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**DET TEKNISK-NATURVITENSKAPELIGE FAKULTET**

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A final appreciation goes to one of my closest friends that I met in my first years of college; Per-Martin Engebretsen, for being a supporting friend and for believing in me.

# Summary

This report is written as documentation of a master thesis in the course constructions and materials at the University of Stavanger. The thesis was performed within January to June 2012 as a further research on an international simulation code comparison project.

The problem description in this thesis is as follows:

- How does an offshore jacket structure respond to different mean wind speeds and different turbulence intensities?

The offshore wind turbine jacket structure was measured to see how changing winds and turbulence intensities affects the loads on the structures. In all simulated cases the wind turbine was in operating condition. Loads at given positions in the simulation were further analyzed to create damage equivalent load cycles.

Simulation results were collected from a multi-body simulation program where the pre modeled wind turbine and jacket structure was tested. The result of the simulations shows loads in given positions of the structure, as well as Eigen frequencies and damage equivalent loads.

Conclusions states:

- The damage equivalent loads rise nearly linearly with rising wind speeds
- By increasing the turbulence intensity the damage equivalent loads rise at a higher rate
- With a wind speed of 9 meters per second and turbulence intensity of 20,2% (2 standard deviations) the wind turbine reacts with resonance behavior.

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# 1 General

## 1.1 Introduction

Our nature is in constant change. As time passes ice melts, rivers dry out, temperature change and continents move. And as the world change, technology has to adapt. Today we see a great concern when it comes to pollution and $CO_2$ emission. The demand for energy continues to rise all over the world and a consequence of extracting power from coal and other fossil fuels is the massive discharge of $CO_2$. How can we prevent emissions as well as keep up with a rising demand?

Emissions can be reduced by choosing more environmental friendly technology. Old technology eventually wears out or needs an upgrade. Implementing the impact on society and environment in our decision criteria is a way to reduce the emissions. To fully utilize the lifecycle of objects is also an important step towards energy saving and emission control, as buying a new more energy effective refrigerator may not be the optimum. The emissions and energy spent on producing a new unit may well exceed the emissions from operating a more ineffective unit until final breakdown.

Emissions and energy demand can be reduced by changing priorities. In America people cross great plains with 3 liter engines while in Europe drivers climb the mountains with 1.3 liter engines. By changing something simple as the light bulb technology, quantities ensure a great energy saving. In example the producer Philips sells new LED bulbs which run on 1 watt and halogen bulbs that run on 23 watts and up.

By producing electrical energy with less environmental impact we reduce pollution as well as meeting the energy demand. The focus in renewable energy sources slowly rises. A reason for the slower progress in renewable energy extraction is the need of new technology and efficiency improvements. We are able to extract power from the wind in sustainable amounts now. But by making wind turbines even more efficient the project effectiveness also rise. Fewer turbines will yield more power and the need for big fields diminishes. It has to be made more lucrative to invest in renewable energy sources. Both as far as production and research is concerned.

## 1.2 Problem

This thesis is a project which serves as a learning curve for me in how to use computer software to analyze constructions and process data. Simulation changes are made by altering mean wind speeds and turbulence intensity. It will also serve as an example on how different theories are combined to solve today's challenges from an engineer's perspective.

The problem is as follows:

- How will rising mean wind speeds affect the load cycles on the substructure?
- How will increasing turbulence intensity affect the load cycles on the substructure?

It is assumed that the loads increase due to higher wind speeds.

During simulations, several results gave indications of resonance behavior. Because of these results the additional task was to see if the reason easily can be located.

## 1.3 Abbreviations

| Abbreviation | Description |
|---|---|
| 1P | Rotor frequency [Hz] (rotations per seconds) |
| 3P | Blade frequency [Hz] (the frequency the blades pass the tower) |
| DAF | Dynamic amplification factor |
| DEL | Damage equivalent load |
| DC | Direct Current |
| ExCo | Executive Commitee |
| FEM | Finite element method |
| FFT | Fast Fourier Transformation |
| IEA | International Energy Association |
| IEC | International Electrotechnical Commission |
| LED | Light emitting diode |
| NREL | National Renewable Energy Laboratory |
| OC3 | Offshore Code Comparison Collaboration |
| OC4 | Offshore Code Comparison Collaboration Continuation |
| OWT | Offshore wind turbine |
| RAM | Random access memory |

## 1.4 Symbols

### 1.4.1 Latin symbols

| Symbol | Description (value/formula) [unit] |
|---|---|
| $A_c$ | Charnock's constant (Between 0,011 and 0,014 for open sea state with developed waves) |
| $A_x$ | Constant dependent on $z_0$ |
| $c$ | Damping coefficient |
| $c_c$ | Critical damping coefficient ($2\sqrt{km}$) |
| $D$ | Damage [%] |
| $D_j^{ST}$ | Short term damage from current dataset 'j' |
| $DEL_j^{STF}$ | Damage equivalent load from dataset 'j' around fixed mean |
| $DEL_j^{ST0}$ | Damage equivalent load from dataset 'j' around zero mean |
| $E$ | Elasticity modulous |
| $E[\sigma_u]$ | Mean value of wind speed standard deviation |
| $F$ | Force in Newton [N] |
| $F_d$ | Damper force [Nm/s] |
| $f^{eq}$ | Frequency of DEL |
| $f_i$ | Force at node i [N] |
| $f_j$ | Force at node j [N] |
| $f_n$ | Natural frequency [Hz] |
| $F_s$ | Spring Force [N] |
| $g$ | Constant of gravity $(9{,}81)$[m/s$^2$] |
| $H$ | Reference wind height [m] |
| $I$ | Moment of inertia |
| $k$ | Stiffness [N/m] |
| $k_a$ | von Karman's constant (0,4) |
| $L$ | Length of element |
| $L_k^M$ | Current cycle's mean load range |
| $L^{MF}$ | Fixed mean load [N] |
| $L_k^R$ | Current cycle's load range |

| | |
|---|---|
| $L_k^{R0}$ | Current cycle's load range about zero mean |
| $L_k^{RF}$ | Current cycles load range about the fixed mean |
| $L^{ult}$ | Ultimate design load [N] |
| $m$ | Mass in kilogram [kg] |
| $N_j^{eq}$ | Equivalent number of cycles until failure in current data set |
| $N_k^F$ | Cycles of current size until failure |
| $N_k$ | Cycles until failure ('k' represents current cycle) |
| $n_{jk}$ | Cycle count for current data set |
| $n_k$ | Cycle count |
| $n_j^{STeq}$ | Total equivalent fatigue counts |
| $t$ | Time in seconds [s] |
| $T_j$ | Time of current data set |
| $U$ | Wind speed [m/s] |
| $u^*$ | Friction velocity |
| $U_{10}$ | 10 minute mean wind speed [m/s] |
| $u_i$ | Displacement of node I [m] |
| $u_j$ | Displacement of node j [m] |
| $U_{(z)}$ | Wind speed at given height $z$ [m/s] |
| $y$ | Position in meters [m] |
| $\dot{y}$ | Velocity in y-axis (Derivative of $y$ with respect to time) [m/s] |
| $\ddot{y}$ | Acceleration in y-axis (Double derivative of $y$ with respect to time) [m/s$^2$] |
| $Y_0$ | Maximum disposition of vibrating mass (Amplitude if undamped system) |
| $z$ | Height above terrain [m] |
| $z_0$ | Terrain roughness parameter. Also known as roughness length. |
| $m$ | Inverse slope of the S-N curve. (Crack growth parameter) |

### 1.4.2 Greek symbols

| Symbols | Description |
|---|---|
| $\Delta$ | Deviation in length (Strain) |
| $\theta$ | Rotation |
| $\kappa$ | Surface friction coefficient |
| $\xi$ | Damping ratio ($c/c_c$) |
| $\pi$ | The number Pi (3,1415926…) |
| $\rho_a$ | Air density |
| $\sigma_U$ | Wind speed standard deviation |
| $\tau$ | Surface shear stress |
| $\phi$ | Phase shift of oscillation |
| $\omega_n$ | Natural Angular frequency [rad/s] |

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## 1.7 Software used

- Adobe Illustrator
- Adobe Photoshop
- Fedem
- MatLab
- Microsoft Office
- Mlife through MatLab
- NREL TurbSim

# 2 Theory

## 2.1 Wind turbines

Wind turbines convert the kinetic energy of the wind into mechanical energy. The wind flows through the turbine rotor forcing it to rotate, thus converting the kinetic energy into mechanical energy. The mechanical energy in the rotor shaft is then transformed into electrical energy through the generator inside the nacelle. By definition a wind turbine generates electricity. A wind mill delivers mechanical work. See Figure 2-2.

Human have harnessed the wind for centuries. Without the wind, the globalization and industrial evolution would probably have taken a completely different path. Great portions of our planet have been discovered by the help of wind power, as ships set sail for new continents and unknown territories. The exploration of our planet led to globalization. Trading both goods and technology gave the industrial evolution a great boost. Wind turbines were mainly taken into use in the early 20$^{th}$ century. As the knowledge in electricity was far below today's standards the electricity had to be generated "on site". The reason for this was massive loss of effect through low voltage DC cables. Wind turbines were usually erected in agricultural areas, hence the expression "agricultural electricians" (Hansen, 2008). An example of the typical farmland wind turbine is illustrated in Figure 2-1.

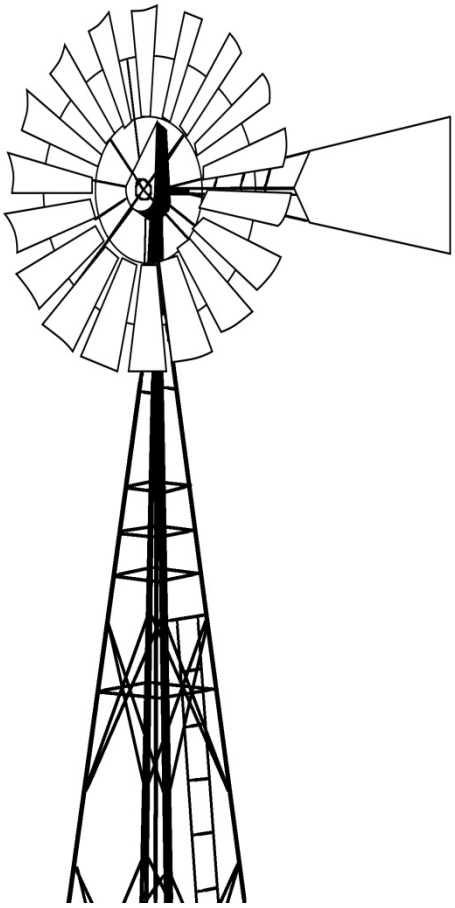


**Figure 2-1: An old American wind turbine.**

### 2.1.1 Anatomy of a wind turbine

On a regular wind turbine the rotor consists of a rotor hub and three blades. A shaft from the rotor (low speed shaft) is connected to a generator through a gearbox. This is inside a box called the nacelle. There is also a pitch controller inside the rotor hub that twists the blades to control the lift force. Inside the nacelle a torque controller is connected to the generator shaft (high speed shaft). Between the nacelle and the tower a yaw motor is installed. The purpose of the yaw motor is to turn the nacelle with rotor towards the wind (Hansen, 2008).

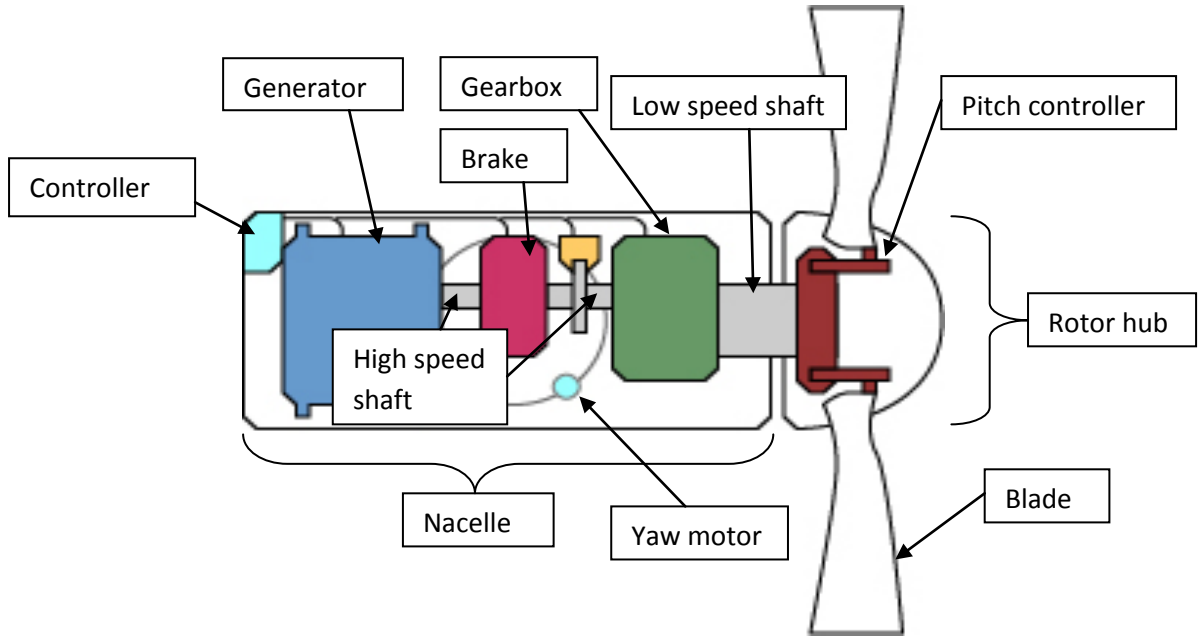



**Figure 2-2: Illustrated top-down view of a nacelle and rotor hub (simplified)**

When the wind stream hits the airfoil, the airfoil separates it into two streams. One travels above the airfoil the other travels below the airfoil. Both streams join at the trailing edge of the airfoil. The path above the airfoil is longer than the path below, resulting in a low pressure area above the airfoil and a high pressure area beneath. The pressure differences push the airfoil skywards (in the case of an airplane). In the case of a wind turbine; it turns the rotor around (Hansen, 2008). Illustrated in Figure 2-3.

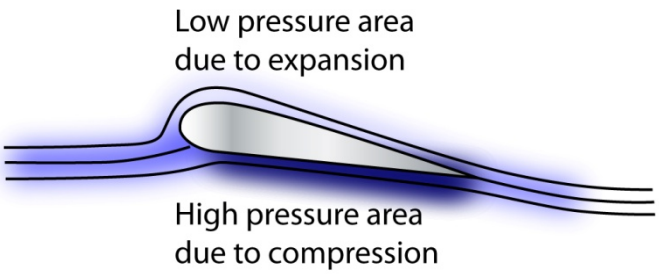



**Figure 2-3: Pressure differences on an airfoil**

When analyzing the airfoil the moment force on the blade also have to be determined. We do not want the twisting to break the blades (Hansen, 2008).

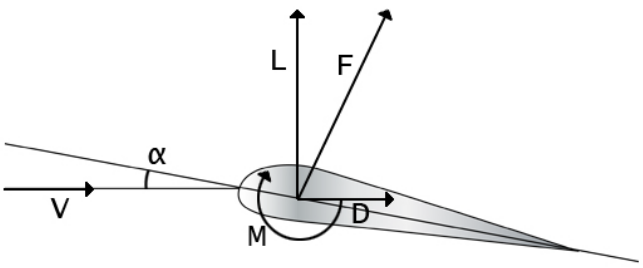



**Figure 2-4: Forces acting on the airfoil**

## 2.2 Structural vibrations

### 2.2.1 The mass spring model:

By explaining a “Mass-spring” problem (Figure 2-5) we may explore the problem of structural vibrations. The mass is considered to be in equilibrium when the force from the spring equals the force pulling the mass hence the mass has no velocity. By exiting the mass with a force we feed our system with energy. The mass is pushed either towards or away from the spring and the potential energy in the spring is raised. By releasing the mass it will oscillate around equilibrium point as potential energy is converted into kinetic energy towards the equilibrium point, and back into potential energy beyond equilibrium.

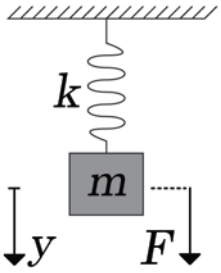



**Figure 2-5: A mass-spring problem**

### 2.2.2 Free vibrations

#### *2.2.2.1 Free vibrations without damping*

Our free vibration system consists of a mass $'m'$ attached to a spring. Ideally this system will vibrate infinitely, but during a real situation both mass and spring object is moving through a medium. The relocation of the air drains energy from our vibration system and works as a damper. The equations and formulas in this chapter are all lecture notes from the course Mechanical vibrations tutored by Professor Jasna Bogunovic Jakobsen at UIS during autumn 2010. It is further backed up by theory from the book Mechanical Vibrations(Rao, 2005).

An ideal undamped vibration system consists of a spring and a mass, but no medium. Assumptions are that the relocation of particles in the air and the gravity is absence. Since our system is fairly simple, we define our equilibrium state as the neutral value of the y axis, (the positive direction pointing upwards). The sum of all forces equals zero. In the equilibrium state, the force from the spring equals zero (Jakobsen, MOM140 Mekaniske svigninger, 2010).

$$\sum F = m\ddot{y} = m\frac{d^2y}{dt^2} \qquad \textbf{2-1}$$

$$m\ddot{y} = F_s \qquad \textbf{2-2}$$

The spring will always push or pull the mass towards equilibrium state. The power of the spring force $'F_s'$ depends on the stiffness of the spring '*k*'. Pushing the mass upwards from equilibrium yields the following equation:

$$F_s = -ky \qquad \textbf{2-3}$$

Combining the equation 2-2 and 2-3 yields:

$$m\ddot{y} + ky = 0 \qquad \textbf{2-4}$$

This is a general differential equation with solution:

Figure 2-6

$$y(t) = Y_0 cos(2\pi f_n t) \qquad \textbf{2-5}$$

The value y is plotted versus time in Figure 2-6. The amplitude is set to 1. The solution represents a simple harmonic motion when plotted versus time. $'f_n'$ is referred to as the natural frequency of the system. The $'Y_0'$ represents the amplitude of the motion (Jakobsen, MOM140 Mekaniske svigninger, 2010).

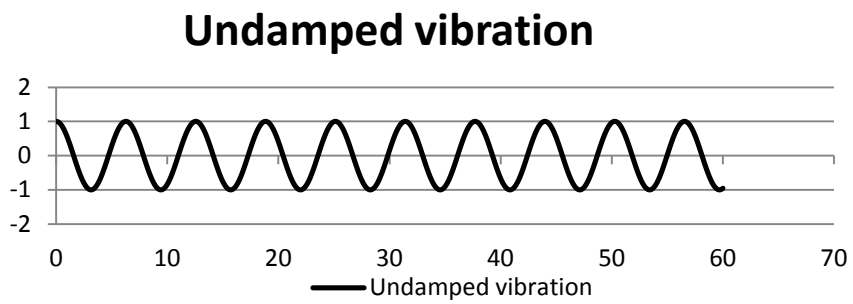



**Figure 2-6: Harmonic undamped free vibration**

The natural frequency $'f_n'$ and natural angular frequency $'\omega_n'$ of the system is defined as:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad \textbf{2-6}$$

$$\omega_n = \sqrt{\frac{k}{m}} \qquad \textbf{2-7}$$

It can be seen that the $2\pi f_n$ part of equation 2-5 represents the angular frequency (Jakobsen, MOM140 Mekaniske svigninger, 2010).

#### *2.2.2.2 Free damped vibrations*

By adding a viscous damper, the problem reflects a real situation to a more extent. The viscous damper is a force dependant of the velocity of our mass, and it resembles the movement of a mass through a fluid (Jakobsen, MOM140 Mekaniske svigninger, 2010). A simple demonstration of a viscous damper is the ease to walk slowly in water. Trying to speed up the movement is more tiring because of the dampening effect of the water.

$$F_d = -c\dot{y} \qquad \textbf{2-8}$$

By including equation 2-8 in equation 2-4 for the undamped case we get:

$$m\ddot{y} + c\dot{y} + ky = 0 \qquad \textbf{2-9}$$

The value of the damping coefficient "$c$" affects our solution. At low values we have an under damped system, as the damping will slowly lessen the amount of vibration until a complete stop. At the exact value of the damping coefficient "$c$" where our system no longer oscillates, we have the state of critical damping. Further increasing the coefficient will result in an over damped system. The system will not vibrate at all. (Jakobsen, MOM140 Mekaniske svigninger, 2010).

