross sectional analysis tool called BECAS is used for the section analysis of special structures like rotor blades. The elastic centre, the shear centre and the mass centre can be determined by the same.

Rotor blades are one of the most important structural elements which have to be evaluated in the aeroelastic modelling. The static, dynamic and aerodynamic forces acting on the rotor blades make the analysis difficult and time consuming. The material used in most light weight rotor blades includes non linear materials like fibre glass or other reinforced plastics. The structural properties depends upon various factors like the material orientation, the number of layers, the orientation of layers and also the way the rotor blades are fabricated.

For the analysis of long and slender structures like rotor blades, beam models are more accurate and computationally efficient compared to that of using shell or solid models [10]. The software used for the cross sectional analysis is called BECAS, Beam Cross section Analysis Software from Danish Technical University is used for the same. The software is able to handle arbitrary cross section geometries, anisotropic materials and material induced couplings.

A finite element beam model of the rotor blade sections has been created using BECAS. 7 Sections are selected along the length of the rotor blades for analysis. The rotor blade sections are taken as the same radius length used for finding the Polars such as coefficient of lift, coefficient of drag and coefficient of Pitch moment used in Solid works flow simulation.

BECAS is a MATLAB based code. The post processing is done in MATLAB. There are two pre-processing tools used to generate input for BECAS. The steps in the process of modelling the aerofoil on BECAS can be explained as in Figure 3.17
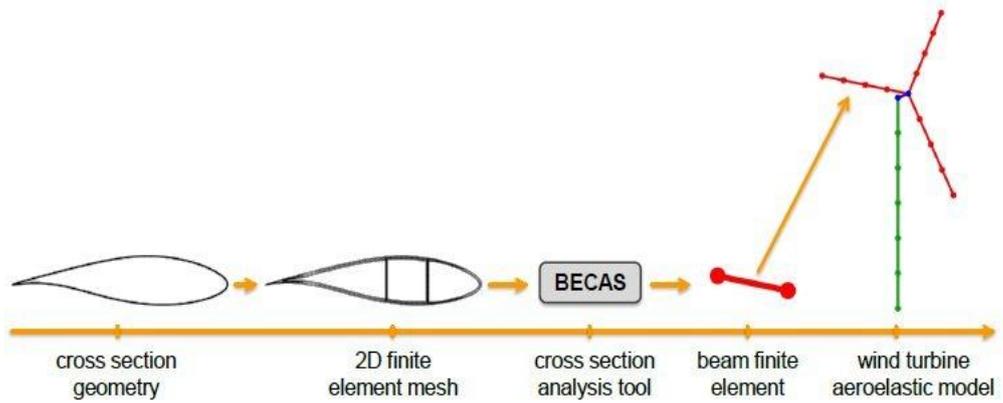
*Fig 3.17 BECAS steps[12]*

### 3.4.2   Airfoil2Becas

Airfoil2BECAS is a python based script used to generate input to BECAS. It is a pre processing tool which works on NumPy which is numerical Python. The same 7 sections along the length of the rotor blades has been chosen for analysis. Apart from the airfoil coordinate data which defines the x and y position which in turn defines the shape, the layup information of the position of fibres and the material used for the fabrication of rotor blades.

The program generates 2D mesh in the airfoil for the analysis in BECAS in the suitable format. 9 key points are defined in between the airfoil coordinates which divides each airfoil section to 8 regions. There is a possibility to assign different material orientation and material properties for different sections. Shear webs are used by wind turbine manufacturers to stabilise the rotor blades and also to decrease the thickness of the fabricating material. A number of shear webs can be defined between the nodal points based on the design of the rotor blades and corresponding material properties are assigned in the airfoil2becas.py python script.

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There is a possibility to discretize the shell to required number of layers. The airfoil2becas is capable to accommodate for the discontinuities in the airfoil coordinate data, except in the boundaries. The fibre plane angles are automatically assigned as per the global coordinate definition. The 2D mesh generated by airfoil2BECAS is shown in Figure 3.18.

A parameter file is created for each aerofoil section according to the python syntax. The minimum value of shell thickness is selected to be 10. The minimum value of shell thickness is selected such that the value should be greater than or equal to the largest number of layers of different material in the airfoil section. In our case the rotor blades are fabricated with single layer polyethylene, the number of layers which equals 10 is found to be a very good number for the analysis. There is a possibility to define shear webs between the nodes which are structural elements used to strengthen rotor blade structure. Since our rotor blades are small enough, there was no need for shear webs inside the blades, the shear webs were deactivated in the case.

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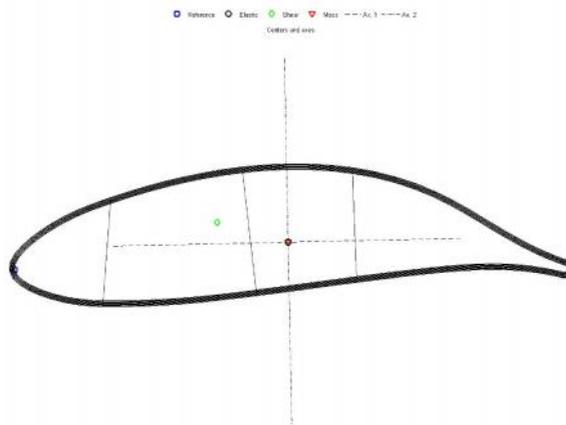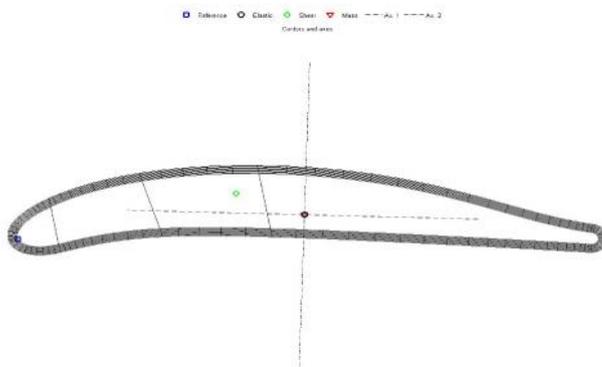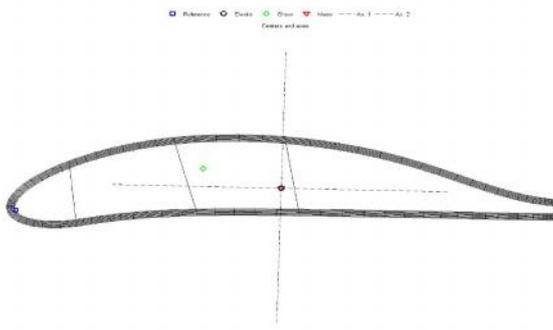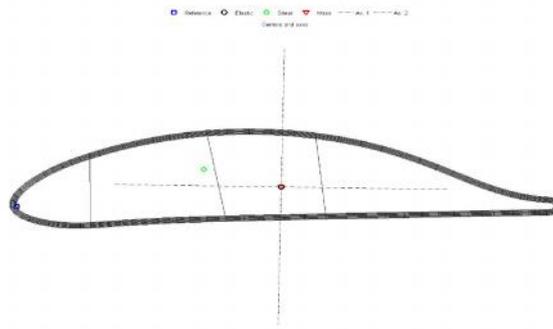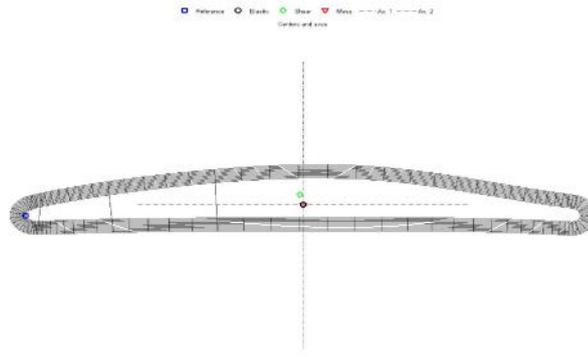
*Figure 3.18 Section 1, 3, 5, 8, 11, 2 D mesh generated by airfoil2BECAS.*

The layup definition includes the thickness of the rotor blades, which is 3 mm in our case. The material selected is polyethylene terephthalate (PET), with 0 degree material orientation angle. 9 Regions are defined along the airfoil, there is special options to define the number of elements in the place where the shear web comes in contact with the Polyethylene. The last stage is to define the material properties of PET such as Young's modulus and rigidity modulus in all three directions and the poisons ratio, and the density has been defined in the same file. The parameter file for each section has been added to the Appendix B. The parameter file is called in Python and run for 7 sections to obtain the input files for BECAS. The shell expander has been saved in the same directory and called while running airfoil2BECAS [13].

Shell expander is an python based pre-processor used to generate input files for BECAS. It basically works on layered shell elements. Expansion is done of each shell elements and they are converted to three dimensional solid elements. Expansion is usually done in the local normal direction. These three dimensional elements are then projected to appropriate planes to generate corresponding two dimensional meshing for the BECAS. The 4-node and 8-node quadrilateral BECAS elements are generated from 4-node and 8-node shell elements [14].

*Figure 3.19 Finite element shell model in BECAS [14]*

The advantage o the beam part is that it is more accurate in predicting the global displacements and computationally efficient compared to the shell elements. The BECAS assumes the deformation of the body as a combination of rigid body motions and also warping displacements. The principle of virtual work is used in the formulation of finite element equations. The three dimensional warping displacements are discretized using two dimensional finite elements. The output from BECAS can be directly taken to HAWC2.

The BECAS2HAWC2 matlab function is capable of giving these 19 calculated values at each section of the rotor blade to the tip section. These values are taken to the structural definition file of HAWC2 for the rotor blades. BECAS calculations have been done for 7 sections along the length of the rotor blade from the centre to the tip. The output from airfoil2BECAS and shell expander is the input files to BECAS. 7 Simulations have been done and the results are exported to HAWC2 structural file.

## 3.5   Definition of wind

The wind is defined at the centre of the hub, 6.2 m in length from the ground in our case. A turbulence box of length 32 m in length along the direction of the wind, and 16 m across the direction of the wind has been created. The total length of the box has to be in accordance with the simulation length. The wind speed is related to the turbulence as per the equation,

$$wsp = \frac{N_x \Delta x}{t_{stop} - t_0} \qquad (3.24)$$

A Mann turbulence model has been used in the definition of the turbulence parameters. The Von Karman isotropic energy system has been used with the parameter in modelling the Mann turbulence. Since we have a down wind turbine a tower shadow potential is also considered. The modelling of downwind wake from a tower in HAWC2 can be seen as shown in the figure. The HAWC2 has inbuilt Mann turbulence box as DLL which can be called and used in the main simulation whenever required. The turbulence box is shown in Figure 3.20.
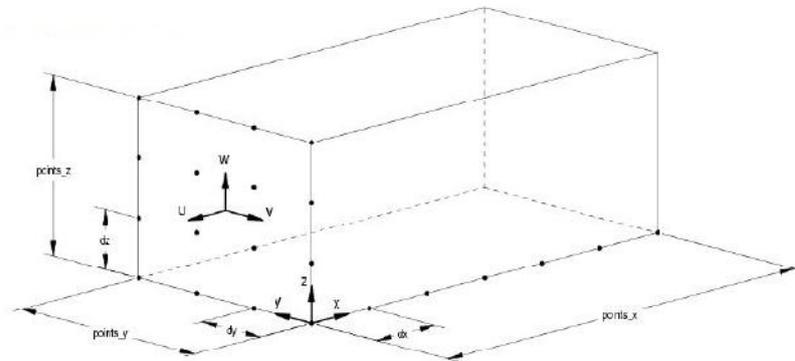


*Figure 3.20. Turbulence box in HAWC2.*

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For 7 m/s wind speed the turbulence box is created with the following dimensions, Number of points in the x direction=1024 with  x is 0.41015625. The wind created for the simulation is shown in Figure 3.21.
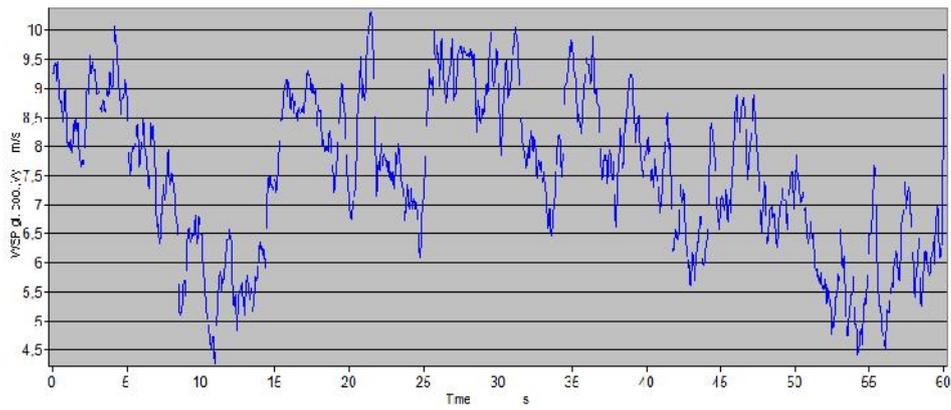


*Figure 3.21. 7 m/s wind inside the turbulence box.*

# 4 Simulation and Natural frequency Analysis

The dynamic response to a system to an excitation depends upon the natural frequency of the system and the damping present in the structures. The structural security of a wind turbine can be increased using stiff structures, but the production costs of main components like tower and rotor blades will increase the production cost. The aeroelastic modelling of the turbine gives the understanding about the structural dynamic response of the wind turbine under various forces of excitation when the wind turbine is operating the under various environmental conditions. This make the design engineers to choose more flexible, light weight structures in designing the wind turbine which makes the wind energy more economical.