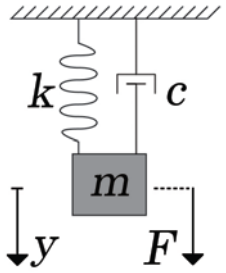



**Figure 2-7: A damped mass spring problem**

For the mass spring case the critical damping equals:

$$c_c = 2\sqrt{km} \qquad \textbf{2-10}$$

Damping ratio is then referred to as:

$$\xi = \frac{\mathrm{c}}{\mathrm{c_c}} \qquad \textbf{2-11}$$

If $\xi = 1$ we have a critically damped situation. Below 1 is underdamped and above 1 is overdamped. The "under damped" situation is the most common situation in structural analysis. The solution for the damped system is:

$$y(t) = Y_0 e^{-\xi\omega_n t}\cos\left(\sqrt{1-\xi^2}\omega_n t - \phi_0\right) \qquad \textbf{2-12}$$

Where $Y_0$ is the starting posision of the vibration and $\phi$ is the phase shift. The function is plotted in Figure 2-8.

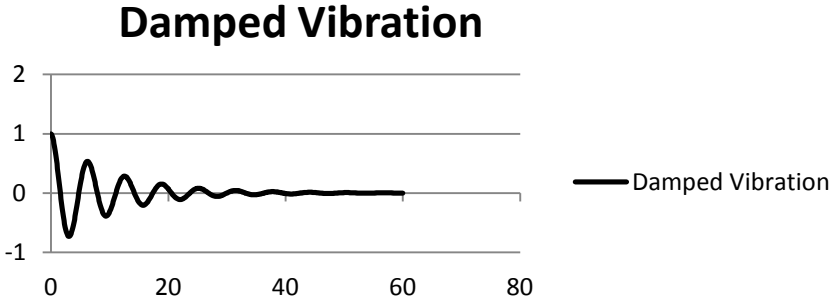



**Figure 2-8: Movement of a damped vibration system**

### 2.2.3 Forced vibrations

Forced vibrations are vibrations of a system with an applied harmonic force or load. Depending on the damping factor and stiffness of the structure we are able to calculate the response of the system. If the forces are acting with a frequency close to the Eigen frequency of the system, resonance will occur (Jakobsen, MOM140 Mekaniske svigninger, 2010).

### 2.2.4 Resonance

Resonance occurs when the frequency of the applied harmonic force is close to the systems natural frequency. The harmonic force then "feeds" the system with kinetic energy. Thus the energy storage increases for every cycle, and the amplitude of the vibration grows dramatically (Jakobsen, MOM140 Mekaniske svigninger, 2010).

The dynamic amplification factor (DAF) tells us how much the amplitude is growing with different load frequencies. In a general picture; very low frequencies will give the same amplitude (A ratio of 1). When the frequency increase and reach the systems natural frequency we receives resonance. By further increasing the frequency the system responds with lower amplitude (Jakobsen, MOM140 Mekaniske svigninger, 2010).

The effect of the DAF can be easily seen in real life. By tying a bottle to a flexible rope and lifting it slowly by the rope, you can see that the bottle follows the movement of your hand. It follows the movement in a 1 to 1 ratio. If you further increase the ratio jerking the rope up and down the bottle moves more until the point where it reaches the systems natural frequency, the motion is stopped either by the floor, or the rope's ability to stretch. If the amplitude of the applied force is further increased the DAF is reduced until it even reaches below 1. You will be standing and jerking the rope up and down as fast as you might, but the bottle hardly moves (Odland, 2011).

### 2.2.5 Vibrations from wind turbines

Since the wind is never uniform, the rotation of the rotor gives the structure different forces from time to time. As an example, an area of the wind may contain stronger currents because of turbulence. These "patches" of wind speed deviations are called eddies. If an airfoil sweeps this area, the wind turbine is exposed to higher loads exactly when the airfoil is inside the eddy. The result is a cyclic load as the airfoil enters and exits for each rotation. The frequency of this load is referred to as the rotor frequency (1P). As the other blades pass there will also be another frequency representing every blade passing the eddy (3P). An important factor when designing a substructure is to make sure the natural frequencies of the system lies away from the 1P and 3P frequencies.(Tempel, 2006)

## 2.3 Finite Element Method

### 2.3.1 The idea of FEM calculation

The finite element method is a way of simplifying problems. In example, large complex objects are divided into smaller simple pieces (also called elements). The element properties are defined (i.e. the way elements transfer forces or temperature from point to point). By knowing each element's properties we are able to simplify the calculation of the elements combined. The equations for the different elements are connected to reveal the calculations for the entire object. Knowledge in matrix algebra is required when working with finite element analysis. The equations for the different element are connected in matrices, and the computational requirements will easily become very complicated. Thanks to today's stronger computers we are now able to compute advanced FEM models, but there is still few steps needed to overwhelm the computer capacity (Arora, 2011).

Calculating advanced objects is time consuming. Each time an analysis is made a matrix set is generated. Sometimes structures consist of similar parts or can be divided into natural sub components. By generating matrices for the different sub components the calculation speed is improved. The matrices for the "new" sub components are now stored and the components work as elements. They are named super elements. Examples of super elements may be aircraft wings, gear teeth, construction parts. Super elements are used mainly to reduce computation time (Once the substructure is processed). It is a great way to rerun analysis without having to calculate the entire FEM model. By altering parts of the FEM model, the solver only has to reanalyze the problem partly (Arora, 2011).

Theory in this chapter is based on lectures by associate Professor Vikas Arora at the University Of Stavanger (UIS) during spring 2011. Online lecture notes written by Professor Yijun Liu from the University of Cincinnati are used as additional reading.

### 2.3.2 Using FEM to calculate stiffness of a spring system:

A single simple spring can be characterized as a FEM element. It contains of two connection points, referred to as nodes. By calculating in one dimension the nodes have the following data of interest: displacement and external force applied to the node. Additional data of interest is the stiffness between the nodes. Our interest during FEM analysis is to be able to accurately compute the dataflow from node 1 to node 2 without running through the advanced details between them (Liu, 2003).

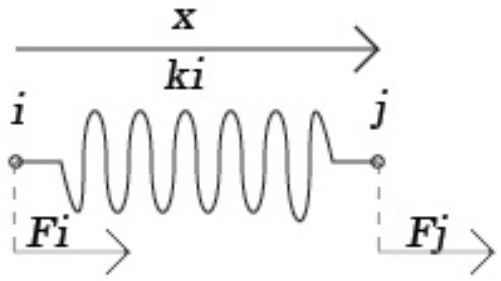



**Figure 2-9: A simple spring element**

Based on the relationship between force and displacement the stretching of a material happens through different phases; Linear elastic, elasto-plastic, and fully plastic. Assuming that the material completely follows a linear elastic line the properties the following equations are applicable:

$$F = k\Delta \qquad \textbf{2-13}$$

$$\Delta = u_i - u_j \qquad \textbf{2-14}$$

Linear elastic means that if the material is applied a force, it is stretched. If unloaded, it returns to its initial shape. Equation 2-13 states that more strain ′Δ′ applied to the spring gives higher force from the spring element. The equilibrium forces for the spring at the nodes are as follows:

$$f_i = -F = -k(u_j - u_i) = ku_j - ku_i \qquad \textbf{2-15}$$

$$f_j = -F = k(u_j - u_i) = -ku_j + ku_i \qquad \textbf{2-16}$$

Where $u_j$ and $u_i$ are the displacement of node I and j. $f_i$ and $f_j$ are the forces in the nodes. Both equations are related to each other. By rewriting equation 2-15 and 2-16 to matrix form:

$$\begin{bmatrix} k & -k \\ -k & k \end{bmatrix} \begin{bmatrix} u_i \\ u_j \end{bmatrix} = \begin{bmatrix} f_i \\ f_j \end{bmatrix} \qquad \textbf{2-17}$$

**ku=f**

These are element matrices where **k** is the element stiffness matrix, **u** is the element displacement matrix and **f** is the element force matrix.

### 2.3.3 Combining elements and applying boundary conditions

The following example is based on example 1.2 from the lecture notes of Yijun Liu.(Liu, 2003)

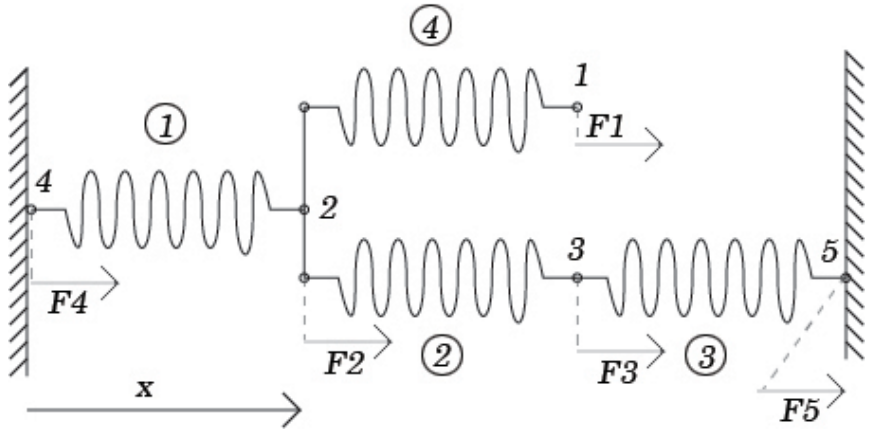



**Figure 2-10: Connected springs example**

The potential in FEM analysis is shown when several elements are connected together to for a final system. The springs in this system are of different stiffness and lengths.

Each element has its own element stiffness matrix. By combining these we are able to get a matrix equation for the problems.

$$K_1 = \begin{matrix} \\ u_4 \\ u_2 \end{matrix}\begin{matrix} \begin{matrix} u_4 & u_2 \end{matrix} \\ \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 \end{bmatrix} \end{matrix} \qquad K_2 = \begin{matrix} \\ u_2 \\ u_3 \end{matrix}\begin{matrix} \begin{matrix} u_2 & u_3 \end{matrix} \\ \begin{bmatrix} k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \end{matrix}$$

$$K_3 = \begin{matrix} \\ u_3 \\ u_5 \end{matrix}\begin{matrix} \begin{matrix} u_3 & u_5 \end{matrix} \\ \begin{bmatrix} k_3 & -k_3 \\ -k_3 & k_3 \end{bmatrix} \end{matrix} \qquad K_4 = \begin{matrix} \\ u_2 \\ u_1 \end{matrix}\begin{matrix} \begin{matrix} u_2 & u_1 \end{matrix} \\ \begin{bmatrix} k_4 & -k_4 \\ -k_4 & k_4 \end{bmatrix} \end{matrix}$$

Connecting the element matrices gives a global matrix. As the element matrix, the global matrix is also symmetric.

$$K_g = \begin{bmatrix} k_4 & -k_4 & 0 & 0 & 0 \\ -k_4 & k_1+k_2+k_4 & -k_2 & -k_1 & 0 \\ 0 & -k_2 & k_2+k_3 & 0 & -k_3 \\ 0 & -k_1 & 0 & k_1 & 0 \\ 0 & 0 & -k_3 & 0 & k_3 \end{bmatrix}$$

To understand the placement of element matrices it is possible to name the columns from $u_1$ to $u_2$ and the rows the same (See the $K_1$ matrix above). E.g. the global stiffness at matrix position $(u_2, u_2)$ is the sum of values found in the element stiffness matrices $k_1, k_2 and\ k_4$ at same coordinate $(u_2, u_2)$.

$$\begin{bmatrix} k_4 & -k_4 & 0 & 0 & 0 \\ -k_4 & k_1+k_2+k_4 & -k_2 & -k_1 & 0 \\ 0 & -k_2 & k_2+k_3 & 0 & -k_3 \\ 0 & -k_1 & 0 & k_1 & 0 \\ 0 & 0 & -k_3 & 0 & k_3 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{bmatrix}$$

Since the nodes numbered 4 and 5 are fixed the values for node deflections equals zero. These are boundary conditions. They signal that column $u_4$ and $u_5$ in the global stiffness as well as row 4 and 5 in the displacement matrix are negligible. The equation is still valid as the (5x3) by (3x1) matrices equal the (5x1) matrix (Arora, 2011).

$$\begin{bmatrix} k_4 & -k_4 & 0 & 0 & 0 \\ -k_4 & k_1+k_2+k_4 & -k_2 & -k_1 & 0 \\ 0 & -k_2 & k_2+k_3 & 0 & -k_3 \\ 0 & -k_1 & 0 & k_1 & 0 \\ 0 & 0 & -k_3 & 0 & k_3 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{bmatrix} = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{bmatrix}$$

### 2.3.4 The simple beam element

Taking the spring example into consideration, we see that even few simple elements makes up for a complex nest of matrices.

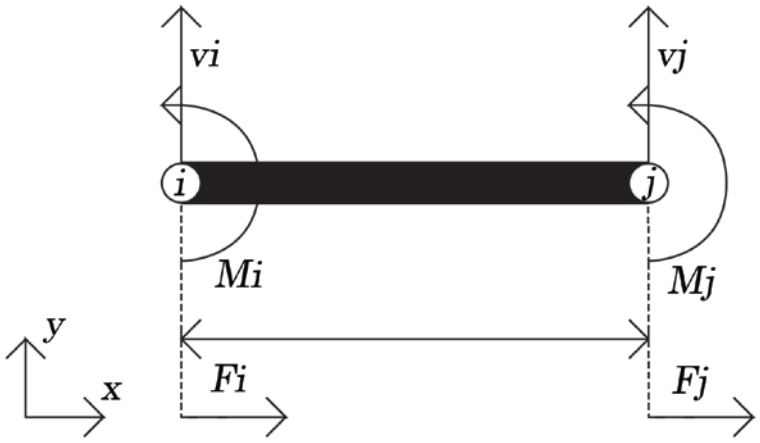



**Figure 2-11: 2 degree of freedom beam element**

A simple one dimensional beam element has 2 degrees of freedom; the rotation and the horizontal displacement of the nodes.

Liu, 2003 (equation 38)

$$\underset{k}{\frac{EI}{L^3}\begin{bmatrix} 12 & 6L & -12 & 6L \\ 6L & 4L^2 & -6L & 2L^2 \\ -12 & -6L & 12 & -6L \\ 6L & 2L^2 & -6L & 4L^2 \end{bmatrix}} \begin{bmatrix} v_i \\ \theta_i \\ v_j \\ \theta_j \end{bmatrix} = \begin{bmatrix} F_i \\ M_i \\ F_j \\ M_j \end{bmatrix}$$

E is the modulus of elasticity and I is the moment of inertia. L is the length of the current element. With one additional boundary condition, the amount of calculation is doubled. The beam elements in the simulation model are made of three dimensional beam elements. With nodes able to turn and deflect about all three axes, the matrix algebra becomes advanced and computer computation is a necessity.

## 2.4 Site specific factors

Offshore is a very suitable place for a wind turbine. The transport of the turbines makes less impact on roads and the roughness of the "terrain" calls for stronger and more stable wind flow. In addition, the turbines do not affect people in the way an onshore turbine does.

## 2.5 Wind Modeling

### 2.5.1 Mean wind speed

The mean wind speed change based on where we are positioned in the world. Onshore there are tabulated measurements from districts in Norway based on statistical data. When the wind measurements are gathered they are normally calculated around 1, 10 or 60 minute mean. The reference height is usually 10 meters above ground level. The notation of the 10 minute mean wind speed is $U_{10}$

The wind speed is affected by:

- The location
- The shape/roughness of the terrain
- The height above the sea or ground level
- The direction of flow
- The season (Temperature, pressure, astronomical conditions)

(Jakobsen, MKO110 Naturlaster, 2011)

### 2.5.2 Wind profile

The wind speed is highly dependent of height. Wind close to the earth is especially variable in speed because of friction against the terrain and the heating of air against the surface. Several models are developed to calculate a mean wind profile. The most commonly used profiles are: Logarithmic, power law model and Frøya model.(DNV-RP-C205, 2010)

A logarithmic wind speed profile may be assumed for neutral atmospheric conditions and can be expressed as:

DNV-RP-C205, 2010 (2.3.2.4): $$U_{(z)} = \frac{u^*}{k_a} ln \frac{z}{z_0}$$ **2-18**

Where $z$ is the height above mean sea level, $z_0$ is the surface roughness parameter and $k_a$ is the von Karman's constant (0,4). The friction velocity u* can be defined as:

DNV-RP-C205, 2010 (2.3.2.3): $$u^* = \sqrt{\tau/\rho_a}$$ **2-19**

Where $\tau$ represents the surface shear stress and $\rho_a$ represents the density of the air. From the reference height of 10 meters and at the 10 minute mean wind speed $U_{10}$ it can be calculated as:

DNV-RP-C205, 2010 (2.3.2.3): $$u^* = U_{10}\sqrt{\kappa}$$ **2-20**

Where $\kappa$ is defined in equation 2-21.

DNV-RP-C205, 2010 (2.3.2.6): $$\kappa = \frac{k_a^2}{\left(ln\frac{H}{z_0}\right)^2}$$ **2-21**

H is the reference wind height. The constant $z_0$ is the terrain roughness parameter. There are predefined values for $z_o$ based on terrain types from the work of Panofsky and Dutton (1984), Simiu and Scanlan (1978), JCSS (2001) and Dyrbye and Hansen (1997). These data are present in table 2-1 in DNV-RP-C205_2010-10.

| **Terrain roughness parameter $z_0$ and power-law exponent α** | | |
|---|---|---|
| Terrain type | Roughness parameter $z_0$ (m) | Power-law exponent α |
| Plane ice | 0.00001-0.0001 | |
| Open sea without waves | 0.0001 | |
| Open sea with waves | 0.0001-0.01 | 0.12 |
| Coastal areas with onshore wind | 0.001-0.01 | |
| Snow surface | 0.001-0.006 | |
| Open country without significant buildings and vegetation | 0.01 | |
| Mown grass | 0.01 | |
| Fallow field | 0.02-0.03 | |
| Long grass, rocky ground | 0.05 | |
| Cultivated land with scattered buildings | 0.05 | 0.16 |
| Pasture land | 0.2 | |
| Forests and suburbs | 0.3 | 0.30 |
| City centres | 1-10 | 0.40 |

**Table 2-1: Terrain roughness parameter and power-law exponent**

For offshore locations the $z_0$ parameter will vary depending on the sea state. It can be solved implicitly with the following equation:

DNV-RP-C205, 2010 (2.3.2.5) $$z_o = \frac{A_c}{g}\left(\frac{k_a U(z)}{\ln\left(\frac{z}{z_0}\right)}\right)^2$$ **2-22**

$A_c$ is Charnock's constant which lies between 0,011 and 0,014 for open sea state with developed waves. The constant of gravity $g$ is 9,81 $m/s^2$.

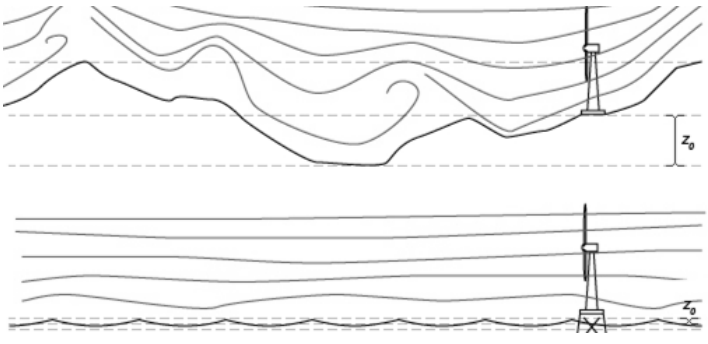



**Figure 2-12: The surface roughness parameter $z_0$**

### 2.5.3 Turbulent wind speed

Wind becomes turbulent when its flow gets disturbed. The particles no longer have a path to travel fluently through. When the wind flows over terrain or texture the shear force creates turbulence. Also when the air gets heated, the atoms with higher temperature rise. This is called the buoyancy effect and is easily observed as ripples in the view over a flame. Turbulence is the standard deviation of mean wind speed about the 10 minute mean (DNV-RP-C205, 2010).

DNV-RP-C205, 2010 (2.1.2.3) $$\frac{\sigma_U}{U_{10}}$$ 2-23

The mean value $\sigma_U$ of the wind speed standard deviation may be calculated through the following equations(DNV-RP-C205, 2010):

DNV-RP-C205, 2010 (2.3.3.6) $$E[\sigma_u] = U_{10} A_x k_a \frac{1}{ln\frac{z}{z_0}}$$ **2-24**

DNV-RP-C205, 2010 (2.3.3.6) $$A_x = \sqrt{4{,}5 - 0{,}856 ln z_0}$$ **2-25**

$E[\sigma_u]$ represents the mean value of the wind speed standard deviation. $A_x$ is a constant dependant on $z_0$.

### 2.5.4 The Kaimal turbulence model

The Kaimal spectrum is given by the following equation (DNV-RP-C205, 2010) for the power spectral density:

DNV-RP-C205, 2010 (2.3.4.7) $$S_u(f) = \sigma_u^2 \frac{6{,}868\frac{L_u}{U_{10}}}{\left(1 + 10{,}32\frac{fL_u}{U_{10}}\right)^{5/3}}$$ **2-26**

DNV-RP-C205, 2010 (2.3.4.7) $$L_u = 300\left(\frac{z}{300}\right)^{0{,}46 + 0{,}074 ln z_0}$$ **2-27**

## 2.6 Foundation Structures

When installing an offshore wind turbine, there are several factors which affect our choice of foundation structure. The offshore wind turbines are commonly installed in shallow water depths, but as technology advance we see the opportunity to expand to deeper waters. Because the distance from seabed to sea surface increase the structures become more slender. This calls for structures with higher stiffness to avoid natural frequencies which responds with the load frequency; thus preventing the resonance effect. Numerous factors have to be considered when choosing the substructure; Turbine type, soil type, water depth, sea states, distance from shore, installation methods, prices and more.