The response of a structure when subjected to an external excitation force can be of three types [15].Quasi static, when the frequency of excitation of the system is well below the natural frequency of the wind turbine. In this case the response of the system will be similar to the excitation force but with a phase lag. Resonance happens when the frequency of excitation is closer to the natural frequency of the system, within a narrow region where the wind turbine response may be several times magnified compared to response under static load case. This can even lead to catastrophic failures of the wind turbine since the magnitude of amplification of the response will be very high and unpredictable.

The amplitude depends upon the damping of the structure since both the inertial and spring forces cancel each other. When the excitation frequency is way above the natural frequency of the structure the mass will not be able to respond to the frequency causing a low response. The response of system to the same force applied at different frequencies of excitation is shown in Figure 4.1, Figure 4.2 and Figure 4.3. In dynamics the frequency of load is as important as the magnitude of the loads. In case of wind turbine, it experiences time varying loads in different wind conditions. The response of the wind turbine as we can see from the figure to a particular type of excitation will be similar to excitation of the force but with a different magnitude and phase.
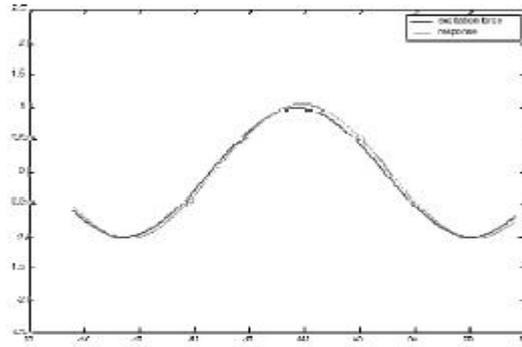
*Figure 4.1. Quasi static response Solid Line F(t), Dashed line Response.*
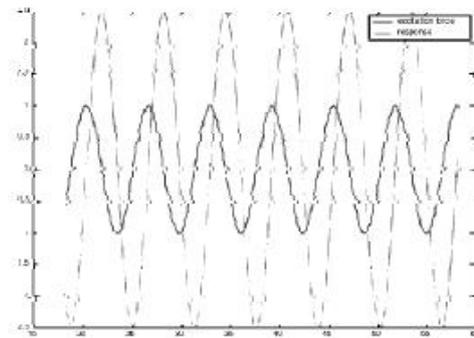


*Figure 4.2 Resonance Solid line: F(t) Dashed line: Simulated response.*
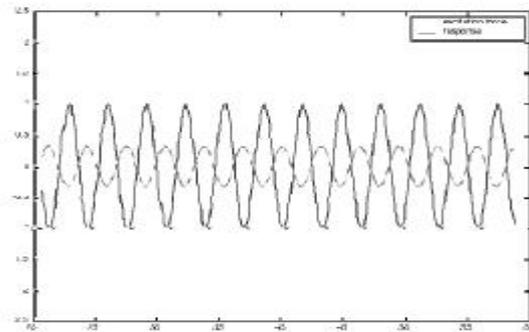


*Figure 4.3 Inertia dominated response line: F(t) Dashed line: Simulated response [15].*

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A clear idea of the natural frequency of the wind turbine structure is necessary in the cost effective selection of structural components like tower and blades. The major loads acting on the structure is from the rotation of the rotor blades, the loads acting on the rotor blades differ in different turbulent conditions and also depending upon the pitch angle, wind shear etc. The major frequency of structural excitation can be calculated from calculating the frequency of rotation of the rotor which is designated as 1$\Omega$. The second rotor frequency of interest is calculated as N times $\Omega$, which in our case is the 3$\Omega$.

For a fixed speed turbine, based on this the structural design can be categorized into three types

- Soft

- Soft and Stiff

- Stiff

The design is said to be said to be soft if the structural designs corresponds to a frequency lesser than 1$\Omega$. It is called soft stiff if the frequency is selected between 1$\Omega$ and 3$\Omega$. Most of the offshore wind turbines are designed in the soft stiff range [15]. The structure is said to stiff if the natural frequency of the structure is selected such that it is greater than 3$\Omega$. For a variable speed turbine the 1$\Omega$ (or 1P) is not a single value but within a particular range. This makes the soft stiff range smaller, which means a very accurate prediction of the natural frequency wind turbine is very important.
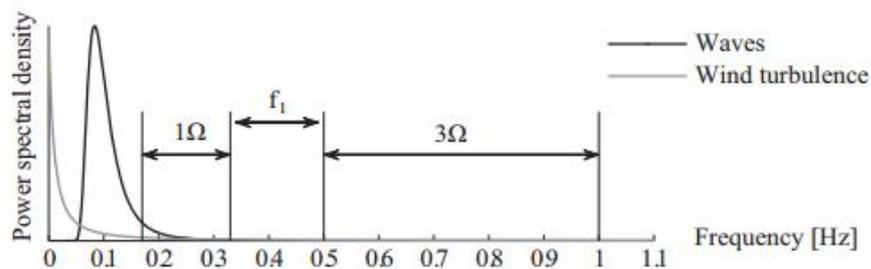


*Figure 4.4 Fixed speed wind turbine, excitation range.*
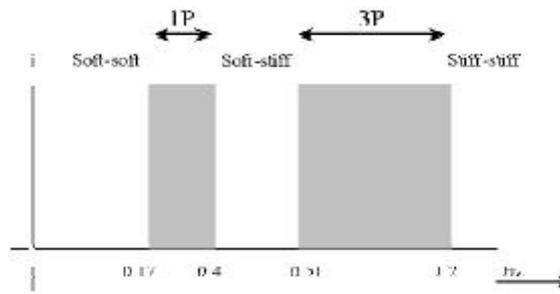
*Figure 4.5 Variable speed turbine, excitation range [15].*

## 4.1 Simulation and Results

The aeroelastic simulation of the wind turbine is done by calling the structural and aerodynamic data together in one platform and analysing the aeroelastic response under different wind conditions. The turbine is modelled structurally in the structural definition part and stored in the .st file and the aerodynamic parameters and the blade span parameters are saved in .pc and .ae files. These files are being called by modelling the turbine centre line, position and orientation of each Timoshenko beam elements with their constraints and elastic properties in .htc file. This .htc file is the main input file which is being run in the hawc2mb.exe platform.
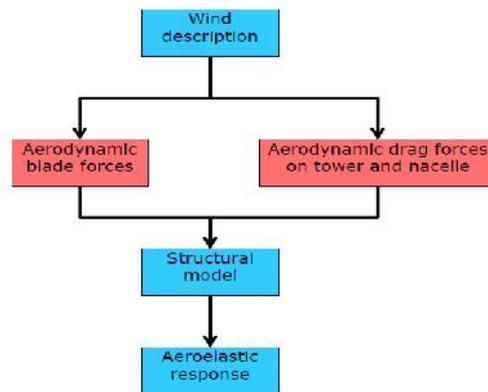


*Figure 4.6. Simulation flow model.*

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The results of the simulation include an animation file which can be used to visualise the turbine working and characteristics like bending, frequency of vibrations etc. The basic flow diagram of HAWC2 simulation can be represented as shown in the Figure 4.7
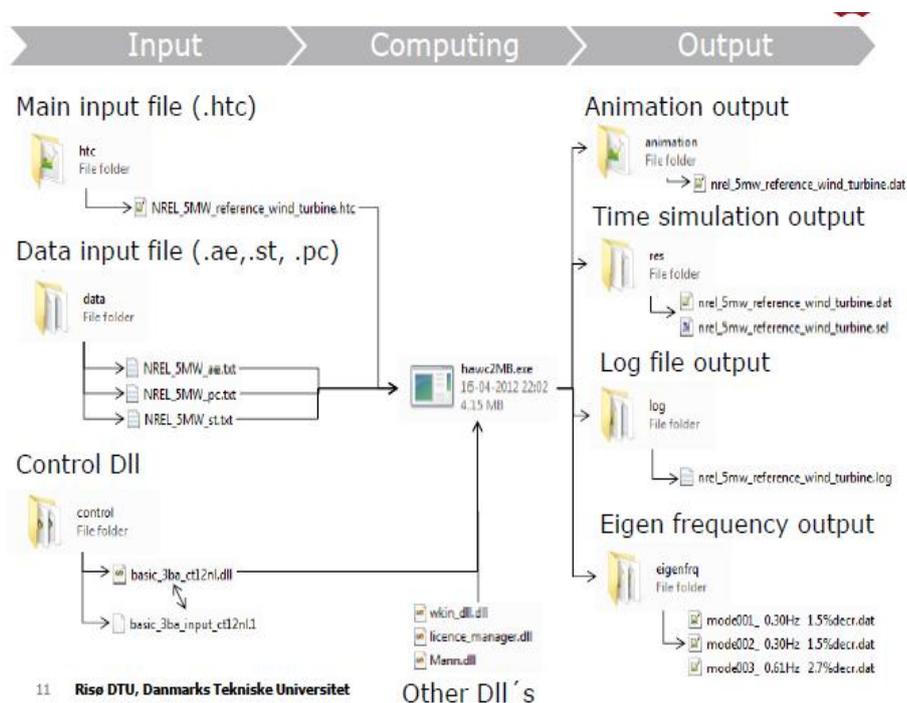


*Figure 4.7 HAWC2 Program Structure [6].*

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The animation of the fully modelled Nimbus 5.2 is shown in the Figure 4.8. The natural frequency analysis is done by the simulation in HAWC2. The mode shapes and Eigen frequencies of the whole turbine structure have been calculated. The natural frequencies of each main body are also calculated. The first 5 natural frequencies of the whole turbine structure are shown in the table below. The natural frequencies are evaluated in 2 cases.

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### 4.1.1    Case 1. Fully rigid structure

In this case both the yaw bearings and the main shaft bearings in the wind turbine structure are deactivated and the turbine is considered as a single rigid structure. The natural frequency of vibration and corresponding mode shapes for the specified case are shown below. The .htc file code for the same has been attached in the Appendix A.
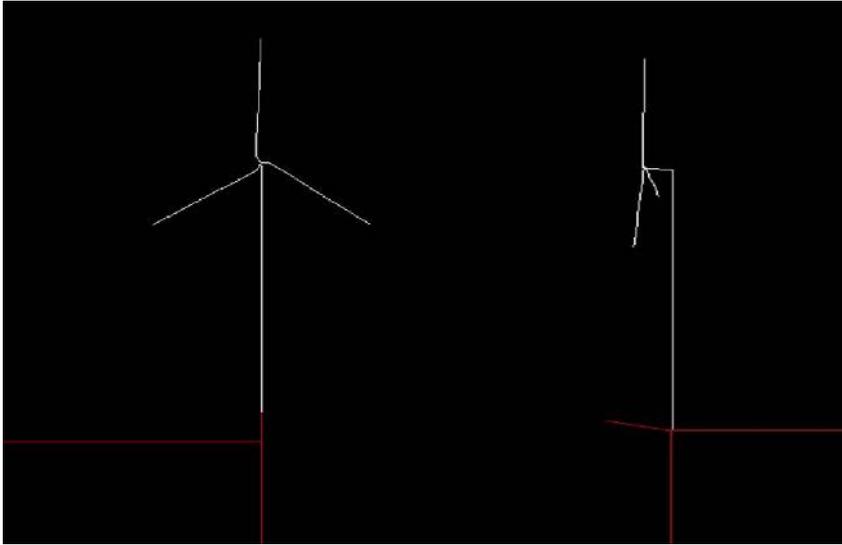


*Figure 4.8. HAWC2 representation of Nimbus 1.6 KW.*

### 4.1.2    Case 2. Main bearing activated

In this case the bearing shaft is being activated and the frequency analysis is conducted again. The natural frequency of vibration slightly varies in this case. The results are shown in table 4.1 shown below