The most popular substructures by time being are the following:

### 2.6.1 Monopile

A large diameter steel pipe is driven deep into the seabed. Mounting is done through a transition piece fixed on top of the monopile. When water depth increase the length of the monopole has to be increased. A more slender structure gives higher Eigen frequencies, thus the thickness have to be increased drastically to meet the excitation frequencies. The use of monopole foundations is best suited in water depths up to 25 meters. (EWEA, Wind in our Sails, 2011)

By the end of 2011 there were a total of 233 monopiles installed. This number represents 69,3% of installed substructures.(EWEA, The European offshore wind industry, 2012)

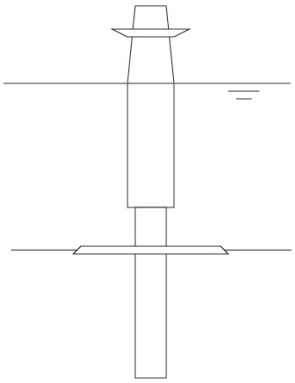


**Figure 2-13: Monopile foundation**

### 2.6.2 Gravity foundation

The gravity foundation type consists mainly of a heavy mass which rests on the subsurface. In this case the stability and support of the wind turbine relies only on the gravity force from the foundation itself. The goal of gravity based substructures is to remove tensile forces between the soil and support structure. The foundation is produced onshore and transported to the installation site by boat. When installed, the foundation is filled with ballast. Currently, the gravity foundations are suitable for water depths up to 30 meters. (EWEA, Wind in our Sails, 2011)

By the end of year 2011 one gravity foundation was installed.(EWEA, The European offshore wind industry, 2012)

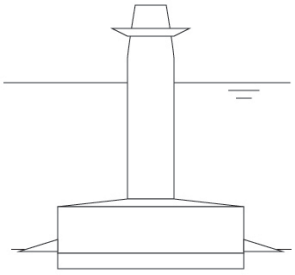


**Figure 2-14: Gravity based foundation**

### 2.6.3 Tripod foundation

The tripod is made of three cylindrical steel tubes pinned to the ground. The turbine is mounted on a central steel shaft. The structure type is suited for water depths between 20 and 50 meters. (EWEA, Wind in our Sails, 2011)

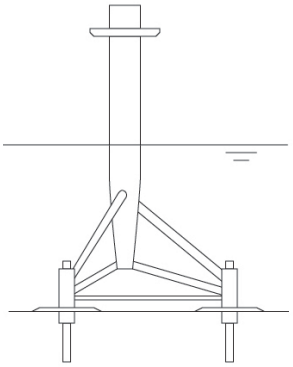


**Figure 2-15: Tripod foundation**

### 2.6.4 Tripile foundation

Three foundation piles are used. The transition piece is mounted above water level on top of the three piles.(EWEA, Wind in our Sails, 2011)

By the end of 2011 EWEA registered a total of 33 turbines with tripile foundations. (EWEA, Wind in our Sails, 2011)

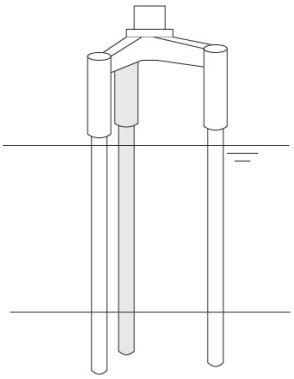


**Figure 2-16: Tripile foundation**

### 2.6.5 Jacket structure

The jacket structure consists of steel legs with bracings. It is piled to the soil at each leg. Due to large area coverage, the steel jacket provides low material costs compared to stiffness.(EWEA, Wind in our Sails, 2011)

66 jacket foundations were installed by 2011 which covers 20% of the total installations.(EWEA, The European offshore wind industry, 2012)

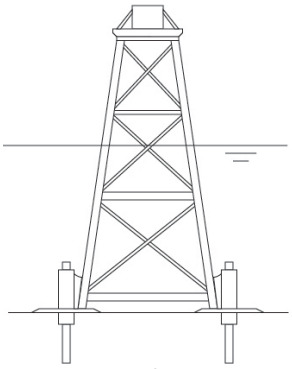


**Figure 2-17: Jacket foundation**

## 2.7 Data analysis

### 2.7.1 Deterministic data

Deterministic data are data which is highly predictable. Events or loads which are fully controllable or known are described as deterministic, and is easily put into analysis. Examples are the frequency of the rotor and the 3P blade frequency. Our wind turbine running between 6.9 and 12.1 rpm produce a 1P frequency from 8.69 Hz to 4.96 Hz. The 3P frequencies are between 2.90 Hz and 1.65 Hz.

### 2.7.2 Stochastic data

The responses recorded on the wind turbine are described as stochastic data. The wind data is simulated after a given set of rules. Embedded in these rules are parameters made to randomize our output. We can clearly see patterns in the data set, with peaks and troughs, sudden drops and irregularities. To take advantage of these data, it is desirable to transform them into other domains.

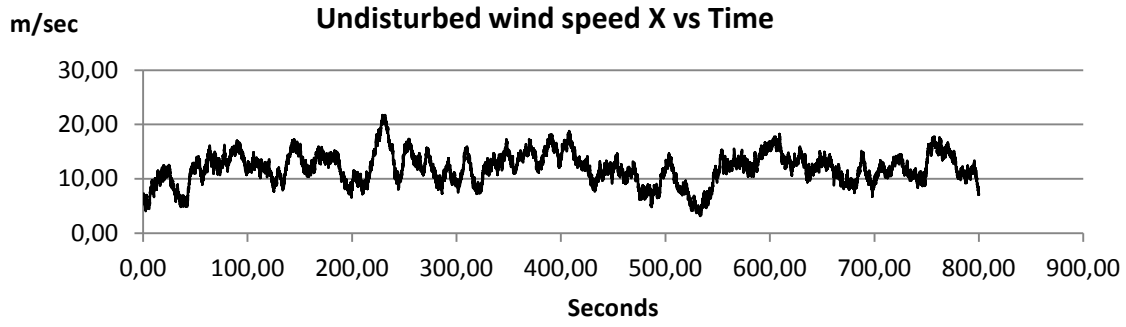



**Figure 2-18: Stochastic wind speed data**

The reason the response is randomized is because of the random component in the wind and wave loads. The wind is predictable to a certain point, but turbulence and sudden gusts makes it variable.

### 2.7.3 How to use the data collected

In order to analyze our problem, the data sometimes has to be post processed. In case of stochastic data sets there might be interesting to see under which frequencies the loads governs, or to give a representative load cycle when fatigue is of concern.

### 2.7.4 Rainflow counting

Ideally, cycles are repetitive and uniform but in complex loading they vary in all ways. To apply Miner's rule load data has to be simplified to waves with different means and amplitudes.

To convert a series of varying data into ideal cycles the Rainflow-counting method is used. Rainflow-Counting is an algorithm developed by Tatsuo Endo and M. Matsuishi. The name is taken from rain that flows down a roof (Ariduru, 2004).

The algorithm:

The readings are reduced to peaks and troughs. To simplify the understanding of the algorithm the sheet is turned 90 degrees clockwise. Now the data is shaped like a "zigzag" going down. It is often referred to as a pagoda roof. See Figure 2-19. By imagining that each tensile peak is a source of water that flows down the roof, the number of cycles can be counted and categorized with simple rules:

Identify the half cycles in the readings. It starts from a water source and ends where the flow is interrupted. The flow is interrupted when it reaches the end of the time history. It is also interrupted if it meets another flow from a deeper tensile peak. When the half cycles are counted, give them the value equal the stress difference between the peak and the interruption. Do the same for troughs. Pair up the half cycles from the two rounds which carries the same value. They will now form new ideal cycles. Often some half cycles will remain unpaired. To ease the dataflow the cycles are binned during counting. (Dowling, 1999)

See Appendix 7.9 for illustrations of the counting.

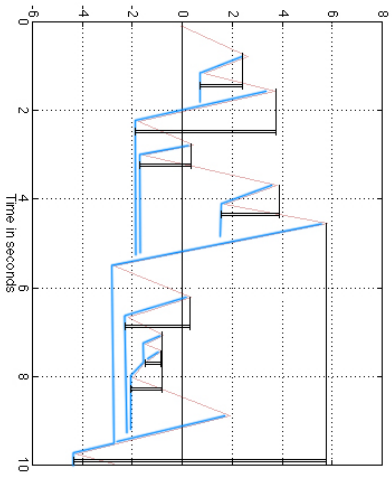



**Figure 2-19: Rainflow counting**

### 2.7.5 Miners Rule - Damage equivalent loads

Mlife makes the fatigue analysis based on Annex G of IEC 61400-1 ed3. The fatigue damage is calculated from fluctuating loads and summarized. The load fluctuation is calculated using rainflow counting. Cycles from the counting are characterized by a mean and load range. The program bases its results on Miner's Rule, where damage accumulation is assumed to be linear with each cycle. For short time DEL. (Hayman, 2011)

Miners rule

$$D = \sum_k \frac{n_k}{N_k(L_k^{RF})} \qquad \textbf{2-28}$$

$$N_k^F = \left( \frac{L^{ult} - |L^{MF}|}{\left(\frac{1}{2} L_k^{RF}\right)} \right)^m \qquad \textbf{2-29}$$

*D* equals the total damage from cycles. $n_k$ is the cycle count and $N_k$ is the number of cycles until failure. $L_k^{RF}$ is the current cycles load range about the fixed mean. $N_k^F$ represents the cycles of current size until failure, $L^{ult}$ is the ultimate design load, $L^{MF}$ is the fixed mean load and the exponent *m* is the inverse slope of the S-N curve.

The S-N curve is generated from material testing, and represents the number of cycles the current material can withstand of given cyclic load (Macdonald, 2010).

#### *2.7.5.1 Conversion of load cycles*

The cycles happen all at different means and ranges, but to be able to use them in these equations they have to be converted to the same mean. Moving a cycle from a high mean to the zero mean also adds to the cycle range. This is done by applying the following formula (Hayman, 2011):

$$L_k^{RF} = L_k^R \left( \frac{\left(L^{ult} - |L^{MF}|\right)}{\left(L^{ult} - \left|L_k^M\right|\right)} \right) \qquad \textbf{2-30}$$

The following figure shows by illustration how the different waves are converted to match fixed load mean. In this case the mean is set to zero. Notice how the scaling increases with distance from the fixed mean.

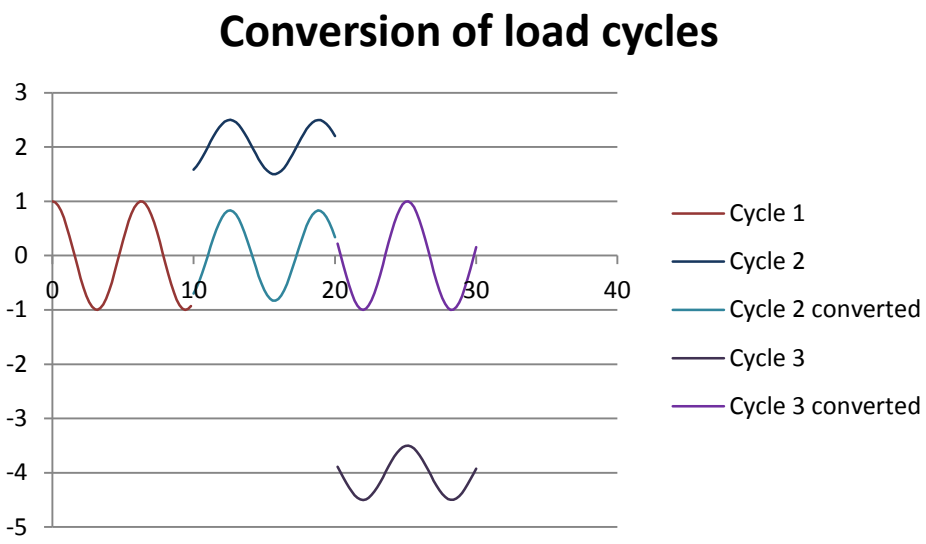



**Figure 2-20: Illustration of load cycle conversions**

For the figure, the following equation is used:

$$L_k^{R0} = L_k^R \left( \frac{L^{ult}}{\left(L^{ult} - \left|L_k^M\right|\right)} \right) \qquad \textbf{2-31}$$

Where $L_k^{R0}$ is the current cycle load range about zero mean,$L_k^R$ is the current cycle load range and $L_k^M$ is the current cycle mean load range.

#### *2.7.5.2 Short time DEL computation*

For computation of the short time DELs, Mlife uses the following equations:

$$D_j^{ST} = \sum_k \frac{n_{jk}}{N_k} = \frac{n_j^{STeq}}{N_j^{eq}} \qquad \textbf{2-32}$$

$$n_j^{STeq} = f^{eq} * T_j \qquad \textbf{2-33}$$

$$N_j^{eq} = \left( \frac{L^{ult} - |L^{MF}|}{\left(\frac{1}{2} DEL_j^{STF}\right)} \right)^m \qquad \textbf{2-34}$$

Where $D_j^{ST}$ is the short term damage from current dataset j. $N_j^{eq}$ is the equivalent number of cycles until failure in current dataset. $n_{jk}$ and $n_j^{STeq}$ is the cycle count for the current dataset and total equivalent fatigue counts for the dataset respectively. $f^{eq}$ and $T_j$ are the frequency and the time of dataset. $DEL_j^{STF}$ is the damage equivalent load from dataset j about a fixed mean.

# 3 Method

Data to be studied in this report is purely quantitative. Several simulation rounds are made, and each simulation run yields output files with tabulated data. The models used are made in purpose to compare and certify codes for offshore wind turbine simulations, but are in this cased used for thesis research.

## 3.1 The OC4 project

OC4 stands for Offshore Code Comparison Collaboration Continuation. It is a collaboration project between countries worldwide. The aim of the project is to verify codes for correctly simulation of offshore wind turbines (OWT) and support structures. This includes simulation with more than 22 simulators and settings to ensure reliable methods and results. The OC4 project follows the OC3 (Offshore Code Comparison Collaboration) project which ran from 2005 until 2009. The OC3 project goal was to verify OWT codes on a monopile, tripod and floating spar buoy configuration. The OC4 project has the same goal, but this time with a jacket foundation and a WindFloat foundation. The WindFloat foundation is a floating substructure. The inputs for the project are already defined. To be able to predict somewhat similar results the cases are all similar. The turbine is an NREL 5-MW wind turbine with a predefined control system. As for the support structures there are the several defined structure types.(Smith, 2011)

The main objectives for the OC4 project are to assess simulation accuracy and reliability, train new analysts how to run codes correctly, investigate capabilities of implemented theories, refine applied analysis methods and identify further research and development needs.(Smith, 2011)

## 3.2 The wind turbine model

The wind turbine structure itself is a 5-MW reference wind turbine for offshore system development. It is developed by the NREL team based on research data from earlier projects where data from the prototypes Multibrid M5000 and Repower 5M. The Repower 5M had the most expected properties thus the specifications for this turbine are used(J. Jonkman, 2009).

| Gross Properties Chosen for the NREL 5-MW Baseline Wind Turbine | |
|---|---|
| Rating | 5 MW |
| Rotor orientation, Configuration | Upwind, 3 Blades |
| Control | Variable Speed, Collective Pitch |
| Drivetrain | High Speed, Multiple-Stage Gearbox |
| Rotor, Hub Diameter | 126 m, 3m |
| Hub Height | 90 m |
| Cut-In, Rated, Cut-Out Wind Speed | 3 m/s, 11.4 m/s, 25 m/s |
| Cut-In, Rated Rotor Speed | 6.9 rpm, 12.1 rpm |
| Rated Tip Speed | 80 m/s |
| Overhang, Shaft Tilt, Precone | 5m, $5^{o}$, $2.5^{o}$ |
| Rotor Mass | 110,000 kg |
| Nacelle Mass | 240,000 kg |
| Tower Mass | 347,460 kg |
| Coordinate Location of Overall CM | -0.2 m, 0.0 m, 64.0 m |

**Figure 3-2: The NREL 5-MW Baseline Wind Turbine Specifications**

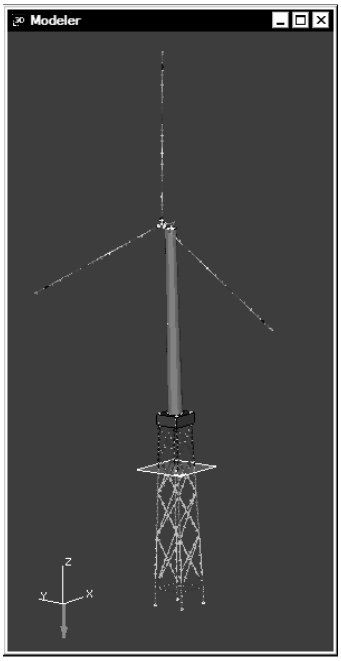



**Figure 3-1: The simulation model**

The reference model consists of the NREL 5-MW baseline turbine mounted on a steel jacket through a concrete transition piece. The reference jacket is designed by Rambøll AS. The structure is made of 4 legs in 4 levels. Each level has cross braces. At the base there are mud braces and four central piles. Water depth is set to be 50 meters. Ref: (Smith, 2011). The model is assembled in Fedem by Kristian Sætertrø from the Fedem team.

### 3.2.1 The data of interest

The "sensors" placed in Fedem are positioned according to the OC4 Load Cases Description. Due to unknown errors some curves were not exported automatically even though the data was set to export, as well as the curves were rebuilt in Fedem. This applies to column number 21 to 26 which are combined curves.

| Column number | Name | Unit | Description |
|---|---|---|---|
| 1 | Time | s | Simulation time |
| 2 | WindVxi | m/s | Longitudinal Wind Speed |
| 3 | TPX | m | Transition Piece Fore-Aft Deflection |
| 4 | TPY | m | Transition Piece Side-to-Side Deflection |
| 5 | TPZ | m | Transition Piece Top-Down Deflection |
| 6 | TPRotX | deg | Transition Piece Rotation around global x-axis |
| 7 | TPRotY | deg | Transition Piece Rotation around global y-axis |
| 8 | TPRotZ | deg | Transition Piece Vertical Rotation |
| 9 | X2S2 | m | Out-of Plane Deflection at Center of X-Joint at level 2 on side 2 |
| 10 | X2S3 | m | Out-of Plane Deflection at Center of X-Joint at level 2 on side 3 |
| 11 | X4S2 | m | Out-of Plane Deflection at Center of X-Joint at level 4 on side 3 |
| 12 | X4S3 | m | Out-of Plane Deflection at Center of X-Joint at level 4 on side 3 |
| 13 | B59Ax | kN | Axial Force in Center of Brace 59 |
| 14 | B59Sh | kN | Out-of-Plane Shear Force in Center of Brace 59 |
| 15 | B61Ax | kN | Axial Force in Center of Brace 61 |
| 16 | B61Sh | kN | Out-of-Plane Shear Force in Center of Brace 61 |
| 17 | K1L2 | kN | Axial Force in Leg 2 at K-Joint level 1 |
| 18 | K1L4 | kN | Axial Force in Leg 4 at K-Joint level 1 |
| 19 | MBL2 | kN | Axial Force in Leg 2 at mudbrace level |
| 20 | MBL4 | kN | Axial Force in Leg 4 at mudbrace level |
| 21 | BSX | kN | Fore-Aft Base Shear |
| 22 | BSY | kN | Side-to-Side Base Shear |
| 23 | OTMX | kNm | Overturning Moment around global x-axis |
| 24 | OTMY | kNm | Overturning Moment around global y-axis |
| 25 | MudMz | kNm | Moment around global z-axis at mudline |
| 26 | MudFz | kN | Summed Force along global z-axis at mudline |

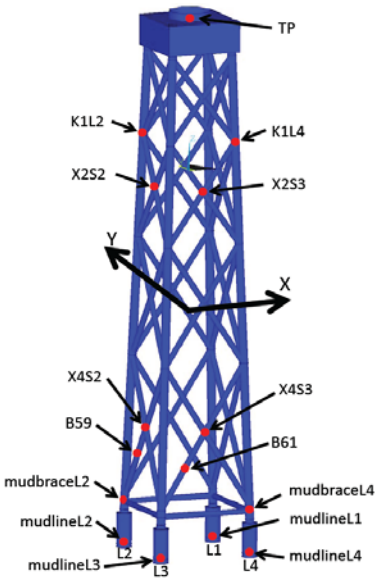



**Figure 3-3: The reference jacket (Vorpahl & Popko, 2011)**

**Figure 3-4: Measured points on the OC4 jacket**

## 3.3 The different simulation cases

### 3.3.1 Simulation case 1: stdev1

The first simulation run is made with 12 different mean wind speeds. To ensure randomness, each wind profile is loaded with 6 randomly generated turbulences. The output specified in TurbSim is Aerodyn form as Aerodyn is the code used by Fedem to interpret the wind data, and translate them to forces on the blades. The turbulence parameter was calculated according to equation 2-24 stated in DNV-RP-C205, 2010 (2.3.3.6). By dividing on mean wind speed the turbulence intensity (TI) is set. The mean wind speed was set to odd numbers from 3 to 25. In this way the complete range of operating wind speeds is simulated.

| Case | TI | $z_0$ | Case | TI | $z_0$ |
|---|---|---|---|---|---|
| **3T** | 9,3 | 0.00001 | **15T** | 10,6 | 0.00024 |
| **5T** | 9,7 | 0.00002 | **17T** | 10,8 | 0.00033 |
| **7T** | 9,9 | 0.00004 | **19T** | 10,9 | 0.00043 |
| **9T** | 10,1 | 0.00007 | **21T** | 11 | 0.00055 |
| **11T** | 10,3 | 0.00013 | **23T** | 11,1 | 0.00068 |
| **13T** | 10,5 | 0.00017 | **25T** | 11,2 | 0.00083 |

**Table 3-1: Parameter for simulation with 1 standard deviation turbulence.**

### 3.3.2 Simulation case 2: stdev1,5

The same mean wind speeds were maintained during simulation run 2. Standard deviation of wind is set to 1,5 so new turbulence intensities were calculated and assigned to the TurbSim input.

| Case | TI | $z_0$ | Case | TI | $z_0$ |
|---|---|---|---|---|---|
| **3T** | 13,6 | 0.00001 | **15T** | 16,0 | 0.00024 |
| **5T** | 14,5 | 0.00002 | **17T** | 16,2 | 0.00033 |
| **7T** | 14,9 | 0.00004 | **19T** | 16,3 | 0.00043 |
| **9T** | 15,2 | 0.00007 | **21T** | 16,5 | 0.00055 |
| **11T** | 15,5 | 0.00013 | **23T** | 16,7 | 0.00068 |
| **13T** | 15,7 | 0.00017 | **25T** | 16,8 | 0.00083 |

**Table 3-2: Parameters for simulation with 1.5 standard deviations turbulence.**

### 3.3.3 Simulation case 3: stdev2

The turbulence of the wind was altered to two standard deviations of mean wind speed.

| Case | TI | $z_0$ | Case | TI | $z_0$ |
|---|---|---|---|---|---|
| **3T** | 18,6 | 0.00001 | **15T** | 21,2 | 0.00024 |
| **5T** | 19,4 | 0.00002 | **17T** | 21,6 | 0.00033 |
| **7T** | 19,8 | 0.00004 | **19T** | 21,8 | 0.00043 |
| **9T** | 20,2 | 0.00007 | **21T** | 22 | 0.00055 |
| **11T** | 20,6 | 0.00013 | **23T** | 22,2 | 0.00068 |
| **13T** | 21 | 0.00017 | **25T** | 22,4 | 0.00083 |

**Table 3-3: Parameters for simulation with 2 standard deviations turbulence.**

For a full parameter table see Appendix 7.1.

## 3.4 Wind modeling

### 3.4.1 TurbSim

Turbulence in a wind profile may be described as the "randomness" of the wind. In the simulations in this thesis, new wind data sets are generated with TurbSim; A stochastic, full-field, turbulent-wind simulator for use with the AeroDyn-based design codes (Neil Kelley, 2011). TurbSim is an application developed by NREL (National Renewable Energy Laboratory) to compute wind data based on different calculation standards. TurbSim generates a rectangular grid which holds the wind data. The grid has to cover the entire rotor diameter to provide sufficient wind data to the aerofoil.

TurbSim relies on an input text file to generate our output wind data. The text input describes both parameters and the wind modeling theory TurbSim will rely on. The program uses these parameters to create time series of wind data. The data is produced in a vector grid, which is later applied to the wind turbine model through AeroDyn and Fedem. Because of the rotation of the rotor, sway of tower and pitch of the rotor, it is important to scale the field to cover the entire area swept by the blades.

### 3.4.2 Input files

To ensure pure randomness, a total of six simulations are run on each case. By doing this we eliminate the chance to meet a biased turbulence model. E.g. one seed may produce an extreme event which deviates from the "normal" turbulence applied. Each wind case is generated with two random seeds. Six simulations will make up for any extreme cases. The seeds are generated with Matlab. See Appendix 7.10 for the MatLab script.

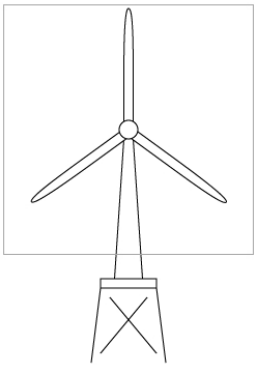


**Figure 3-5: Grid placement on a wind turbine simulation model**

The output settings are set to "full-field time series data in TurbSim/AeroDyn form". Grid settings and position are matched with the rotor diameter, and the center of the grid is positioned at hub height. This represents a grid size of 130 times 130 meters centered at 19.55 meters. As for analysis time, the scope is set to 1050 seconds in case the range of simulation is altered during the project. The additional 200 seconds of wind data is generated before the data is stored. This is done to ensure enough randomness in the wind. For meteorological boundary conditions; The TurbSim application is directed to use the Kaimal turbulence model and follow standard IEC 61400-3 (Offshore). The turbulence intensity is set to 35% for all cases. Normal wind type is chosen with a logarithmic profile. Reference height is set to 90.25 meters. This is the height where the mean wind speed is simulated. So for the 16m/s wind case, the mean of 16m/s acts at the altitude 90.25 meters. For each case the roughness factor is calculated and set in the input file.

See Appendix 7.2 for a sample input file.

## 3.5 Simulation

### 3.5.1 Fedem Simulation software

The structure in this thesis is analyzed in a program called Fedem. It is by writing time in the development phase. Fedem is a multi-body simulation application designed to dynamically simulate mechanical systems. The software outputs movements and vibrations as well as stresses, strains and construction lifetime. Fedem simulation has successfully been applied to a variety of projects. Examples are:

Offshore wind turbines, car suspensions, industrial robots, processing plants, wellheads and both rigid and flexible risers (Fedem Technology AS, 2011).

In Fedem, finite element analysis is brought to life. 3D-models known as links are imported into the project. When running the solver, an additional program code reduces the 3D-models into super elements. By doing this the program now has matrices for the different 3D-models stored, and the distribution of a load through the element is described in the stored matrix. It is an effective way to calculate from A to D while skipping B and C. In our case loads are to be transferred from the rotor through the nacelle, tower and transition piece into the foundation. To skip calculation of middle nodes the tower and transition piece are reduced to super elements. The program stores the new reduced models, and uses them during calculations.

The simulation model was given by the OC4 project. It contained the reference turbine mounted on the OC4 steel jacket. The wind cases generated by TurbSim were linked with the model. Through AeroDyn the loads were calculated for the airfoils (blade elements) and applied to the blades in the simulation model (beam elements).

During simulation it was necessary to generate some data before a stability of the structure is achieved. In real life the wind turbine would not experience a sudden change from 0 m/s to 9 m/s. Because of this, the 50 first seconds of analysis are neglected.

The results are exported automatically in single result files which are later analyzed in Mlife. See Appendix 7.3 for the Fedem file structure.

## 3.6 Analysis

### 3.6.1 Mlife

Mlife is a program based on MatLab. Its purpose it to make fatigue estimations based on aero-elastic and dynamic simulations of wind turbines. Its input is based on a configuration file which includes parameters and configuration of the input data file. In addition the data series are loaded. Mlife can compute short term and lifetime damage equivalent loads (DEL), accumulated lifetime damage and time until failure. In this thesis Mlife is used to compute the short term DEL's. A short term DEL is a load cycle with constant mean, amplitude and frequency which will give the same damage as the variable loads in the data set and hence the different load time histories are easy to compare.

Mlife refers to the columns of data as channels. In the configuration file, the different data channels are identified and scaled. No lifetime analysis is to be done, and no channels are to be calculated. Since Mlife use the Weibull distribution to model wind during lifetime analysis, these options are ignored. During rainflow counting the results are binned. The ultimate loads are determined from the loads at 25 m/s windspeed. The ultimate load is set to ten times the maximum absolute load. The reason for this is that we need to make sure that every load cycle is counted and binned. The bin with is determined by taking the lowest measurements (3m/s) and divide the lowest range by 50. This gives the number 0,17 which states that a bin with of 0,2 will give approximately 43 cycle bins on the lowest measured range. 43 bins on the lowest measurements should be sufficient for calculations. Additional calculations with larger bin widths were performed to check for differences. The results show convergence in all measured areas. The slope of the S/N curve is set to 5 (Matha, 2009).

See Appendix 7.4 for a sample file and Appendix 7.5 for data from bin-testing.

For this thesis the short term DEL is calculated about the fixed mean of zero. Solving equation 2-34 for $DEL_j^{STF}$ gives:

$$DEL_j^{ST0} = \left( \frac{\sum_k \left( n_k \left( L_k^{R0} \right)^m \right)}{n_j^{STeq}} \right)^{\frac{1}{m}} \quad \textbf{3-1}$$

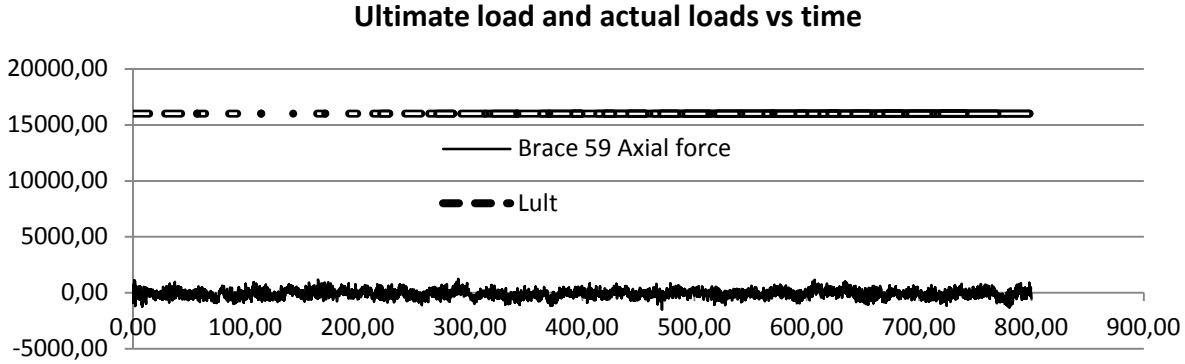



**Figure 3-6: Ultimate load and actual load versus time**

## 3.7 Signal processing

### 3.7.1 Power spectral density with Fast Fourier Transformation in Matlab

In this thesis, the calculation of power spectral density is made by using fast Fourier transformation (FFT) in Matlab.

This example is based on the online Matlab documentation. (MathWorks) It resembles the construction of a dataserie with two waves and a noise applied, and how the fast Fourier transform recognizes the two frequencies inside the combined dataset.

The script is found in Appendix 7.10.

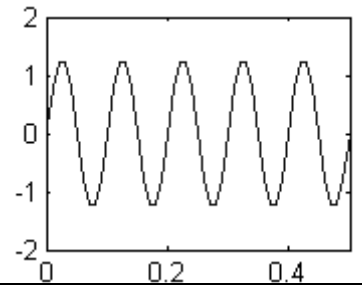
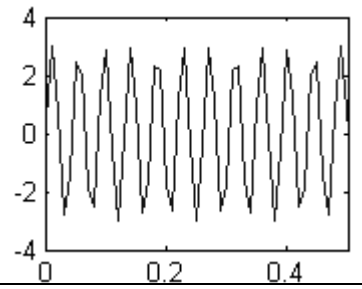
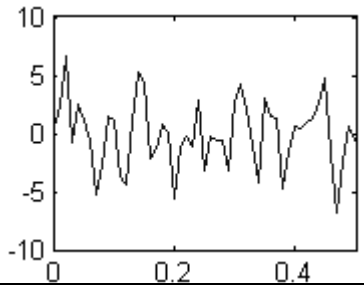
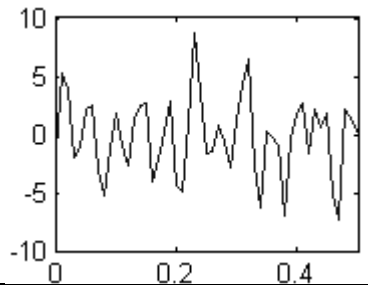
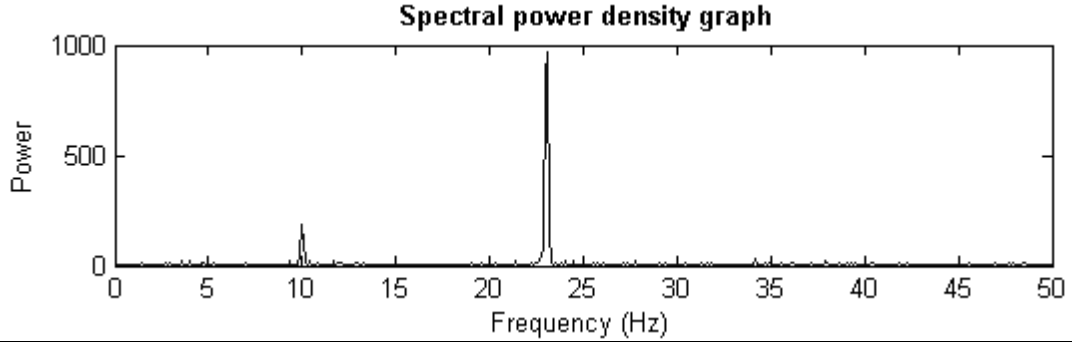
| A=1.3*sin(2*pi*10*t) Signal | B=3*sin(2*pi*23*t) Signal | C=Random(size(t)) signal (noise) |
|---|---|---|
|  |  |  |
| ABC=A+B+C | | |
|  | | |
| The power spectral density of the signal ABC | | |
|   | | |

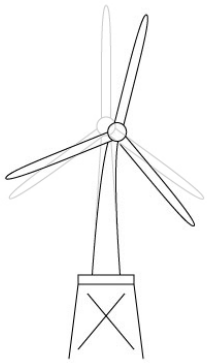
**Table 3-4: Combination of signals and noise and corresponding spectral density graph**

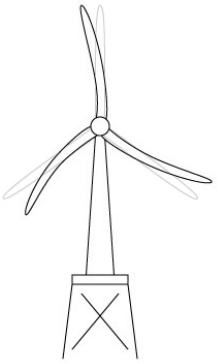
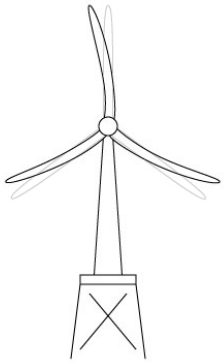
# 4 Results

## 4.1 Vibration analysis

### 4.1.1 The Eigen modes

The following tabulated Eigen frequencies for the original OC4 structure are calculated by Fedem. Additional screenshots are listed in Appendix 7.11.

| **Mode 1: 0,31Hz** | **Mode 2: 0,31Hz** | **Mode 3: 0,67Hz** | **Mode 4: 0,70Hz** |
|---|---|---|---|
|  | | | |
| Tower: Sideways | Tower: Fore and aft | Tower: Twist | Blades: 2/1 Fore and aft |

| **Mode 5: 0,73Hz** | **Mode 6: 0,94Hz** | **Mode 7: 1,08Hz** | **Mode 8: 1,09Hz** |
|---|---|---|---|
| |  | Vibration of blades. See appendix 7.11. |  |
| Blades: Fore and aft | Blades: Sideways | | Blades: 2/1 Sideways |

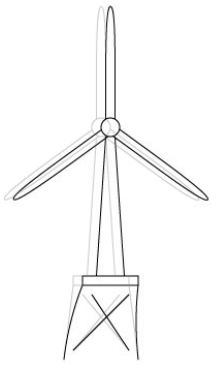
| **Mode 9: 1,17Hz** | **Mode 10: 1,26Hz** |
|---|---|
| |  |
| Jacket: Back and forth | Jacket: Sideways |

**Table 4-1: Illustration of different Eigen modes**

By manipulating the jacket structure it is possible to control the frequency response of the system. As an example we see the increasing Eigen frequencies as the stiffness and mass of the jacket increase.

| Description | Eigen modes | 100 % | 110 % | 125 % | 150 % | 175 % | 200 % |
|---|---|---|---|---|---|---|---|
| Tower: Sideways | Mode 1 | 0,31 | 0,32 | 0,32 | 0,33 | 0,34 | 0,35 |
| Tower: Fore and aft | Mode 2 | 0,31 | 0,32 | 0,32 | 0,33 | 0,34 | 0,35 |
| Tower: Twist | Mode 3 | 0,67 | 0,67 | 0,67 | 0,67 | 0,67 | 0,67 |
| Blades: 2/1 Fore and aft | Mode 4 | 0,7 | 0,71 | 0,71 | 0,71 | 0,71 | 0,71 |
| Blades: Fore and aft | Mode 5 | 0,73 | 0,74 | 0,74 | 0,74 | 0,74 | 0,74 |
| Blades: Sideways | Mode 6 | 0,94 | 0,95 | 0,96 | 0,98 | 0,99 | 0,99 |
| Blades: | Mode 7 | 1,08 | 1,08 | 1,08 | 1,08 | 1,08 | 1,08 |
| Blades: 2/1 Sideways | Mode 8 | 1,09 | 1,09 | 1,09 | 1,09 | 1,09 | 1,09 |
| Jacket: Back and forth | Mode 9 | 1,17 | 1,19 | 1,24 | 1,3 | 1,35 | 1,41 |
| Jacket: Sideways | Mode 10 | 1,26 | 1,28 | 1,31 | 1,36 | 1,41 | 1,46 |

**Table 4-2: Eigen modes recorded from Fedem**

Since the complete model is connected, we see that all Eigen frequencies are affected by a stiffer substructure. However the effect lies mainly on the frequencies of the substructure itself.

Figure 4-1 below shows the Eigen frequencies plotted in the frequency domain. Combining this figure with other frequency domain figures may give an illustration on how excitations may lead to resonance.

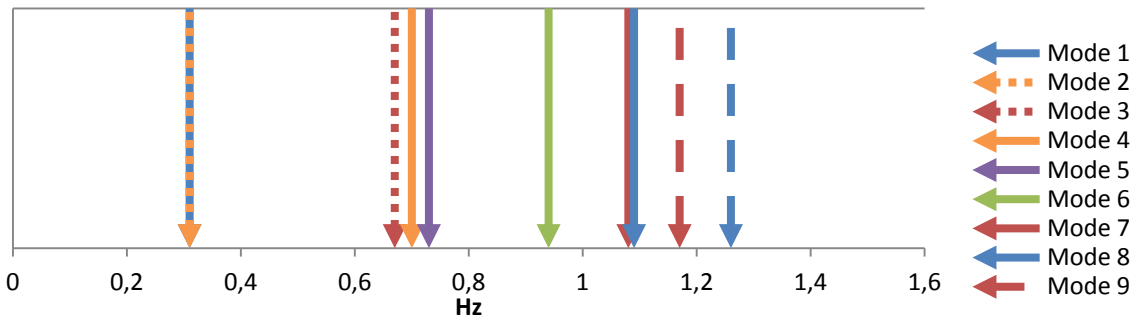



**Figure 4-1: The Eigen frequencies in the frequency domain**

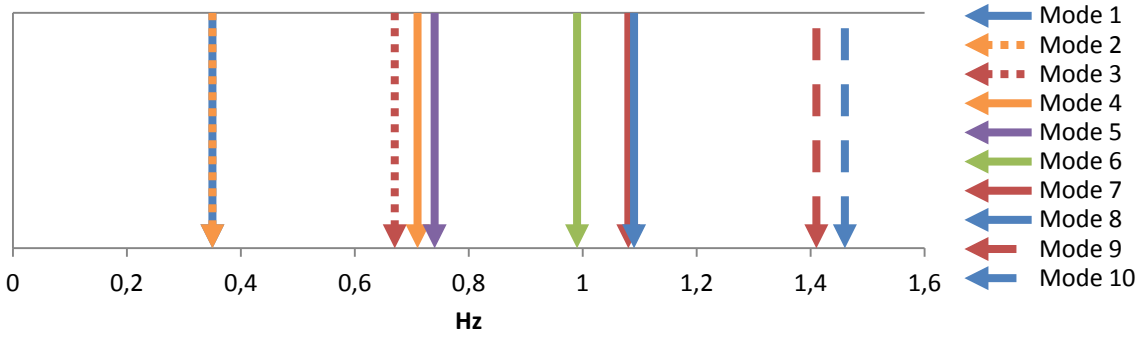



**Figure 4-2: The manipulated Eigen frequencies in the frequency domain (Stiffness and mass set to 200%)**

### 4.1.2 Frequencies from the rotor and blades

With a cut-in rotor speed of 6,7rpm and a rated speed of 12,1rpm the frequencies of the blades passing the tower is variable. The rotor frequency 1P is from 0,202Hz (cut-in) to 0,111Hz (Rated speed). As for blade frequency 3P, the blades will pass the tower with a frequency from 0,606Hz (cut-in) to 0,333Hz (rated speed). The 1P and 3P frequencies are plotted in the frequency domain in Figure 4-3.