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*Table 4.1. Natural frequency of the structure*

| Mode Shapes | Case 1. Fixed Shaft Natural Frequency(Hz) | Case2. Bearing Shaft Natural Frequency(Hz) |
|---|---|---|
| $1^{st}$ *tower transverse* | *1.29174E+00* | *1.29220E+00* |
| $1^{st}$ *tower longitudinal* | *1.31710E+00* | *1.31723E+00* |
| $1^{st}$ *rotor torsion* | *2.02101E+00* | *2.02314E+00* |
| $1^{st}$ *asymmetric rotor flap/yaw* | *2.87379E+00* | *2.87908E+00* |
| $1^{st}$ *asymmetric rotor flap* | *2.99097E+00* | *2.99822E+00* |
| $1^{st}$ *rotor edge 1* | *4.74724E+00* | *4.74725E+00* |
| $1^{st}$ *rotor edge 2* | *5.96903E+00* | *5.97965E+00* |
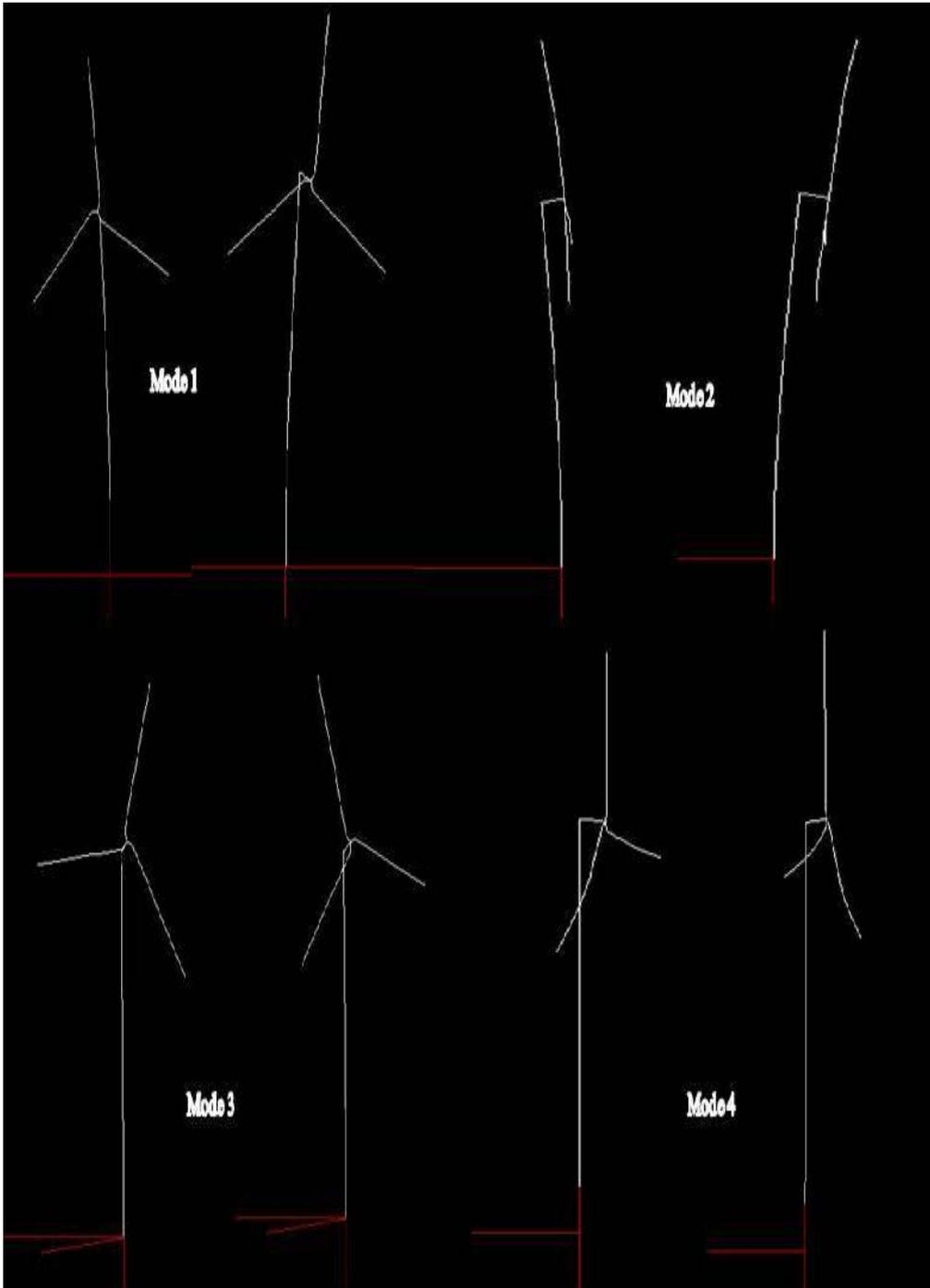
*Figure 4.9. First four natural frequency and corresponding mode shapes.*

# 5    Conclusions

The estimation of natural frequency of the system has been done with suitable linearisation of the whole system. The damping of the system has not been tuned to obtain the the damped frequency of the system. It is important to find the damped frequency and correspondonding mode shapes based on the need of the requirements of the study. The damping in the real structure can be far more different from the damping in the real case which depends upon the material , the material plane orientation, the friction acting between the layers etc. The more precise estimation of damping requires experience with usage of the material and suitable experimental case. Another way of addressing this problem is to estimate the required damping and give the design engineers the amount of damping corresponds to the particular mode shapes. Designers can achieve this value by tuned mass damper by distributing the mass accordingly or to choose fixation points which dissipate enough energy to insert sufficient damping.

Its very important to understand that how linearisation has been done in the design process. As we can see that the rotor blades are placed such that the first rotor blade is kept exactly vertical and the other two rotor blades at an angle of 120 degrees apart. This can be visualised in a clock as 0, 4 and 8 O'clock configurations. The mass of the rotor blades are distributed in this manner will be different when the rotor blades starts rotating. To taken this into account the eigen frequencies of the HAWT has been analysed by keeping the two rotor blades up and the third one, when we look in a clock its like, 2 O'clock, 6 O'clock and 10 O'clock.

This configuration is then analysed and it is found that the natural frequencies remains the same. The changes of the natural frequency in between these two configurations is given below. It has been found that the natural frequency of the structure has no change with respect to the different configurations depending upon how the rotor mass is being distributed at any instant of time. This can been interpreted from the fact that the mass of the rotor blades are very less compared to the mass of the big structural components like the tower or the hub mass.