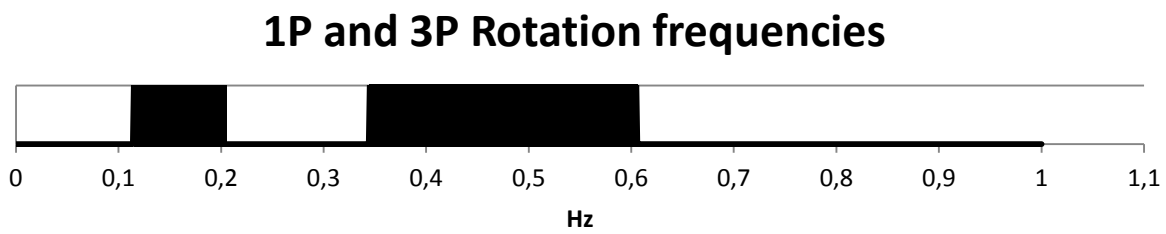



**Figure 4-3: 1P and 3P rotation frequency ranges**

### 4.1.3 Frequencies from the wind

The following spectrums are calculated through fast Fourier transformation in MatLab. The first spectrum is for the 9m/s case which provokes resonant behavior in the structure. The second is for a 9m/s simulation that gives regular responses from the model. The smooth line represents the Kaimal spectra.

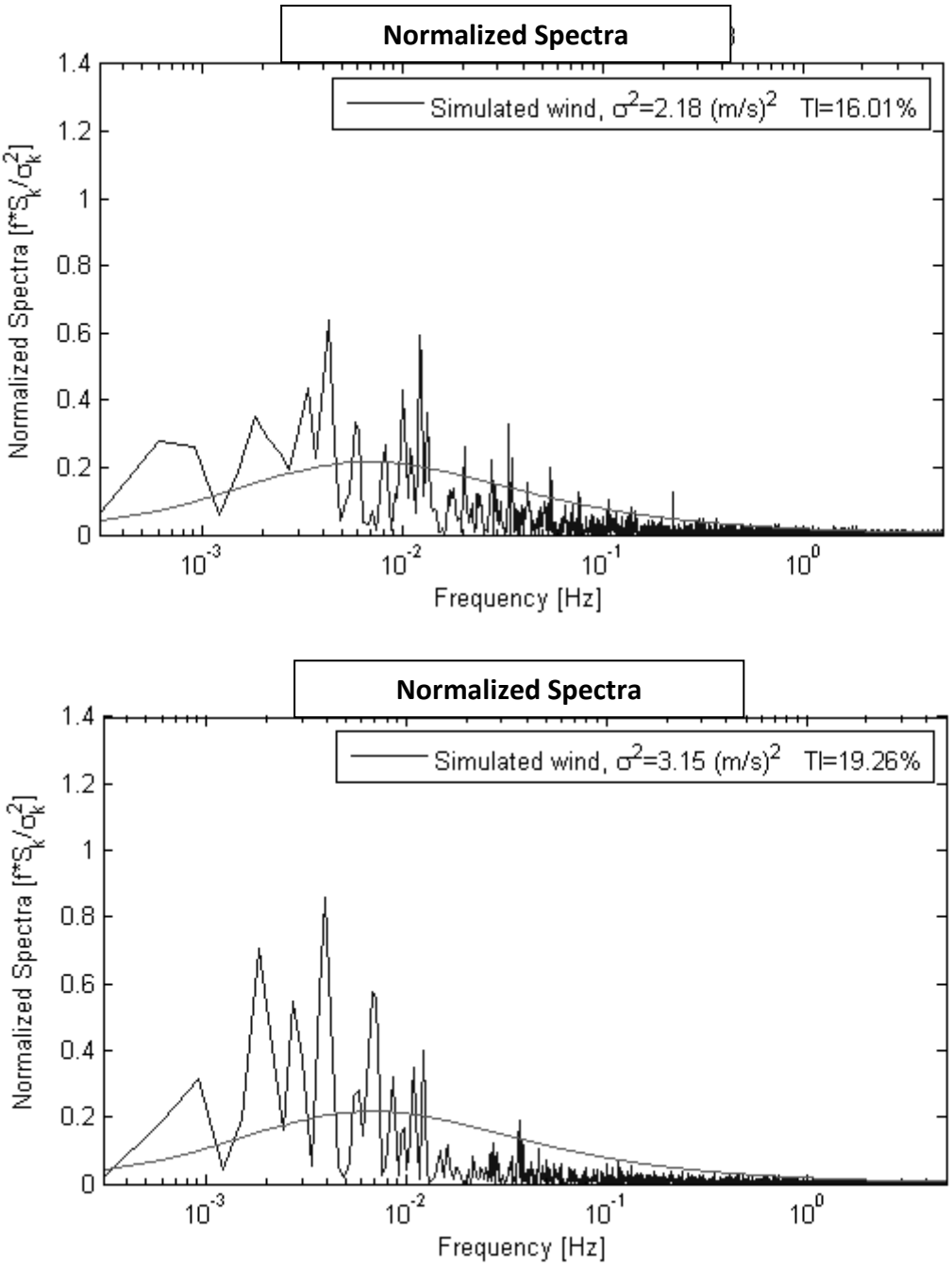



**Figure 4-4: 9m/s Wind spectra. (Upper spectrum gives resonance behavior)**

Frequencies below 0,0015 Hz may be ignored as they represents periods which are beyond the time scope of the simulations.

### 4.1.4 Frequencies from wave loads

The simulations during this thesis are made with a wave frequency of 0,1Hz throughout every case. When thoroughly testing a structure for loads and vibrations, it is important to check for different sea states as well as wind states.

As the waves meet the structure every 10 seconds in a pure sine wave, it is important that the structure in this case do not have an Eigen frequency around 0,1Hz. However in a real situation, the spectrum of the waves would look fairly similar to a general wind spectrum, except with a higher peak, and a less broad frequency range (Jakobsen, MKO110 Naturlaster, 2011).

## 4.2 Fatigue analysis

### 4.2.1 Simulation with 1 standard deviation:

The short term damage equivalent loads represent the loads endured transformed into a single load cycle which is repeated throughout the simulation time. It is therefore assumed that the rising wind speeds create a rising DEL for each point of interest. The first set of results from Mlife shows a rising pattern in short time DELs through the increasing wind speed.

### 4.2.2 Simulation run with 1,5 standard deviation:

The second simulation run shows an increase in the short time DEL's.

### 4.2.3 Simulation run with 2 standard deviation

The third simulation run shows signs of resonance as one of the 9m/s simulations prints very high short time DEL's.

### 4.2.4 Mean short time DEL's for different wind speeds

| 3m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 71,25 | 4,94 | 459,98 | 0,64 | 345,38 | 329,75 | 1597,50 | 1510,50 |
| **1,5stdev** | 75,63 | 4,94 | 462,65 | 0,66 | 410,32 | 398,00 | 1642,83 | 1554,83 |
| **2stdev** | 80,37 | 4,95 | 466,22 | 0,69 | 481,57 | 472,75 | 1691,33 | 1604,83 |

| 9m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 105,72 | 5,09 | 491,95 | 0,68 | 459,93 | 466,20 | 1712,33 | 1677,00 |
| **1,5stdev** | 134,82 | 5,23 | 518,07 | 0,76 | 662,40 | 683,98 | 1922,67 | 1898,50 |
| **2stdev** | 713,25 | 15,89 | 1022,32 | 6,28 | 1629,80 | 1653,33 | 3543,33 | 3533,50 |

| 25m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 317,12 | 6,47 | 677,38 | 1,33 | 1655,17 | 1698,50 | 3250,17 | 3243,33 |
| **1,5stdev** | 466,37 | 7,24 | 824,93 | 1,79 | 2487,17 | 2554,83 | 4370,67 | 4401,83 |
| **2stdev** | 625,52 | 8,09 | 980,87 | 2,29 | 3255,00 | 3345,17 | 5419,83 | 5486,50 |

See Appendix 7.6 for full results.

## 4.3 Discussion

### 4.3.1 Effect from increasing wind speeds and turbulence intensity

By graphing the mean short time DEL's, we are able to see that they increase nearly linear with wind speeds. This is shown in Figure 4-5 where the short time DEL's of brace 59 are graphed.

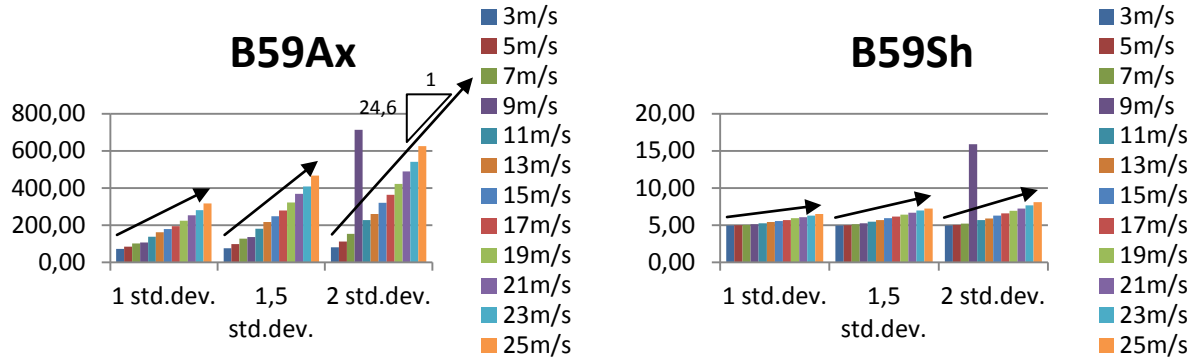



**Figure 4-5: The mean damage equivalent loads at brace 59**

The same tendency is shown for all points of interest. See Appendix 7.7 and 7.8 for all calculated results from Mlife.

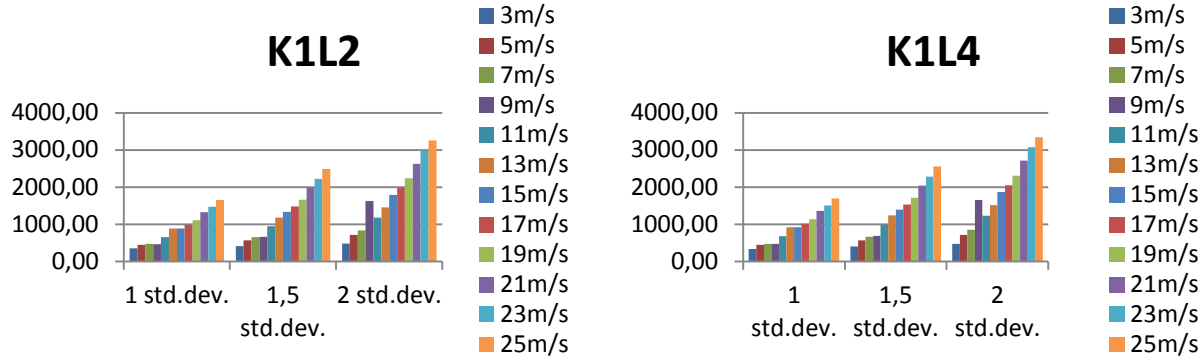



**Figure 4-6: The mean equivalent loads at K-joint 1 (Leg 2 and 4)**

Running a straight line through the measurements using least squares fit reveals the slope of the load increase. The values in Table 4-3 represents the slope of the line fitted. (The 'a' in the linear function Y=a*x+b)

| Slope. | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1 Std.Dev.** | 11,02 | 0,07 | 9,92 | 0,03 | 59,16 | 61,58 | 76,52 | 79,83 |
| **1,5 Std.Dev.** | 17,55 | 0,11 | 16,27 | 0,05 | 93,97 | 97,37 | 125,17 | 130,40 |
| **2 Std.Dev.** | 24,61 | 0,14 | 23,07 | 0,06 | 127,80 | 133,23 | 173,99 | 182,59 |

**Table 4-3: Slope of the lines drawn through the result DEL's**

During line fitting of the second standard deviation, the measurements from the 9m/s simulation case are neglected as they pose completely biased compared to the other measurements.

### 4.3.2 The resonance case

During one 9m/s simulation with 20,2% turbulence intensity the response shows resonance behavior. Resonance was not expected in this case so it was likely to believe an error had been made.

The following possible reasons were evaluated:

- Input errors
- Data generation errors
- Resonance

#### *4.3.2.1 Input errors*

If input error were made, they would likely occur in the following areas:

- Path to the wind link in Fedem
- Path to the actual wind data (.bts) in the link file (.ipt)
- Error in the input file for TurbSim (.inp)

They were relatively easy to check, as there were only parameter changes. This is why these were first checked. Checks however revealed no errors in setting files or the file path.

#### *4.3.2.2 Generated errors*

Data generated errors are very unlikely if parameters are correct, but should not be neglected as a cause of errors.

Checking the exported data sets showed a sudden increase in all responses after a couple of minutes. The reactions occurred simultaneous. Recorded undisturbed wind showed no sign of deviation from the other wind data.

#### *4.3.2.3 Resonance*

Resonance could be the answer to the question. An approach is to take a look at the different events that may lead our structure into a resonance state.

- Frequencies due to wind loads
- Frequencies due to wave loads
- Frequencies due to the rotation of the rotor (1P and 3P)

Resonance can be avoided by choosing different materials and stiffening the bracings and legs of the jacket. This is where cost estimation is important as the cost of substructures is highly dependent of assembly, transportation and material costs.

Figure 4-7 is made by combining the results acquired in the following chapters;

- 4.1.1 – The Eigen modes
- 4.1.2 – Frequencies from the rotation
- 4.1.3 – Frequencies from the applied wind loads
- 4.1.4 – Frequencies from the applied wave load

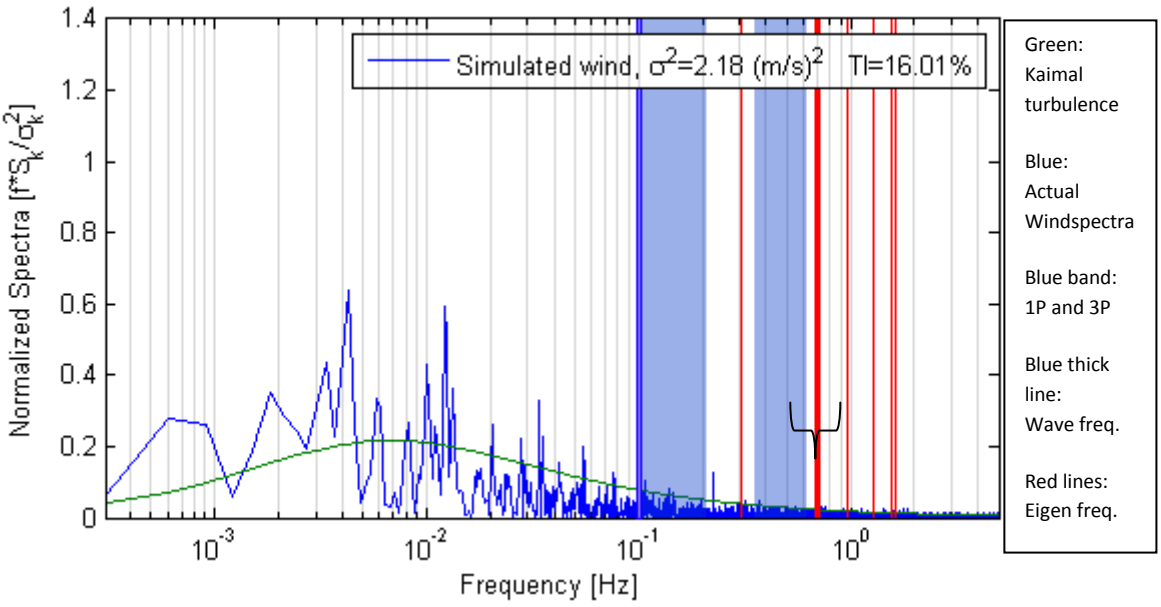



**Figure 4-7: Combined spectrum**

It is shown by the combined spectrum how the load frequencies are distributed. Loads are displayed in blue and Eigen frequencies are displayed in red. Resonance occurs when loads are applied in the same frequency as one of the Eigen frequencies. A suggestion by the supervisor states the results do not take into account that the frequencies of the blades change according to the rotor speed. With higher rotational speeds the Eigen frequencies of the blades splits. A figure is attached to the graph at around 0,7Hz shows how one of the Eigen frequencies in the thick red line may split and proceed into the 3P load frequency. Fedem calculates Eigen frequencies before dynamics. Because of this fact testing revealed the same Eigen frequencies for all cases.

# 5 Closure

## 5.1 Conclusion

Simulations made shows that the short time DEL's increase linearly with increasing mean wind speed in all points monitored. By increasing the turbulence intensity, the slope increases as shown in Figure 4-5.

More simulations have to be done around 9 m/s mean wind speed. As one out of six simulations reported resonance, possibilities are that resonance will occur at even lower turbulence intensities. Whether the resonance is true or an error in simulation is unknown. But results shows that even if the structure withstands the most intense wind speeds with high turbulence intensity, the danger may lie in lower wind speeds. It shows the importance of assessing constructions throughout all its uses and situations.

## 5.2 Future work

Future work on this report may be to find the reason for resonance in the 9m/s mean wind. Increasing the turbulence intensity further towards 30% yields resonance behavior in almost every case within 8 m/s and 9 m/s mean wind speed. 30% turbulence intensity is too high as it represents approximately 3 standard deviations from the mean wind speed.

## 5.3 Problems and workarounds

During the tutorial of the program there were several problems that caused delays.

*Reducer error.*

During project execution some unexpected time was spent on the analysis of a test model, due to an error in the 64bit version of the implemented link reducer. The problem was solved by skipping the erring part.

*Insufficient hard drive capacity.*

As one 10 minute simulation yields 4.1GB the conclusion was to run the simulations locally on the terminals, and backup exported results regularly.

*Insufficient random access memory.*

A virtual command prompt was established to give direct read access to the local Fedem applications. In this way the dynamics solver was accessed by command prompt instead of graphical user interface. The solver was initiated as the only running application. It solved and stored the data to the hard drive resulting in a more efficient solving operation with less than half the memory usage.

*No auto export of the OC4 output data.*

Some graphs were made by navigating to the different elements and extract the data through a resource selector in Fedem however, sectional forces in links could not be found in the resource selector. A temporary solution was to create new graphs in the project with empty curves. When created in the graphical user interface, the curve data was assigned new unique id. By copying the curve data from the attached OC4 file into the original project file (ignoring assembly data and identification values), new unique id was given the curves. The automatic export of data was now working properly as if completely new curves were extracted from the resource databases.

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# 7 Appendix

## 7.1 The different wind cases with parameters

| Case | Seed1 | Seed2 | TI (σ=1) | TI (σ=1,5) | TI (σ=2) | $z_0$ |
|---|---|---|---|---|---|---|
| 3T1 | 893516 | 706960 | 9,3 | 13,96 | 18,60 | 0,00001 |
| 3T2 | 413689 | 591990 | 9,3 | 13,96 | 18,60 | 0,00001 |
| 3T3 | 120217 | 565039 | 9,3 | 13,96 | 18,60 | 0,00001 |
| 3T4 | 378407 | 895426 | 9,3 | 13,96 | 18,60 | 0,00001 |
| 3T5 | 383526 | 144419 | 9,3 | 13,96 | 18,60 | 0,00001 |
| 3T6 | 634989 | 213914 | 9,3 | 13,96 | 18,60 | 0,00001 |
| 5T1 | 566824 | 979863 | 9,7 | 14,50 | 19,40 | 0,00002 |
| 5T2 | 229766 | 362013 | 9,7 | 14,50 | 19,40 | 0,00002 |
| 5T3 | 464054 | 533842 | 9,7 | 14,50 | 19,40 | 0,00002 |
| 5T4 | 278639 | 750886 | 9,7 | 14,50 | 19,40 | 0,00002 |
| 5T5 | 518078 | 186960 | 9,7 | 14,50 | 19,40 | 0,00002 |
| 5T6 | 423665 | 282991 | 9,7 | 14,50 | 19,40 | 0,00002 |
| 7T1 | 354062 | 904889 | 9,9 | 14,90 | 19,80 | 0,00004 |
| 7T2 | 724217 | 396256 | 9,9 | 14,90 | 19,80 | 0,00004 |
| 7T3 | 62144 | 596495 | 9,9 | 14,90 | 19,80 | 0,00004 |
| 7T4 | 921429 | 550728 | 9,9 | 14,90 | 19,80 | 0,00004 |
| 7T5 | 325473 | 238829 | 9,9 | 14,90 | 19,80 | 0,00004 |
| 7T6 | 330714 | 193411 | 9,9 | 14,90 | 19,80 | 0,00004 |
| 9T1 | 500860 | 355609 | 10,1 | 15,22 | 20,20 | 0,00007 |
| 9T2 | 262896 | 439799 | 10,1 | 15,22 | 20,20 | 0,00007 |
| 9T3 | 114495 | 323329 | 10,1 | 15,22 | 20,20 | 0,00007 |
| 9T4 | 825354 | 483007 | 10,1 | 15,22 | 20,20 | 0,00007 |
| 9T5 | 996037 | 115340 | 10,1 | 15,22 | 20,20 | 0,00007 |
| 9T6 | 511621 | 336565 | 10,1 | 15,22 | 20,20 | 0,00007 |
| 11T1 | 957507 | 800280 | 10,3 | 15,50 | 20,60 | 0,00013 |
| 11T2 | 913376 | 964889 | 10,3 | 15,50 | 20,60 | 0,00013 |
| 11T3 | 632359 | 157613 | 10,3 | 15,50 | 20,60 | 0,00013 |
| 11T4 | 097540 | 970593 | 10,3 | 15,50 | 20,60 | 0,00013 |
| 11T5 | 278498 | 957167 | 10,3 | 15,50 | 20,60 | 0,00013 |
| 11T6 | 546882 | 485376 | 10,3 | 15,50 | 20,60 | 0,00013 |
| 13T1 | 760081 | 220342 | 10,5 | 15,74 | 21,00 | 0,00017 |
| 13T2 | 382057 | 982223 | 10,5 | 15,74 | 21,00 | 0,00017 |
| 13T3 | 589360 | 454487 | 10,5 | 15,74 | 21,00 | 0,00017 |
| 13T4 | 194007 | 809470 | 10,5 | 15,74 | 21,00 | 0,00017 |
| 13T5 | 103083 | 762822 | 10,5 | 15,74 | 21,00 | 0,00017 |
| 13T6 | 869736 | 429582 | 10,5 | 15,74 | 21,00 | 0,00017 |

| Case | Seed1 | Seed2 | TI (σ=1) | TI (σ=1,5) | TI (σ=2) | $z_0$ |
|---|---|---|---|---|---|---|
| 15T1 | 972169 | 382237 | 10,6 | 15,96 | 21,20 | 0,00024 |
| 15T2 | 251872 | 014871 | 10,6 | 15,96 | 21,20 | 0,00024 |
| 15T3 | 314568 | 686008 | 10,6 | 15,96 | 21,20 | 0,00024 |
| 15T4 | 401808 | 575209 | 10,6 | 15,96 | 21,20 | 0,00024 |
| 15T5 | 075967 | 059780 | 10,6 | 15,96 | 21,20 | 0,00024 |
| 15T6 | 239916 | 234780 | 10,6 | 15,96 | 21,20 | 0,00024 |
| 17T1 | 123319 | 353159 | 10,8 | 16,16 | 21,60 | 0,00033 |
| 17T2 | 183908 | 821194 | 10,8 | 16,16 | 21,60 | 0,00033 |
| 17T3 | 239953 | 015403 | 10,8 | 16,16 | 21,60 | 0,00033 |
| 17T4 | 417267 | 043024 | 10,8 | 16,16 | 21,60 | 0,00033 |
| 17T5 | 049654 | 168990 | 10,8 | 16,16 | 21,60 | 0,00033 |
| 17T6 | 902716 | 649115 | 10,8 | 16,16 | 21,60 | 0,00033 |
| 19T1 | 944787 | 731722 | 10,9 | 16,34 | 21,80 | 0,00043 |
| 19T2 | 490864 | 647746 | 10,9 | 16,34 | 21,80 | 0,00043 |
| 19T3 | 489253 | 450924 | 10,9 | 16,34 | 21,80 | 0,00043 |
| 19T4 | 337719 | 547009 | 10,9 | 16,34 | 21,80 | 0,00043 |
| 19T5 | 900054 | 296321 | 10,9 | 16,34 | 21,80 | 0,00043 |
| 19T6 | 369247 | 744693 | 10,9 | 16,34 | 21,80 | 0,00043 |
| 21T1 | 111203 | 188955 | 11 | 16,51 | 22,00 | 0,00055 |
| 21T2 | 780252 | 686775 | 11 | 16,51 | 22,00 | 0,00055 |
| 21T3 | 389739 | 183511 | 11 | 16,51 | 22,00 | 0,00055 |
| 21T4 | 241691 | 368485 | 11 | 16,51 | 22,00 | 0,00055 |
| 21T5 | 403912 | 625619 | 11 | 16,51 | 22,00 | 0,00055 |
| 21T6 | 096455 | 780227 | 11 | 16,51 | 22,00 | 0,00055 |
| 23T1 | 131973 | 081126 | 11,1 | 16,67 | 22,20 | 0,00068 |
| 23T2 | 942051 | 929386 | 11,1 | 16,67 | 22,20 | 0,00068 |
| 23T3 | 956135 | 775713 | 11,1 | 16,67 | 22,20 | 0,00068 |
| 23T4 | 486792 | 225922 | 11,1 | 16,67 | 22,20 | 0,00068 |
| 23T5 | 435859 | 170708 | 11,1 | 16,67 | 22,20 | 0,00068 |
| 23T6 | 446784 | 227664 | 11,1 | 16,67 | 22,20 | 0,00068 |
| 25T1 | 306349 | 435699 | 11,2 | 16,83 | 22,40 | 0,00083 |
| 25T2 | 508509 | 311102 | 11,2 | 16,83 | 22,40 | 0,00083 |
| 25T3 | 510772 | 923380 | 11,2 | 16,83 | 22,40 | 0,00083 |
| 25T4 | 817628 | 430207 | 11,2 | 16,83 | 22,40 | 0,00083 |
| 25T5 | 794831 | 184816 | 11,2 | 16,83 | 22,40 | 0,00083 |
| 25T6 | 644318 | 904881 | 11,2 | 16,83 | 22,40 | 0,00083 |

## 7.2 **TurbSim input file**

The following text serves as input for the TurbSim wind generator. The font in green and bold is the parameters adjusted during the simulations:

```
TurbSim Input File. Valid for TurbSim v1.50, 25-Sep-2009. Input File for Certification Test.

---------Runtime Options-----------------------------------
546882           RandSeed1       - First random seed  (-2147483648 to 2147483647)
485376           RandSeed2       - Second random seed (-2147483648 to 2147483647) for intrinsic pRNG, or an
alternative pRNG: "RanLux" or "RNSNLW"
False            WrBHHTP         - Output hub-height turbulence parameters in GenPro-binary form?
(Generates RootName.bin)
True             WrFHHTP         - Output hub-height turbulence parameters in formatted form?  (Generates
RootName.dat)
False            WrADHH          - Output hub-height time-series data in AeroDyn form?  (Generates
RootName.hh)
True             WrADFF          - Output full-field time-series data in TurbSim/AeroDyn form? (Generates
RootName.bts)
False            WrBLFF          - Output full-field time-series data in BLADED/AeroDyn form?  (Generates
RootName.wnd)
False            WrADTWR         - Output tower time-series data? (Generates RootName.twr)
False            WrFMTFF         - Output full-field time-series data in formatted (readable) form?
(Generates RootName.u, RootName.v, RootName.w)
True             WrACT           - Output coherent turbulence time steps in AeroDyn form? (Generates
RootName.cts)
True             Clockwise       - Clockwise rotation looking downwind? (used only for full-field binary
files - not necessary for AeroDyn)
 0               ScaleIEC        - Scale IEC turbulence models to exact target standard deviation? [0=no
additional scaling; 1=use hub scale uniformly; 2=use individual scales]

--------Turbine/Model Specifications-----------------------
10               NumGrid_Z       - Vertical grid-point matrix dimension
10               NumGrid_Y       - Horizontal grid-point matrix dimension
0.025            TimeStep        - Time step [seconds]
1050.0           AnalysisTime    - Length of analysis time series [seconds] (program will add time if
necessary: AnalysisTime = MAX(AnalysisTime, UsableTime+GridWidth/MeanHHWS) )
850.0            UsableTime      - Usable length of output time series [seconds] (program will add
GridWidth/MeanHHWS seconds)
90.55            HubHt           - Hub height [m] (should be > 0.5*GridHeight)
130.00           GridHeight      - Grid height [m]
130.00           GridWidth       - Grid width [m] (should be >= 2*(RotorRadius+ShaftLength))
 0               VFlowAng        - Vertical mean flow (uptilt) angle [degrees]
 0               HFlowAng        - Horizontal mean flow (skew) angle [degrees]

--------Meteorological Boundary Conditions-------------------
"IECKAI"         TurbModel       - Turbulence model ("IECKAI"=Kaimal, "IECVKM"=von Karman, "GP_LLJ",
"NWTCUP", "SMOOTH", "WF_UPW", "WF_07D", "WF_14D", or "NONE")
3                IECstandard     - Number of IEC 61400-x standard (x=1,2, or 3 with optional 61400-1
edition number (i.e. "1-Ed2") )
35               IECturbc        - IEC turbulence characteristic ("A", "B", "C" or the turbulence intensity
in percent) ("KHTEST" option with NWTCUP, not used for other models)
NTM              IEC_WindType    - IEC turbulence type ("NTM"=normal, "xETM"=extreme turbulence,
"xEWM1"=extreme 1-year wind, "xEWM50"=extreme 50-year wind, where x=wind turbine class 1, 2, or 3)
default          ETMc            - IEC ETM "c" parameter [m/s] (or "default")
LOG              WindProfileType - Wind profile type ("JET"=LOw-level jet,"LOG"=Logarithmic,"PL"=Power law,
"IEC"=PL on rotor & LOG elsewhere, or "default")
90.25            RefHt           - Height of the reference wind speed [m]
16.0             URef            - Mean (total) wind speed at the reference height [m/s]
350              ZJetMax         - Jet height [m] (used only for JET wind profile, valid 70-490 m)
default          PLExp           - Power law exponent  (or "default")
0.00028          Z0              - Surface roughness length [m] (or "default")

--------Non-IEC Meteorological Boundary Conditions------------
default          Latitude        - Site latitude [degrees] (or "default")
0.05             RICH_NO         - Gradient Richardson number
default          UStar           - Friction or shear velocity [m/s] (or "default")
default          ZI              - Mixing layer depth [m] (or "default")
default          PC_UW           - Mean hub u'w' Reynolds stress (or "default" or "none")
default          PC_UV           - Mean hub u'v' Reynolds stress (or "default" or "none")
default          PC_VW           - Mean hub v'w' Reynolds stress (or "default" or "none")
default          IncDec1         - u-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or
"default")
default          IncDec2         - v-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or
"default")
default          IncDec3         - w-component coherence parameters (e.g. "10.0  0.3e-3" in quotes) (or
"default")
default          CohExp          - Coherence exponent (or "default")
--------Coherent Turbulence Scaling Parameters-------------------
".\EventData"    CTEventPath     - Name of the path where event data files are located
LES              CTEventFile     - Type of event files ("random", "les" or "dns")
true             Randomize       - Randomize disturbance scale and location? (true/false)
1.0              DistScl         - Disturbance scale (ratio of dataset height to rotor disk).
0.5              CTLy            - Fractional location of tower centerline from right (looking downwind) to
left side of the dataset.
0.5              CTLz            - Fractional location of hub height from the bottom of the dataset.
30.0             CTStartTime     - Minimum start time for coherent structures in RootName.cts [seconds]
```

## 7.3 **Fedem exported curves**

When the 'auto export curves' box is ticked, Fedem exports its data curves into an ".rsp" file. The data are stored in columns with each series. It also includes a file header with version info, parent filename, username and calculation date.

| #FEDEM | R6.0-i6 9 Aug 2011 18:45:55 | | | | |
|---|---|---|---|---|---|
| #PARENT | D:\FEDEM\OC4_jacket\OC4_8T5_II.fmm | | | | |
| #FILE | ..\..\8T5_II.rsp | | | | |
| #USER | 212549,00 | | | | |
| #DATE | Thu May 10 20:46:32 2012 | | | | |
| # | | | | | |
| Time | Dataset 1 (Wind) | Dataset 2 | Dataset 3 | Dataset 4 | Dataset 5.. |
| 0,00 | 11,89 | 0,00 | 0,00 | -0,01 | 0,00 |
| 0,05 | 11,74 | 0,00 | 0,00 | -0,01 | 0,00 |
| 0,10 | 11,79 | 0,00 | 0,00 | -0,01 | 0,00 |
| 0,15 | 11,88 | 0,00 | 0,00 | -0,01 | 0,00 |
| 0,20 | 11,96 | 0,00 | 0,00 | -0,01 | 0,01 |
| 0,25 | 11,79 | 0,00 | 0,00 | -0,01 | 0,01 |
| 0,30 | 11,93 | 0,00 | 0,00 | -0,01 | 0,01 |
| 0,35 | 11,73 | 0,01 | 0,00 | -0,01 | 0,01 |
| 0,40 | 11,66 | 0,01 | -0,01 | -0,01 | 0,01 |
| 0,45 | 11,60 | 0,01 | -0,01 | -0,01 | 0,01 |
| 0,50 | 11,66 | 0,01 | -0,02 | -0,01 | 0,01 |
| 0,55 | 11,71 | 0,02 | -0,02 | -0,01 | 0,01 |
| 0,60 | 11,77 | 0,02 | -0,02 | -0,01 | 0,01 |
| 0,65 | 11,51 | 0,03 | -0,01 | -0,01 | 0,02 |
| 0,70 | 11,56 | 0,04 | -0,01 | -0,01 | 0,02 |
| 0,75 | 11,32 | 0,04 | 0,00 | -0,01 | 0,02 |
| 0,80 | 11,26 | 0,05 | 0,00 | -0,01 | 0,02 |

## 7.4 **Mlife input file**

The input file tells Mlife how it will read the data files. It also affects which operations are to be done by Mlife.

```
-----  MLife version 1.0 Input File  ------------------------------------------
Test #01 (-Names, -Chans, +CC, -TSp, +Stats, -SwT, -SwX, +SF, -EE, -Bins, -Bp, -PDF, -PDFp, -PSD, -PSDp, -
PSDtxt, -PSDxls, +F, -FBR, -FBM, +DEL, -CF, +FwDELt, -FwDELx, +FwRFt, -FwRFx, -FpBC, -FpPE, -FpCC, -FpRM,
+TbDEL, -Multi).
-----  Job Options  -----------------------------------------------------------
false             EchoInp           Echo input to <rootname>.echo as this file is being read.
false             StrNames          Use channel names following a "$" instead of numbers when specifying
channels in this input file.
false             OutData           Output modified data array after scaling and calculated channels.
(currently unavailable)
"%11.3e"          RealFmt           Format for outputting floating-point values.
"OC4"             AggRoot           Root name for aggregate output files.
-----  Input-Data Layout  -----------------------------------------------------
0                 TitleLine         The row with the file title on it (zero if no title is available).
7                 NamesLine         The row with the channel names on it (zero if no names are available or
are specified below).
0                 UnitsLine         The row with the channel units on it (zero if no units are available or
are specified below).
4008              FirstDataLine     The first row of data.
26                NumChans:         The number of channels in each input file.
ChanTitle  ChanUnits    Scale  Offset     NumCols rows of data follow.  Title and units strings must be 10
characters or less.
"Time"    "s"    1.0   0.0
"WindX"   "m/s   1.0   0.0
"TPX"     "m"    1.0   0.0
"TPY"     "m"    1.0   0.0
"TPZ"     "m"    1.0   0.0
"TPRotX"  "deg"  1.0   0.0
"TPRotY"  "deg"  1.0   0.0
"TPRotZ"  "deg   1.0   0.0
"X2S2"    "m"    1.0   0.0
"X2S3"    "m"    1.0   0.0
"X4S2"    "m"    1.0   0.0
"X4S3"    "m"    1.0   0.0
"B59Ax"   "kN"   1.0   0.0
"B59Sh"   "kN"   1.0   0.0
"B61Ax"   "kN"   1.0   0.0
"B61Sh"   "kN"   1.0   0.0
"K1L2"    "kN″   1.0   0.0
"K1L4"    "kN"   1.0   0.0
"MBL2"    "kN"   1.0   0.0
"MBL4"    "kN"   1.0   0.0
" "    "s"   1.0   0.0
" "    "s"   1.0   0.0
" "    "s"   1.0   0.0
" "    "s"   1.0   0.0
" "    "s"   1.0   0.0
" "    "s"   1.0   0.0
-----  Calculated Channels  ---------------------------------------------------
0                 NumCChan          The number calculated channels to generate.
1234567890        Seed              The integer seed for the random number generator (-2,147,483,648 to
2,147,483,647).
Col_Title   Units    Equation       Put each field in quotes.  Titles and units are limited to 10
characters.  NumCChan rows of data follow.
-----  Time and Wind Speed  ---------------------------------------------------
1                 TimeChan          The channel containing time.
2                 WSChan            The primary wind-speed channel (used for mean wind speed and turbulence
intensity, 0 for none).
-----  Statistics and Extreme Events  -----------------------------------------
false             DoStats           Generate statistics of all the channels.
true              WrStatsTxt        Write the stats to a text file?
false             WrStatsXLS        Write the stats to an Excel file?
0                 NumSFChans        Number of channels that will have summary statistics generated for
them.
1                 SFChans           List of channels that will have summary statistics generated for them.
Must number NumSFChans.
-----  Fatigue  ---------------------------------------------------------------
8                 nFatigueChannels  The number of rainflow channels.  Next six lines ignored if zero.
0                 FiltRatio         The fraction of the maximum range of each channel used as a cutoff
range for the racetrack filter.  Use zero for no filter.
630720000         DesignLife        Number of seconds in the design lifetime (20 years = 630720000
seconds).
true              BinCycles         Bin the rainflow cycles?
0.5               UCMult            Multiplier for binning unclosed cycles.  (0 discards, 1 counts as a
full cycle)
true              DoSimpDELs        Compute short-term (file-based) damage-equivalent loads?
false             DoLife            Do lifetime-related calculations?
10                WeibullMeanWS     Weibull-average wind speed.
2                 WeibullShapeFactor Shape parameter for Weibull distribution.  2 = Rayleigh distribution
3                 WSmin             Starting value for the wind-speed bins for the Weibull distribution.
BW                WSBinFlag         BN = number of bins specified or BW = bin width specified
6                 WSBinVal          Number of bins or the width of the wind-speed bins for the Weibull
distribution.
true              WrDELsTxt         Write DELs to plain-text files?
false             WrDELsXLS         Write DELs to an Excel workbook?
false             WrLifeTxt         Write lifetime results to plain-text files?
false             WrLifeXLS         Write lifetime results to an Excel workbook?
1                 EquivFreq         The frequency of the damage equivalent load (Hz)
true              DEL_AsRange       true = report DELs as a range value,  false = report as a one-sided
amplitude
```

```
Channel#  NSlopes  SNslopeLst      BinFlag  BinWidth/Number  TypeLMF     LUlt    BinWidth not used when
BinCycles is false. nFatigueChannels rows of data follow.  LUlt >> LMF
13       1        5            BW       0.2    5        16000
14       1        5            BW       0.2    5        100
15       1        5            BW       0.2    5        16000
16       1        5            BW       0.2    5        100
17       1        5            BW       0.2    5        130000
18       1        5            BW       0.2    5        130000
19       1        5            BW       0.2    5        150000
20       1        5            BW       0.2    5        150000
1                 NumDELGroups
NChannels      ChannelList
8              1 2 3 4 5 6 7 8
-----  Input Files  ------------------------------------------------------------
78                NumFiles          The number of input files to read.
"3T1.rsp"
"3T2.rsp"
..the rest of the files to be analyzed by Mlife
==EOF==                             DO NOT REMOVE OR CHANGE.  MUST COME JUST AFTER LAST LINE OF VALID
INPUT.
```

## 7.5 **Mlife bin width testing**

Bin width testing was made with 11,4m/s and 27m/s winds.