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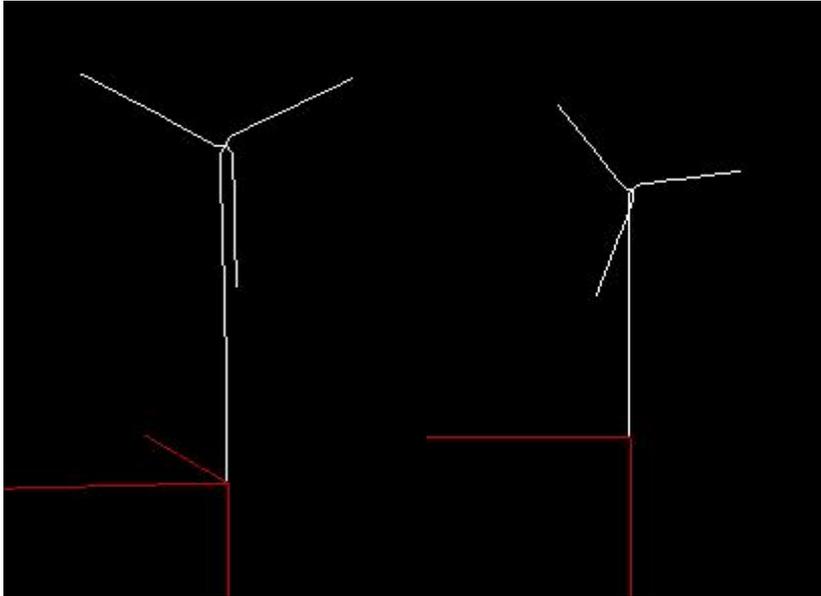
*Figure 5.1. (a) 2 O'clock, 6 O'clock and 10 O'clock configuration (b)3O'clock, 7 O'clock and 11 O'clock configuratin*

| Mode shapes | Natural frequency $F_N$ (Hz) Default | Natural frequency $F_N$ (Hz) Configuration 2 | Natural frequency $F_N$ (Hz) Configuration 3 |
|---|---|---|---|
| Mode nr: 1 | 1.29174E+00 | 1.29174E+00 | 1.29174E+00 |
| Mode nr: 2 | 1.31710E+00 | 1.31710E+00 | 1.31710E+00 |
| Mode nr: 3 | 2.02101E+00 | 2.02101E+00 | 2.02101E+00 |
| Mode nr: 4 | 2.87379E+00 | 2.87379E+00 | 2.87379E+00 |
| Mode nr: 5 | 2.99097E+00 | 2.99097E+00 | 2.99097E+00 |

# 6   Future works

The structural and aerodynamic modelling of the whole wind turbine is completed. The wind is modelled inside the turbulence box and the wind turbine is being positioned inside the turbulence box and has been simulated. It can be seen that at some instant of the simulation the simulation colapses due to the hitting of the rotor blades into the tower. This is due to the the lack of time in estimating the correct damping in the structure. As discussed before it is really hard to estimate the real damping in the structure due to its complex behaviour in the real structures compared to theoretical model. The major future works required are

- Estimation of real damping in the structures and implementing in the model.

- Tuning of damping for 3% logarithimic decrement between mode shapes as per RISOE DTU HAWC2 program developers method.

- Implementing Enbreeze pitch control mechanism DLL and connect it to the HAWC2 interface

- IEC simulations for certifications procedures.

- Modelling of Soil and foundation.

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# A. HAWC2 structural input file, fixed rotor

```
begin Simulation;
  time_stop   0.1;
  solvertype  1 ;   (newmark)
  on_no_convergence continue ;
  convergence_limits 1E3 1.0 0.7 ;
  logfile ./logfiles/structure_enbreeze.log ;
  begin newmark;
    deltat   0.02;
  end newmark;
end simulation;
;
begin new_htc_structure;
  beam_output_file_name  ./logfiles/structure_beam_enbreeze.dat;              Optional - Calculated beam
properties of the bodies are written to file
  body_output_file_name  ./logfiles/structure_body_enbreeze.dat;             Optional - Body initial position and
orientation are written to file
  body_eigenanalysis_file_name ./eigenfrq/structure_body_eigen_enbreeze.dat;
  structure_eigenanalysis_file_name ./eigenfrq/structure_strc_eigen_enbreeze.dat;
;--------------------------------------------------------------------------------------------------------------------------
------------------------
  begin main_body;        tower 87m
    name      tower ;
    type      timoschenko ;
    nbodies    1 ;
    node_distribution    c2_def ;
    damping_posdef   8.142E-04 8.14E-04 4.0E-03 4.3E-04 4.3E-04 4.3E-03 ; Mx My Mz Kx Ky Kz , M´s raises
overall level, K´s raises high freguency level
    begin timoschenko_input;
      filename ./data/NREL_5MW_st_enbreeze.txt ;
      set 1 2 ;
    end timoschenko_input;
    begin c2_def;          Definition of centerline (main_body coordinates)
      nsec 8;
```

```
    sec 1 0.0 0.0 0.0    0.0 ;  x,y,z,twist
    sec 2 0.0 0.0 -1.0  0.0 ;
    sec 3 0.0 0.0 -2.0  0.0 ;
    sec 4 0.0 0.0 -3.0  0.0 ;
    sec 5 0.0 0.0 -4.0  0.0 ;
    sec 6 0.0 0.0 -5.0  0.0 ;
    sec 7 0.0 0.0 -5.5  0.0 ;
    sec 8 0.0 0.0 -6.0  0.0 ;
    end c2_def ;
   end main_body;
;
  begin main_body;
    name       towertop ;
    type       timoschenko ;
    nbodies     1 ;
    node_distribution     c2_def ;
;   damping_posdef   9.025E-06 9.025E-06 8.0E-05 8.3E-06 8.3E-06 8.5E-05 ;
    damping  2.50E-04  1.40E-04  2.00E-03  3.00E-05  3.00E-05  2.00E-04  ;
    concentrated_mass 2 0.0  0.0 0.0 242.3 34.50  32.64 29.06
                    begin timoschenko_input;
    filename ./data/NREL_5MW_st_enbreeze.txt ;
    set 2 2 ;
    end timoschenko_input;
   begin c2_def;           Definition of centerline (main_body coordinates)
    nsec 2;
    sec 1 0.0 0.0 0.0       0.0 ; x,y,z,twist
    sec 2 0.0 0.0 -0.2  0.0 ;
   end c2_def ;
  end main_body;
;
  begin main_body;
    name       shaft ;
    type       timoschenko ;
    nbodies     1 ;
    node_distribution     c2_def ;
;  damping_posdef  7.00E-3  7.00E-03  7.00E-02  3.48E-04  3.48E-04  1.156E-03 ;
```