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 382,40 | 381,20 | 378,70 | 377,10 | 376,70 | 376,20 | 376,20 | 376,20 | 376,20 | 376,20 | 376,20 |
| 11_4T2 | 374,90 | 370,20 | 365,90 | 366,60 | 366,90 | 366,80 | 366,70 | 366,50 | 366,50 | 366,50 | 366,50 |
| 11_4T3 | 405,40 | 396,20 | 391,50 | 392,10 | 391,70 | 391,40 | 391,20 | 391,20 | 391,20 | 391,20 | 391,20 |
| 11_4T4 | 376,80 | 366,70 | 366,20 | 365,00 | 364,40 | 364,30 | 364,30 | 364,20 | 364,30 | 364,30 | 364,30 |
| 11_4T5 | 390,40 | 383,40 | 379,00 | 377,20 | 377,40 | 377,30 | 377,40 | 377,30 | 377,30 | 377,30 | 377,30 |
| 11_4T6 | 388,10 | 380,50 | 375,60 | 375,70 | 376,70 | 376,50 | 376,60 | 376,60 | 376,60 | 376,60 | 376,60 |
| Difference from previous | | 0,983 | 0,991 | 0,999 | 1,000 | 0,999 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**B59Ax**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 1080,00 | 1074,00 | 1073,00 | 1073,00 | 1072,00 | 1070,00 | 1073,00 | 1073,00 | 1073,00 | 1073,00 | 1073,00 |
| 27T2 | 1121,00 | 1121,00 | 1123,00 | 1124,00 | 1124,00 | 1130,00 | 1125,00 | 1125,00 | 1125,00 | 1125,00 | 1125,00 |
| 27T3 | 1028,00 | 1022,00 | 1020,00 | 1019,00 | 1019,00 | 1020,00 | 1020,00 | 1020,00 | 1020,00 | 1020,00 | 1020,00 |
| 27T4 | 1114,00 | 1107,00 | 1105,00 | 1105,00 | 1105,00 | 1110,00 | 1105,00 | 1105,00 | 1105,00 | 1105,00 | 1105,00 |
| 27T5 | 1081,00 | 1076,00 | 1073,00 | 1072,00 | 1071,00 | 1070,00 | 1071,00 | 1071,00 | 1071,00 | 1071,00 | 1071,00 |
| 27T6 | 1117,00 | 1122,00 | 1121,00 | 1122,00 | 1122,00 | 1120,00 | 1122,00 | 1122,00 | 1122,00 | 1122,00 | 1122,00 |
| Difference from previous | | 0,997 | 0,999 | 1,000 | 1,000 | 1,001 | 0,999 | 1,000 | 1,000 | 1,000 | 1,000 |

**B59Ax**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 145,10 | 72,55 | 36,270 | 18,140 | 9,068 | 6,588 | 6,557 | 6,420 | 6,405 | 6,404 | 6,417 |
| 11_4T2 | 145,40 | 72,69 | 36,350 | 18,170 | 9,087 | 6,590 | 6,234 | 6,222 | 6,208 | 6,206 | 6,207 |
| 11_4T3 | 145,20 | 72,59 | 36,290 | 18,150 | 9,073 | 6,579 | 6,339 | 6,344 | 6,353 | 6,343 | 6,345 |
| 11_4T4 | 145,30 | 72,63 | 36,320 | 18,160 | 9,079 | 6,580 | 6,373 | 6,324 | 6,343 | 6,314 | 6,304 |
| 11_4T5 | 144,90 | 72,46 | 36,230 | 18,110 | 9,057 | 6,578 | 6,550 | 6,415 | 6,358 | 6,364 | 6,372 |
| 11_4T6 | 145,30 | 72,66 | 36,330 | 18,160 | 9,082 | 6,590 | 6,280 | 6,243 | 6,286 | 6,287 | 6,287 |
| Difference from previous | | 0,500 | 0,500 | 0,500 | 0,500 | 0,726 | 0,970 | 0,990 | 1,000 | 0,999 | 1,000 |

**B59Sh**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 145,30 | 72,64 | 36,32 | 18,16 | 12,97 | 11,90 | 11,51 | 11,37 | 11,35 | 11,34 | 11,34 |
| 27T2 | 145,20 | 72,60 | 36,30 | 18,15 | 13,16 | 11,90 | 11,60 | 11,52 | 11,51 | 11,49 | 11,48 |
| 27T3 | 145,20 | 72,62 | 36,31 | 18,15 | 13,20 | 12,00 | 11,58 | 11,48 | 11,48 | 11,47 | 11,48 |
| 27T4 | 145,30 | 72,65 | 36,33 | 18,16 | 13,23 | 12,10 | 11,58 | 11,40 | 11,36 | 11,36 | 11,36 |
| 27T5 | 145,20 | 72,62 | 36,31 | 18,15 | 13,16 | 12,30 | 11,78 | 11,67 | 11,63 | 11,64 | 11,64 |
| 27T6 | 145,20 | 72,61 | 36,30 | 18,15 | 13,39 | 12,00 | 11,45 | 11,35 | 11,39 | 11,35 | 11,35 |
| Difference from previous | | 0,500 | 0,500 | 0,500 | 0,726 | 0,913 | 0,963 | 0,990 | 0,999 | 0,999 | 1,000 |

**B59Sh**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 779,70 | 776,60 | 775,60 | 775,20 | 775,40 | 774,90 | 774,60 | 774,70 | 774,70 | 774,60 | 774,60 |
| 11_4T2 | 725,30 | 721,70 | 722,80 | 721,90 | 722,10 | 722,20 | 722,30 | 722,30 | 722,20 | 722,20 | 722,20 |
| 11_4T3 | 758,70 | 760,60 | 760,00 | 760,00 | 760,70 | 760,90 | 760,70 | 760,80 | 760,80 | 760,80 | 760,80 |
| 11_4T4 | 756,70 | 754,60 | 753,50 | 753,80 | 754,40 | 754,40 | 754,20 | 754,00 | 754,00 | 754,10 | 754,10 |
| 11_4T5 | 782,50 | 774,90 | 777,90 | 777,10 | 777,20 | 777,10 | 776,80 | 776,70 | 776,80 | 776,80 | 776,80 |
| 11_4T6 | 755,80 | 749,90 | 749,30 | 749,50 | 750,10 | 749,90 | 750,10 | 750,10 | 750,10 | 750,10 | 750,10 |
| Difference from previous | | 0,996 | 1,000 | 1,000 | 1,001 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**B61Ax**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 1485,00 | 1490,00 | 1492,00 | 1493,00 | 1493,00 | 1490,00 | 1493,00 | 1493,00 | 1493,00 | 1493,00 | 1493,00 |
| 27T2 | 1538,00 | 1544,00 | 1542,00 | 1542,00 | 1542,00 | 1540,00 | 1542,00 | 1542,00 | 1542,00 | 1542,00 | 1542,00 |
| 27T3 | 1426,00 | 1417,00 | 1414,00 | 1414,00 | 1413,00 | 1410,00 | 1414,00 | 1414,00 | 1414,00 | 1414,00 | 1414,00 |
| 27T4 | 1482,00 | 1486,00 | 1482,00 | 1481,00 | 1481,00 | 1480,00 | 1481,00 | 1481,00 | 1481,00 | 1481,00 | 1481,00 |
| 27T5 | 1479,00 | 1480,00 | 1480,00 | 1481,00 | 1481,00 | 1480,00 | 1481,00 | 1481,00 | 1481,00 | 1481,00 | 1481,00 |
| 27T6 | 1460,00 | 1456,00 | 1457,00 | 1455,00 | 1455,00 | 1460,00 | 1455,00 | 1455,00 | 1455,00 | 1455,00 | 1455,00 |
| Difference from previous | | 1,000 | 0,999 | 1,000 | 1,000 | 0,999 | 1,001 | 1,000 | 1,000 | 1,000 | 1,000 |

**B61Ax**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 136,80 | 68,39 | 34,200 | 17,100 | 8,549 | 4,275 | 2,211 | 1,659 | 1,546 | 1,497 | 1,470 |
| 11_4T2 | 138,20 | 69,08 | 34,540 | 17,270 | 8,635 | 4,318 | 2,183 | 1,588 | 1,452 | 1,413 | 1,407 |
| 11_4T3 | 137,00 | 68,51 | 34,250 | 17,130 | 8,563 | 4,282 | 2,141 | 1,543 | 1,453 | 1,406 | 1,405 |
| 11_4T4 | 137,60 | 68,78 | 34,390 | 17,190 | 8,597 | 4,298 | 2,243 | 1,666 | 1,551 | 1,497 | 1,481 |
| 11_4T5 | 136,60 | 68,32 | 34,160 | 17,080 | 8,539 | 4,270 | 2,161 | 1,593 | 1,474 | 1,436 | 1,417 |
| 11_4T6 | 137,70 | 68,85 | 34,430 | 17,210 | 8,606 | 4,303 | 2,176 | 1,576 | 1,494 | 1,454 | 1,446 |
| Difference from previous | | 0,500 | 0,500 | 0,500 | 0,500 | 0,500 | 0,509 | 0,734 | 0,932 | 0,970 | 0,991 |

**B61Sh**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 143,20 | 71,60 | 35,80 | 17,90 | 8,95 | 5,44 | 4,77 | 4,55 | 4,48 | 4,47 | 4,47 |
| 27T2 | 143,10 | 71,57 | 35,79 | 17,89 | 8,95 | 5,40 | 4,67 | 4,46 | 4,40 | 4,37 | 4,36 |
| 27T3 | 143,40 | 71,68 | 35,84 | 17,92 | 8,96 | 4,78 | 4,04 | 3,92 | 3,87 | 3,87 | 3,87 |
| 27T4 | 143,20 | 71,58 | 35,79 | 17,89 | 8,95 | 5,13 | 4,39 | 4,29 | 4,20 | 4,20 | 4,20 |
| 27T5 | 143,00 | 71,50 | 35,75 | 17,88 | 8,94 | 5,31 | 4,55 | 4,36 | 4,28 | 4,28 | 4,27 |
| 27T6 | 143,30 | 71,63 | 35,82 | 17,91 | 8,95 | 5,08 | 4,31 | 4,13 | 4,03 | 4,01 | 4,00 |
| Difference from previous | | 0,500 | 0,500 | 0,500 | 0,500 | 0,580 | 0,858 | 0,962 | 0,982 | 0,998 | 0,999 |

**B61Sh**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 1971,00 | 1964,00 | 1967,00 | 1968,00 | 1969,00 | 1968,00 | 1968,00 | 1968,00 | 1968,00 | 1968,00 | 1968,00 |
| 11_4T2 | 2074,00 | 2072,00 | 2073,00 | 2072,00 | 2073,00 | 2073,00 | 2072,00 | 2072,00 | 2072,00 | 2072,00 | 2072,00 |
| 11_4T3 | 1825,00 | 1823,00 | 1822,00 | 1822,00 | 1821,00 | 1821,00 | 1821,00 | 1821,00 | 1821,00 | 1821,00 | 1821,00 |
| 11_4T4 | 1948,00 | 1942,00 | 1943,00 | 1943,00 | 1943,00 | 1943,00 | 1943,00 | 1943,00 | 1943,00 | 1943,00 | 1943,00 |
| 11_4T5 | 1941,00 | 1928,00 | 1930,00 | 1932,00 | 1931,00 | 1931,00 | 1931,00 | 1931,00 | 1931,00 | 1931,00 | 1931,00 |
| 11_4T6 | 1904,00 | 1909,00 | 1908,00 | 1908,00 | 1908,00 | 1908,00 | 1908,00 | 1908,00 | 1908,00 | 1908,00 | 1908,00 |
| Difference from previous | | 0,998 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**K1L2**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 5380,00 | 5377,00 | 5379,00 | 5380,00 | 5379,00 | 5380,00 | 5380,00 | 5380,00 | 5380,00 | 5379,00 | 5379,00 |
| 27T2 | 6450,00 | 6451,00 | 6450,00 | 6451,00 | 6451,00 | 6450,00 | 6452,00 | 6452,00 | 6452,00 | 6452,00 | 6452,00 |
| 27T3 | 5580,00 | 5580,00 | 5579,00 | 5579,00 | 5579,00 | 5580,00 | 5578,00 | 5578,00 | 5578,00 | 5578,00 | 5578,00 |
| 27T4 | 5389,00 | 5387,00 | 5385,00 | 5384,00 | 5384,00 | 5380,00 | 5384,00 | 5384,00 | 5384,00 | 5384,00 | 5384,00 |
| 27T5 | 6085,00 | 6079,00 | 6077,00 | 6076,00 | 6076,00 | 6080,00 | 6076,00 | 6076,00 | 6076,00 | 6076,00 | 6076,00 |
| 27T6 | 5513,00 | 5521,00 | 5520,00 | 5519,00 | 5519,00 | 5520,00 | 5518,00 | 5518,00 | 5518,00 | 5518,00 | 5518,00 |
| Difference from previous | | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**K1L2**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 2034,0 | 2042,0 | 2048,0 | 2048,0 | 2048,0 | 2048,0 | 2048,0 | 2048,0 | 2048,0 | 2048,0 | 2048,0 |
| 11_4T2 | 2131,0 | 2136,0 | 2141,0 | 2141,0 | 2141,0 | 2141,0 | 2141,0 | 2141,0 | 2141,0 | 2141,0 | 2141,0 |
| 11_4T3 | 1918,0 | 1915,0 | 1914,0 | 1913,0 | 1913,0 | 1913,0 | 1913,0 | 1913,0 | 1913,0 | 1913,0 | 1913,0 |
| 11_4T4 | 2033,0 | 2037,0 | 2035,0 | 2035,0 | 2036,0 | 2036,0 | 2035,0 | 2035,0 | 2035,0 | 2035,0 | 2035,0 |
| 11_4T5 | 2024,0 | 2022,0 | 2021,0 | 2020,0 | 2020,0 | 2020,0 | 2020,0 | 2020,0 | 2020,0 | 2020,0 | 2020,0 |
| 11_4T6 | 2010,0 | 2009,0 | 2004,0 | 2004,0 | 2004,0 | 2003,0 | 2003,0 | 2003,0 | 2003,0 | 2003,0 | 2003,0 |
| Difference from previous | | 1,001 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**K1L4**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 5520,0 | 5517,0 | 5523,0 | 5524,0 | 5524,0 | 5520,0 | 5524,0 | 5524,0 | 5524,0 | 5524,0 | 5524,0 |
| 27T2 | 6622,0 | 6619,0 | 6617,0 | 6618,0 | 6618,0 | 6620,0 | 6618,0 | 6618,0 | 6618,0 | 6618,0 | 6618,0 |
| 27T3 | 5748,0 | 5753,0 | 5758,0 | 5758,0 | 5758,0 | 5760,0 | 5758,0 | 5758,0 | 5758,0 | 5758,0 | 5758,0 |
| 27T4 | 5522,0 | 5523,0 | 5520,0 | 5519,0 | 5520,0 | 5520,0 | 5520,0 | 5520,0 | 5520,0 | 5520,0 | 5520,0 |
| 27T5 | 6249,0 | 6244,0 | 6247,0 | 6246,0 | 6246,0 | 6250,0 | 6246,0 | 6246,0 | 6246,0 | 6246,0 | 6246,0 |
| 27T6 | 5636,0 | 5641,0 | 5641,0 | 5640,0 | 5640,0 | 5640,0 | 5641,0 | 5641,0 | 5641,0 | 5641,0 | 5641,0 |
| Difference from previous | | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**K1L4**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 3803,00 | 3806,00 | 3804,00 | 3804,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 |
| 11_4T2 | 3682,00 | 3688,00 | 3684,00 | 3684,00 | 3685,00 | 3685,00 | 3685,00 | 3685,00 | 3685,00 | 3685,00 | 3685,00 |
| 11_4T3 | 3586,00 | 3586,00 | 3585,00 | 3586,00 | 3586,00 | 3586,00 | 3586,00 | 3586,00 | 3586,00 | 3586,00 | 3586,00 |
| 11_4T4 | 3793,00 | 3798,00 | 3804,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 | 3805,00 |
| 11_4T5 | 3849,00 | 3847,00 | 3843,00 | 3843,00 | 3843,00 | 3843,00 | 3842,00 | 3842,00 | 3842,00 | 3842,00 | 3842,00 |
| 11_4T6 | 3683,00 | 3673,00 | 3671,00 | 3671,00 | 3670,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 |
| Difference from previous | | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**MBL2**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 8876,00 | 8876,00 | 8876,00 | 8876,00 | 8876,00 | 8880,00 | 8876,00 | 8876,00 | 8876,00 | 8876,00 | 8876,00 |
| 27T2 | 9800,00 | 9798,00 | 9798,00 | 9799,00 | 9799,00 | 9800,00 | 9799,00 | 9799,00 | 9799,00 | 9799,00 | 9799,00 |
| 27T3 | 8693,00 | 8691,00 | 8690,00 | 8689,00 | 8689,00 | 8690,00 | 8688,00 | 8689,00 | 8689,00 | 8688,00 | 8689,00 |
| 27T4 | 8509,00 | 8511,00 | 8512,00 | 8512,00 | 8512,00 | 8510,00 | 8512,00 | 8512,00 | 8512,00 | 8512,00 | 8512,00 |
| 27T5 | 9419,00 | 9419,00 | 9419,00 | 9420,00 | 9420,00 | 9420,00 | 9420,00 | 9420,00 | 9420,00 | 9420,00 | 9420,00 |
| 27T6 | 8914,00 | 8910,00 | 8909,00 | 8909,00 | 8910,00 | 8910,00 | 8910,00 | 8909,00 | 8909,00 | 8910,00 | 8910,00 |
| Difference from previous | | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**MBL2**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11_4T1 | 3888,00 | 3887,00 | 3883,00 | 3882,00 | 3882,00 | 3882,00 | 3882,00 | 3882,00 | 3882,00 | 3882,00 | 3882,00 |
| 11_4T2 | 3743,00 | 3749,00 | 3750,00 | 3749,00 | 3749,00 | 3749,00 | 3749,00 | 3749,00 | 3749,00 | 3749,00 | 3749,00 |
| 11_4T3 | 3664,00 | 3669,00 | 3670,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 | 3671,00 |
| 11_4T4 | 3896,00 | 3888,00 | 3886,00 | 3887,00 | 3887,00 | 3887,00 | 3887,00 | 3887,00 | 3887,00 | 3887,00 | 3887,00 |
| 11_4T5 | 3924,00 | 3929,00 | 3934,00 | 3934,00 | 3934,00 | 3933,00 | 3933,00 | 3933,00 | 3933,00 | 3933,00 | 3933,00 |
| 11_4T6 | 3760,00 | 3755,00 | 3756,00 | 3756,00 | 3756,00 | 3756,00 | 3756,00 | 3756,00 | 3756,00 | 3756,00 | 3756,00 |
| Difference from previous | | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**MBL4**

| BW | 204,80 | 102,40 | 51,2 | 25,6 | 12,8 | 6,4 | 3,2 | 1,6 | 0,8 | 0,4 | 0,2 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 27T1 | 9066,00 | 9065,00 | 9067,00 | 9066,00 | 9066,00 | 9070,00 | 9066,00 | 9066,00 | 9066,00 | 9066,00 | 9066,00 |
| 27T2 | 9995,00 | 9998,00 | 9996,00 | 9996,00 | 9996,00 | 10000,00 | 9996,00 | 9996,00 | 9996,00 | 9996,00 | 9996,00 |
| 27T3 | 8879,00 | 8878,00 | 8876,00 | 8877,00 | 8877,00 | 8880,00 | 8877,00 | 8877,00 | 8877,00 | 8877,00 | 8877,00 |
| 27T4 | 8691,00 | 8689,00 | 8692,00 | 8694,00 | 8694,00 | 8690,00 | 8694,00 | 8694,00 | 8694,00 | 8694,00 | 8694,00 |
| 27T5 | 9645,00 | 9640,00 | 9640,00 | 9641,00 | 9641,00 | 9640,00 | 9641,00 | 9641,00 | 9641,00 | 9641,00 | 9641,00 |
| 27T6 | 9037,00 | 9039,00 | 9041,00 | 9042,00 | 9042,00 | 9040,00 | 9042,00 | 9042,00 | 9042,00 | 9042,00 | 9042,00 |
| Difference from previous | | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 |