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```
          damping_posdef  7.00E-3  7.00E-03  7.00E-02  6.5E-04  6.5E-04  1.84E-02 ;
                              concentrated_mass 1 0.0 0.0 0.0 0.0 0.0 0.0 0.066 ;generator equivalent slow shaft
          concentrated_mass 5 0.0 0.0 0.0 90.8 0.0 0.0 25.09 ; hub mass and inertia;
                              begin timoschenko_input;
            filename ./data/NREL_5MW_st_enbreeze.txt ;
            set 3 2 ;
          end timoschenko_input;
          begin c2_def;              Definition of centerline (main_body coordinates)
            nsec 5;
            sec 1 0.0 0.0 0.0        0.0 ; Tower top x,y,z,twist
            sec 2 0.0 0.0 0.15       0.0 ;
            sec 3 0.0 0.0 0.25       0.0 ;
            sec 4 0.0 0.0 0.35       0.0 ; Main bearing
            sec 5 0.0 0.0 0.50       0.0 ; Rotor centre
          end c2_def ;
        end main_body;
;
        begin main_body;
          name        hub1 ;
          type        timoschenko ;
          nbodies     1 ;
          node_distribution    c2_def ;
          damping_posdef  2.00E-05  2.00E-05  2.00E-04  3.00E-06  3.00E-06  2.00E-05;
                              begin timoschenko_input;
            filename ./data/NREL_5MW_st_enbreeze.txt ;
            set 4 2 ;
          end timoschenko_input;
          begin c2_def;              Definition of centerline (main_body coordinates)
            nsec 2;
            sec 1 0.0 0.0 0.0        0.0 ; x,y,z,twist
            sec 2 -0.1 0.0 0.141     0.0 ;
          end c2_def ;
        end main_body;
;
        begin main_body;
          name        hub2 ;
```

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```
    copy_main_body hub1;
   end main_body;
;
  begin main_body;
   name        hub3 ;
   copy_main_body hub1 ;
  end main_body;
;
  begin main_body;
   name        blade1 ;
   type        timoschenko ;
   nbodies     1 ;
   node_distribution    c2_def;
 ;  damping_posdef   1.16e-4 5.75e-5 6.1e-6 6.5e-4 5.1e-4 6.4e-4 ;
   damping_posdef   3.1E-03 2.1E-03 3.6E-05 1.45E-03 2.3E-03 4.5E-05 ;
  begin timoschenko_input ;
    filename ./data/NREL_5MW_st_enbreeze.txt ;
    set 5 2 ;           set subset
   end timoschenko_input;
   begin c2_def;         Definition of centerline (main_body coordinates)
    nsec 7 ;
```

| sec 1 | 0.0000  | 0.0000 | 0.000 | 0.000 ;x.y.z. twist |
|-------|---------|--------|-------|---------------------|
| sec 2 | 0.0000  | 0.0000 | 0.700 | -0.000;             |
| sec 3 | 0.13086 | 0.001  | 1.000 | -8.56449;           |
| sec 4 | 0.09687 | 0.008  | 1.300 | -5.40606;           |
| sec 5 | 0.08149 | 0.011  | 1.600 | -3.33675;           |
| sec 6 | 0.07216 | 0.012  | 2.050 | -1.56943;           |
| sec 7 | 0.03336 | 0.006  | 2.500 | 0.00000;            |

```
    end c2_def ;
   end main_body;
;
  begin main_body;
   name        blade2 ;
   copy_main_body blade1;
  end main_body;
;
```

```
begin main_body;

  name          blade3 ;

  copy_main_body blade1 ;

end main_body;
;----------------------------------------------------------------------------------------------------------------------------------------
------------------------
begin orientation;
;
  begin base;

    body   tower;

    inipos      0.0 0.0 0.0 ;        initial position of node 1

    body_eulerang 0.0 0.0 0.0;

  end base;
;
  begin relative;

    body1  tower last;

    body2  towertop 1;

    body2_eulerang 0.0 0.0 0.0;

  end relative;
;
  begin relative;

    body1  towertop last;

    body2  shaft 1;

    body2_eulerang 90.0 0.0 0.0;

    body2_eulerang 0.0 0.0 0.0;    0 deg tilt angle

    body2_ini_rotvec_d1 0.0 0.0 -1.0 0.2 ; body initial rotation velocity x.y.z.angle velocity[rad/s]   (body 2
coordinates)

;     body2_ini_rotvec_d1 0.0 0.0 -1.0 0.9424 ; body initial rotation velocity x.y.z.angle velocity[rad/s]   (body 2
coordinates)

  end relative;
;
  begin relative;

    body1  shaft last;

    body2  hub1 1;

    body2_eulerang -90.0 0.0 0.0;

    body2_eulerang 0.0 180.0 0.0;

    body2_eulerang 0.0 0.0 0.0;     0deg cone angle

  end relative;
```

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```
;
   begin relative;
    body1  shaft last;
    body2  hub2 1;
    body2_eulerang -90.0 0.0 0.0;
    body2_eulerang 0.0 -60.0 0.0;
    body2_eulerang 0.0 0.0 0.0;     0deg cone angle
   end relative;
;
   begin relative;
    body1  shaft last;
    body2  hub3 1;
    body2_eulerang -90.0 0.0 0.0;
    body2_eulerang 0.0 60.0 0.0;
    body2_eulerang 0.0 0.0 0.0;     0deg cone angle
   end relative;
;
   begin relative;
    body1  hub1 last;
    body2  blade1 1;
    body2_eulerang 0.0 0.0 0;
   end relative;
;
   begin relative;
    body1  hub2 last;
    body2  blade2 1;
    body2_eulerang 0.0 0.0 0.0;
   end relative;
;
   begin relative;
    body1  hub3 last;
    body2  blade3 1;
    body2_eulerang 0.0 0.0 0.0;
   end relative;
;
 end orientation;
```

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```
begin constraint;
;
  begin fix0;  fixed to ground in translation and rotation of node 1
    body tower;
  end fix0;
;
 begin fix1;
 body1 tower last ;
 body2 towertop 1;
 end fix1;
; ;
  ; begin bearing1;                free bearing
  ; name  shaft_rot;
  ; body1 towertop last;
  ; body2 shaft 1;
    ; bearing_vector 2 0.0 0.0 -1.0;        x=coo (0=global.1=body1.2=body2) vector in body2 coordinates where
the free rotation is present
  ; end bearing1;
; ;
;
;   begin bearing3;              fixed speed bearing
;    name  shaft_rot ;
;    body1 tower last;
;    body2 shaft 1;
;     bearing_vector 2 0.0 0.0 -1.0;        x=coo (0=global,1=body1,2=body2) vector in body2 coordinates where
the free rotation is present
;    omegas 0.93245 ;
;   end bearing3;
;
begin fix1;
body1 towertop last ;
body2 shaft 1;
end fix1;
;
begin fix1;
body1 shaft last ;
body2 hub1 1;
```

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```
end fix1;
;
begin fix1;
body1 shaft last ;
 body2 hub2 1;
 end fix1;
;
begin fix1;
body1 shaft last ;
body2 hub3 1;
end fix1;
;
begin bearing2;
name pitch1;
body1 hub1 last;
body2 blade1 1;
bearing_vector 2 0.0 0.0 -1.0;
 end bearing2;
;
 begin bearing2;
 name pitch2;
 body1 hub2 last;
 body2 blade2 1;
bearing_vector 2 0.0 0.0 -1.0;
 end bearing2;
;
begin bearing2;
    name pitch3;
    body1 hub3 last;
    body2 blade3 1;
bearing_vector 2 0.0 0.0 -1.0;
   end bearing2;
end constraint;
;
end new_htc_structure;
exit;
```

# B. Parameter File airfoil2BECAS, rotor blade section 3.

# This is a sample parameter filed to be used with airfoil2becas.py

# ################################################################

# Name of the directory for storing results

# ################################################################

outputdir = "testairfoil_BECAS_input_section3"

# The directory will be generated in the current working directory.

# If the directory already exists, it is deleted.


# Name of the file containing the x-y-coordinates of the airfoil

# ################################################################

airfoilfilename = "testairfoil_section3.dat"


# The number of elements used to discretize the shell thickness.

# The minimum value is the largest number of layers of different material

# anywhere in the airfoil.

element_layers = 10


# Shear Webs

# ################################################################

# Shear webs are defined as straight lines connecting two airfoil

# nodes. Any number of shear webs can be defined. The syntax is:

# shear_webs = [ [web1_from_node, web1_to_node],

#              [web2_from_node, web2_to_node] ]

# If no shear webs should be generated, an empty list must be defined:

# shear_webs = []

# The corresponding regions for layup assignment are:

# REGION09, REGION10, ...

shear_webs = [ [25, 73],

        [30, 68],

        [40, 60] ]

```
# Layup defintion
# ###############################################################
# The layup is defined as a list of lists using the following syntax:
# [ [layerthickness1, int. points1, materialname1, orientationangle1, plyname1],
#   [layerthickness2, int. points2, materialname2, orientationangle2, plyname2],
#   [layerthickness3, int. points3, materialname3, orientationangle3, plyname3] ]
# The first layer is the outer most layer.
# The second item ("int. points") and the fifth item ("plyname") are not
# relevant. The are kept for compatibility with the ABAQUS input syntax.
layup_of_elset = {} # initialize empty dictionary
layup_of_elset['REGION01'] = [ [0.003, 3, 'PE', 0.0, 'Ply01'] ]
layup_of_elset['REGION02'] =  layup_of_elset['REGION01']
layup_of_elset['REGION03'] = [ [0.003, 3, 'PE', 0.0, 'Ply05'] ]
layup_of_elset['REGION04'] = layup_of_elset['REGION01']
layup_of_elset['REGION05'] = layup_of_elset['REGION04']
layup_of_elset['REGION06'] = layup_of_elset['REGION03']
layup_of_elset['REGION07'] = layup_of_elset['REGION02']
layup_of_elset['REGION08'] = layup_of_elset['REGION01']
layup_of_elset['REGION09'] = [ [0.00000001, 3, 'PE', 0.0, 'Ply09'],
                    [0.00000001,  3, 'PE', 0.0, 'Ply10'],
                    [0.00000001, 3, 'PE', 0.0, 'Ply11'] ]
layup_of_elset['REGION10'] = layup_of_elset['REGION09']
layup_of_elset['REGION11'] = layup_of_elset['REGION09']



# Number of elements in each shear web
# ###############################################################
# The "height" of the elements representing the web must be larger
# than the thickness of the cap.
# Check the mesh at the intersection of the shear web and the cap.
# A list of integer numbers (one for each shear web) must be given.
# e.g. number_of_web_elements = [10, 12, 8]
# If no shear webs should be generated, an empty list must be defined:
# number_of_web_elements = []
number_of_web_elements = [5, 5, 3]
```

```python
# Reverse normals
# Should the normals be reversed? That is, should the material
# layers be added in the other direction?  Default: False
# WARNING: Only set this to True if you exactely know what you
# are doing!
reverse_normals = False


# Material Parameters
# ################################################################
# The definition of an orthotropic material requires 9 elastic constants:
# E1, E2, E3, nu12, nu13, nu23, G12, G13, G23.
# In the case of an isotropic material use:
# E1 = E2 = E3 = E
# nu12 = nu13 = nu23 = nu
# G12 = G13 = G23 = E/(2*(1+nu))
# 'rho' is the mass density

material_properties = {}  # initialize empty dictionary

material_properties['PE'] = {
'E1':  900E6,
'E2':  900E6,
'E3':  900E6,
'nu12': 0.46,
'nu13': 0.46,
'nu23': 0.46,
'G12':  308E+6,
'G13':  308E+6,
'G23':  308E+6,
'rho':  958 }
```

# C. Wind Turbulence Box, HAWC2

```
begin wind ;
  density            1.225 ; to be checked
  wsp              7 ;
  tint             0.2 ;
  horizontal_input     1    ;        0=false, 1=true
  windfield_rotations    -0.0  0.0  0.0 ;   yaw, tilt, rotation
  center_pos0         0.0 0.0 -6.2 ;
  shear_format          3  0.2  ;0=none,1=constant,2=log,3=power,4=linear
  turb_format          1   ; 0=none, 1=mann,2=flex
  tower_shadow_method    1   ; 0=none, 1=potential flow, 2=jet
; scale_time_start      0 ;
; wind_ramp_factor   0.0 [t0] [wsp factor] 1.0 ;
; [gust] iec_gust [gust_type] [gust_A] [gust_phi0] [gust_t0] [gust_T] ;
;
  begin mann;
  create_turb_parameters 29.4 1.0 3.7 1 1.0 ;     L, alfaeps,gamma,seed, highfrq compensation
    filename_u   ./turb/u.bin ;
    filename_v   ./turb/v.bin ;
    filename_w   ./turb/w.bin ;
    box_dim_u   1024 0.410155625 ;
    box_dim_v   32 0.5;
    box_dim_w   32 0.5;
    std_scaling   1.0 0.7 0.5 ;
  end mann;
;
  begin tower_shadow_potential;
   tower_offset 0.0 ;
   nsec  2;
   radius    0.0   0.076 ;
   radius    -6.0   0.076 ;
  end tower_shadow_potential;
end wind;
```