**MBL4**

## 7.6 Mlife Results: Short time DEL's at zero mean.

### 7.6.1 1 standard deviation turbulence

| Filename | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **3T1** | 71,21 | 4,95 | 459,80 | 0,64 | 348,30 | 332,10 | 1601,00 | 1514,00 |
| **3T2** | 71,77 | 4,95 | 460,70 | 0,64 | 353,40 | 339,00 | 1601,00 | 1514,00 |
| **3T3** | 71,55 | 4,94 | 459,90 | 0,64 | 351,00 | 336,00 | 1602,00 | 1515,00 |
| **3T4** | 70,43 | 4,95 | 459,80 | 0,63 | 322,10 | 303,30 | 1591,00 | 1502,00 |
| **3T5** | 70,79 | 4,94 | 459,90 | 0,64 | 347,80 | 332,50 | 1598,00 | 1511,00 |
| **3T6** | 71,74 | 4,94 | 459,80 | 0,64 | 349,70 | 335,60 | 1592,00 | 1507,00 |
| **5T1** | 83,22 | 4,96 | 475,50 | 0,69 | 449,40 | 444,50 | 1690,00 | 1613,00 |
| **5T2** | 84,91 | 4,96 | 472,90 | 0,69 | 453,60 | 448,70 | 1677,00 | 1602,00 |
| **5T3** | 84,51 | 4,96 | 474,20 | 0,68 | 453,30 | 451,80 | 1665,00 | 1590,00 |
| **5T4** | 84,41 | 4,95 | 472,80 | 0,69 | 421,00 | 415,30 | 1677,00 | 1606,00 |
| **5T5** | 83,65 | 4,97 | 473,20 | 0,70 | 454,20 | 448,60 | 1678,00 | 1605,00 |
| **5T6** | 85,05 | 4,97 | 477,00 | 0,69 | 451,00 | 448,60 | 1695,00 | 1619,00 |
| **7T1** | 99,69 | 5,02 | 482,40 | 0,70 | 487,60 | 487,70 | 1720,00 | 1666,00 |
| **7T2** | 100,60 | 5,02 | 483,20 | 0,69 | 458,40 | 453,40 | 1714,00 | 1656,00 |
| **7T3** | 102,60 | 5,02 | 483,20 | 0,67 | 448,40 | 451,20 | 1687,00 | 1632,00 |
| **7T4** | 99,68 | 5,02 | 481,80 | 0,69 | 458,00 | 461,70 | 1687,00 | 1629,00 |
| **7T5** | 102,90 | 5,00 | 481,50 | 0,68 | 454,50 | 456,70 | 1685,00 | 1627,00 |
| **7T6** | 103,30 | 5,02 | 486,10 | 0,69 | 502,20 | 500,60 | 1710,00 | 1654,00 |
| **9T1** | 109,70 | 5,10 | 497,60 | 0,68 | 483,60 | 500,80 | 1721,00 | 1690,00 |
| **9T2** | 104,80 | 5,08 | 493,70 | 0,69 | 463,50 | 474,70 | 1720,00 | 1688,00 |
| **9T3** | 104,80 | 5,10 | 491,50 | 0,68 | 467,10 | 471,60 | 1722,00 | 1688,00 |
| **9T4** | 106,50 | 5,08 | 491,10 | 0,67 | 436,50 | 433,90 | 1704,00 | 1668,00 |
| **9T5** | 105,70 | 5,11 | 491,00 | 0,68 | 507,70 | 511,70 | 1728,00 | 1694,00 |
| **9T6** | 102,80 | 5,08 | 486,80 | 0,66 | 401,20 | 404,50 | 1679,00 | 1634,00 |
| **11T1** | 142,90 | 5,25 | 530,90 | 0,81 | 729,30 | 757,00 | 2084,00 | 2088,00 |
| **11T2** | 134,90 | 5,20 | 524,20 | 0,78 | 617,20 | 650,70 | 1956,00 | 1937,00 |
| **11T3** | 138,90 | 5,23 | 525,40 | 0,78 | 615,20 | 631,80 | 1990,00 | 1977,00 |
| **11T4** | 137,50 | 5,23 | 526,80 | 0,80 | 715,40 | 748,50 | 1973,00 | 1964,00 |
| **11T5** | 132,10 | 5,25 | 535,80 | 0,76 | 581,40 | 628,50 | 1928,00 | 1912,00 |
| **11T6** | 134,50 | 5,25 | 520,20 | 0,78 | 646,20 | 664,40 | 1998,00 | 1981,00 |
| **13T1** | 157,40 | 5,41 | 542,40 | 0,83 | 905,50 | 931,40 | 2237,00 | 2229,00 |
| **13T2** | 162,20 | 5,38 | 543,10 | 0,85 | 837,00 | 862,80 | 2219,00 | 2216,00 |
| **13T3** | 161,90 | 5,40 | 546,50 | 0,86 | 826,10 | 862,50 | 2206,00 | 2200,00 |
| **13T4** | 159,60 | 5,43 | 543,50 | 0,88 | 967,40 | 1011,00 | 2325,00 | 2334,00 |
| **13T5** | 162,00 | 5,41 | 543,00 | 0,90 | 904,50 | 943,30 | 2241,00 | 2248,00 |
| **13T6** | 161,30 | 5,41 | 545,40 | 0,87 | 869,60 | 883,10 | 2202,00 | 2193,00 |
| **15T1** | 179,20 | 5,53 | 565,50 | 0,83 | 864,60 | 889,40 | 2255,00 | 2238,00 |
| **15T2** | 179,70 | 5,58 | 562,00 | 0,87 | 889,90 | 916,30 | 2294,00 | 2283,00 |
| **15T3** | 179,10 | 5,54 | 557,50 | 0,89 | 868,70 | 895,00 | 2245,00 | 2227,00 |
| **15T4** | 172,80 | 5,60 | 558,10 | 0,88 | 881,70 | 908,20 | 2297,00 | 2278,00 |
| **15T5** | 178,30 | 5,58 | 558,10 | 0,87 | 910,50 | 949,80 | 2232,00 | 2217,00 |
| **15T6** | 183,70 | 5,55 | 564,90 | 0,88 | 906,20 | 945,20 | 2322,00 | 2320,00 |

| Filename | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **17T1** | 208,90 | 5,78 | 589,60 | 0,94 | 1072,00 | 1104,00 | 2535,00 | 2516,00 |
| **17T2** | 198,80 | 5,73 | 581,40 | 0,93 | 961,40 | 989,40 | 2441,00 | 2423,00 |
| **17T3** | 189,00 | 5,68 | 574,90 | 0,94 | 982,00 | 1018,00 | 2421,00 | 2393,00 |
| **17T4** | 203,30 | 5,75 | 587,60 | 0,91 | 998,50 | 1038,00 | 2457,00 | 2455,00 |
| **17T5** | 157,40 | 5,41 | 542,40 | 0,83 | 905,50 | 931,40 | 2237,00 | 2229,00 |
| **17T6** | 204,90 | 5,72 | 588,60 | 0,94 | 972,50 | 998,20 | 2429,00 | 2412,00 |
| **19T1** | 225,60 | 5,95 | 597,40 | 1,00 | 1172,00 | 1207,00 | 2652,00 | 2639,00 |
| **19T2** | 217,50 | 5,94 | 602,50 | 1,00 | 1168,00 | 1199,00 | 2589,00 | 2580,00 |
| **19T3** | 221,70 | 5,87 | 601,10 | 1,03 | 1031,00 | 1052,00 | 2546,00 | 2528,00 |
| **19T4** | 224,00 | 5,94 | 599,60 | 1,00 | 1040,00 | 1065,00 | 2532,00 | 2511,00 |
| **19T5** | 228,20 | 5,91 | 603,40 | 1,00 | 1041,00 | 1074,00 | 2568,00 | 2559,00 |
| **19T6** | 225,70 | 5,91 | 603,30 | 1,01 | 1189,00 | 1224,00 | 2657,00 | 2645,00 |
| **21T1** | 247,40 | 6,02 | 613,30 | 1,06 | 1217,00 | 1255,00 | 2610,00 | 2591,00 |
| **21T2** | 257,80 | 6,09 | 626,60 | 1,08 | 1432,00 | 1472,00 | 2875,00 | 2861,00 |
| **21T3** | 264,00 | 6,10 | 633,40 | 1,12 | 1548,00 | 1594,00 | 3007,00 | 2998,00 |
| **21T4** | 244,90 | 6,01 | 615,80 | 1,07 | 1219,00 | 1254,00 | 2660,00 | 2640,00 |
| **21T5** | 248,80 | 6,07 | 627,00 | 1,06 | 1155,00 | 1191,00 | 2711,00 | 2700,00 |
| **21T6** | 250,20 | 6,06 | 627,50 | 1,14 | 1352,00 | 1390,00 | 2909,00 | 2904,00 |
| **23T1** | 282,80 | 6,26 | 651,50 | 1,19 | 1511,00 | 1557,00 | 3000,00 | 3010,00 |
| **23T2** | 278,90 | 6,29 | 651,90 | 1,26 | 1444,00 | 1469,00 | 3118,00 | 3108,00 |
| **23T3** | 283,50 | 6,29 | 644,90 | 1,22 | 1477,00 | 1519,00 | 2962,00 | 2966,00 |
| **23T4** | 278,80 | 6,28 | 658,70 | 1,21 | 1594,00 | 1627,00 | 3226,00 | 3215,00 |
| **23T5** | 286,90 | 6,25 | 650,00 | 1,23 | 1398,00 | 1422,00 | 3036,00 | 3019,00 |
| **23T6** | 272,50 | 6,26 | 643,40 | 1,16 | 1415,00 | 1450,00 | 2876,00 | 2866,00 |
| **25T1** | 319,00 | 6,44 | 672,10 | 1,36 | 1589,00 | 1625,00 | 3126,00 | 3110,00 |
| **25T2** | 313,00 | 6,43 | 685,90 | 1,36 | 1644,00 | 1689,00 | 3239,00 | 3222,00 |
| **25T3** | 319,80 | 6,52 | 689,20 | 1,32 | 1693,00 | 1731,00 | 3293,00 | 3286,00 |
| **25T4** | 316,70 | 6,47 | 670,70 | 1,30 | 1612,00 | 1657,00 | 3138,00 | 3138,00 |
| **25T5** | 323,70 | 6,52 | 677,20 | 1,32 | 1786,00 | 1838,00 | 3418,00 | 3419,00 |
| **25T6** | 310,50 | 6,44 | 669,20 | 1,34 | 1607,00 | 1651,00 | 3287,00 | 3285,00 |

### 7.6.2 1,5 standard deviations turbulence

| Filename | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **3T1** | 75,51 | 4,94 | 461,90 | 0,66 | 415,90 | 404,00 | 1642,00 | 1555,00 |
| **3T2** | 76,79 | 4,93 | 463,60 | 0,66 | 418,90 | 408,30 | 1650,00 | 1561,00 |
| **3T3** | 76,04 | 4,94 | 463,20 | 0,67 | 420,10 | 409,60 | 1648,00 | 1562,00 |
| **3T4** | 74,01 | 4,95 | 461,80 | 0,66 | 375,20 | 359,00 | 1627,00 | 1536,00 |
| **3T5** | 74,94 | 4,94 | 462,30 | 0,67 | 415,90 | 403,70 | 1643,00 | 1555,00 |
| **3T6** | 76,46 | 4,95 | 463,10 | 0,66 | 415,90 | 403,40 | 1647,00 | 1560,00 |
| **5T1** | 94,83 | 4,99 | 485,70 | 0,74 | 592,80 | 594,90 | 1817,00 | 1743,00 |
| **5T2** | 96,48 | 4,99 | 486,90 | 0,73 | 567,80 | 564,30 | 1778,00 | 1709,00 |
| **5T3** | 97,47 | 4,99 | 484,40 | 0,74 | 572,70 | 576,00 | 1772,00 | 1699,00 |
| **5T4** | 96,88 | 5,00 | 485,30 | 0,72 | 532,30 | 532,20 | 1771,00 | 1695,00 |
| **5T5** | 96,42 | 5,00 | 486,80 | 0,73 | 540,40 | 536,40 | 1785,00 | 1714,00 |
| **5T6** | 99,35 | 4,99 | 487,80 | 0,73 | 597,30 | 600,50 | 1825,00 | 1750,00 |
| **7T1** | 124,70 | 5,10 | 504,40 | 0,77 | 666,10 | 680,80 | 1900,00 | 1850,00 |
| **7T2** | 122,60 | 5,13 | 504,90 | 0,76 | 663,00 | 671,70 | 1892,00 | 1841,00 |
| **7T3** | 127,80 | 5,10 | 506,80 | 0,74 | 602,10 | 605,10 | 1848,00 | 1792,00 |
| **7T4** | 124,30 | 5,12 | 505,60 | 0,76 | 648,50 | 655,50 | 1869,00 | 1817,00 |
| **7T5** | 128,80 | 5,11 | 503,80 | 0,75 | 666,00 | 675,50 | 1855,00 | 1807,00 |
| **7T6** | 129,30 | 5,10 | 504,70 | 0,76 | 684,70 | 690,00 | 1894,00 | 1844,00 |
| **9T1** | 141,70 | 5,26 | 518,70 | 0,76 | 756,10 | 790,50 | 1997,00 | 1984,00 |
| **9T2** | 134,80 | 5,25 | 524,60 | 0,76 | 661,90 | 691,90 | 1923,00 | 1909,00 |
| **9T3** | 131,00 | 5,24 | 520,00 | 0,76 | 642,60 | 664,20 | 1925,00 | 1897,00 |
| **9T4** | 138,10 | 5,21 | 517,20 | 0,76 | 628,90 | 640,40 | 1923,00 | 1892,00 |
| **9T5** | 132,90 | 5,22 | 516,40 | 0,76 | 687,50 | 704,90 | 1916,00 | 1887,00 |
| **9T6** | 130,40 | 5,23 | 511,50 | 0,74 | 597,40 | 612,00 | 1852,00 | 1822,00 |
| **11T1** | 191,20 | 5,51 | 574,50 | 0,95 | 1114,00 | 1164,00 | 2545,00 | 2568,00 |
| **11T2** | 180,20 | 5,43 | 562,30 | 0,91 | 904,00 | 955,10 | 2304,00 | 2307,00 |
| **11T4** | 180,30 | 5,47 | 564,80 | 0,89 | 954,30 | 994,00 | 2329,00 | 2345,00 |
| **11T5** | 176,70 | 5,44 | 576,00 | 0,87 | 907,80 | 957,90 | 2239,00 | 2246,00 |
| **11T6** | 177,00 | 5,49 | 565,60 | 0,88 | 842,90 | 884,50 | 2303,00 | 2301,00 |
| **13T1** | 209,20 | 5,66 | 596,90 | 1,00 | 1174,00 | 1228,00 | 2549,00 | 2561,00 |
| **13T2** | 218,80 | 5,67 | 597,50 | 1,01 | 1108,00 | 1157,00 | 2595,00 | 2620,00 |
| **13T3** | 226,60 | 5,68 | 607,70 | 1,02 | 1200,00 | 1257,00 | 2613,00 | 2638,00 |
| **13T4** | 210,60 | 5,69 | 589,40 | 1,03 | 1200,00 | 1260,00 | 2600,00 | 2617,00 |
| **13T5** | 220,30 | 5,72 | 598,40 | 1,03 | 1209,00 | 1271,00 | 2677,00 | 2702,00 |
| **15T1** | 250,10 | 5,87 | 630,70 | 1,02 | 1300,00 | 1344,00 | 2768,00 | 2777,00 |
| **15T2** | 251,90 | 5,98 | 629,50 | 1,09 | 1332,00 | 1381,00 | 2848,00 | 2863,00 |
| **15T3** | 248,70 | 5,92 | 619,70 | 1,09 | 1348,00 | 1402,00 | 2781,00 | 2793,00 |
| **15T4** | 237,20 | 5,96 | 616,10 | 1,07 | 1309,00 | 1364,00 | 2823,00 | 2827,00 |
| **15T5** | 247,70 | 5,94 | 621,60 | 1,08 | 1356,00 | 1415,00 | 2770,00 | 2777,00 |
| **15T6** | 253,60 | 5,96 | 635,40 | 1,09 | 1366,00 | 1428,00 | 2883,00 | 2913,00 |

| Filename | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **17T1** | 289,70 | 6,26 | 669,40 | 1,16 | 1600,00 | 1653,00 | 3188,00 | 3195,00 |
| **17T2** | 278,60 | 6,16 | 654,70 | 1,13 | 1473,00 | 1521,00 | 3070,00 | 3079,00 |
| **17T3** | 263,50 | 6,08 | 643,80 | 1,15 | 1452,00 | 1502,00 | 2970,00 | 2961,00 |
| **17T4** | 278,80 | 6,18 | 660,90 | 1,13 | 1465,00 | 1529,00 | 3035,00 | 3064,00 |
| **17T5** | 277,50 | 6,21 | 660,50 | 1,19 | 1476,00 | 1519,00 | 3103,00 | 3106,00 |
| **17T6** | 285,30 | 6,07 | 669,10 | 1,17 | 1415,00 | 1460,00 | 3002,00 | 3009,00 |
| **19T1** | 326,00 | 6,45 | 687,40 | 1,26 | 1730,00 | 1784,00 | 3385,00 | 3405,00 |
| **19T2** | 315,00 | 6,39 | 684,80 | 1,24 | 1729,00 | 1788,00 | 3256,00 | 3276,00 |
| **19T3** | 322,10 | 6,34 | 691,20 | 1,29 | 1606,00 | 1648,00 | 3247,00 | 3256,00 |
| **19T4** | 321,60 | 6,41 | 696,80 | 1,25 | 1580,00 | 1626,00 | 3195,00 | 3205,00 |
| **19T5** | 320,50 | 6,39 | 685,00 | 1,25 | 1558,00 | 1612,00 | 3221,00 | 3237,00 |
| **19T6** | 321,30 | 6,42 | 692,50 | 1,30 | 1777,00 | 1830,00 | 3424,00 | 3437,00 |
| **21T1** | 367,70 | 6,63 | 716,20 | 1,41 | 1797,00 | 1854,00 | 3351,00 | 3360,00 |
| **21T2** | 379,20 | 6,77 | 731,90 | 1,39 | 2102,00 | 2168,00 | 3690,00 | 3712,00 |
| **21T3** | 375,40 | 6,66 | 744,30 | 1,45 | 2291,00 | 2365,00 | 3973,00 | 4011,00 |
| **21T4** | 357,70 | 6,62 | 713,40 | 1,37 | 1865,00 | 1919,00 | 3456,00 | 3466,00 |
| **21T5** | 362,70 | 6,67 | 734,10 | 1,36 | 1769,00 | 1827,00 | 3609,00 | 3641,00 |
| **21T6** | 367,70 | 6,66 | 742,40 | 1,48 | 2065,00 | 2124,00 | 3878,00 | 3921,00 |
| **23T1** | 411,90 | 6,98 | 779,40 | 1,60 | 2265,00 | 2342,00 | 3971,00 | 4024,00 |
| **23T2** | 399,70 | 6,89 | 777,70 | 1,68 | 2143,00 | 2193,00 | 4004,00 | 4023,00 |
| **23T3** | 409,00 | 7,00 | 771,30 | 1,65 | 2313,00 | 2388,00 | 4043,00 | 4099,00 |
| **23T4** | 407,80 | 7,04 | 784,60 | 1,59 | 2451,00 | 2512,00 | 4289,00 | 4322,00 |
| **23T5** | 415,90 | 6,97 | 760,80 | 1,63 | 2084,00 | 2126,00 | 3989,00 | 4008,00 |
| **23T6** | 398,00 | 6,94 | 765,00 | 1,51 | 2049,00 | 2101,00 | 3735,00 | 3757,00 |
| **25T1** | 474,40 | 7,26 | 819,30 | 1,81 | 2367,00 | 2429,00 | 4215,00 | 4236,00 |
| **25T2** | 459,20 | 7,28 | 840,70 | 1,86 | 2427,00 | 2498,00 | 4302,00 | 4313,00 |
| **25T3** | 467,10 | 7,27 | 833,70 | 1,76 | 2421,00 | 2479,00 | 4321,00 | 4358,00 |
| **25T4** | 458,50 | 7,25 | 814,40 | 1,74 | 2458,00 | 2524,00 | 4274,00 | 4320,00 |
| **25T5** | 480,10 | 7,25 | 826,20 | 1,76 | 2881,00 | 2968,00 | 4743,00 | 4794,00 |
| **25T6** | 458,90 | 7,12 | 815,30 | 1,82 | 2369,00 | 2431,00 | 4369,00 | 4390,00 |

### 7.6.3 2 standard deviations turbulence

| Filename | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **3T1** | 79,07 | 4,95 | 465,70 | 0,69 | 488,10 | 479,90 | 1686,00 | 1598,00 |
| **3T2** | 82,23 | 4,94 | 466,70 | 0,69 | 487,50 | 478,50 | 1707,00 | 1618,00 |
| **3T3** | 80,07 | 4,95 | 465,60 | 0,69 | 484,50 | 477,40 | 1691,00 | 1608,00 |
| **3T4** | 78,06 | 4,94 | 466,90 | 0,68 | 447,70 | 434,60 | 1674,00 | 1582,00 |
| **3T5** | 79,36 | 4,94 | 465,40 | 0,70 | 487,60 | 479,10 | 1692,00 | 1607,00 |
| **3T6** | 83,43 | 4,95 | 467,00 | 0,69 | 494,00 | 487,00 | 1698,00 | 1616,00 |
| **5T1** | 108,10 | 5,04 | 496,60 | 0,80 | 753,40 | 757,80 | 1954,00 | 1887,00 |
| **5T2** | 108,50 | 5,05 | 496,90 | 0,78 | 692,10 | 689,90 | 1910,00 | 1846,00 |
| **5T3** | 110,80 | 5,03 | 496,50 | 0,78 | 694,80 | 702,30 | 1894,00 | 1824,00 |
| **5T4** | 110,90 | 5,04 | 500,00 | 0,78 | 664,90 | 667,10 | 1903,00 | 1833,00 |
| **5T5** | 109,90 | 5,03 | 502,10 | 0,79 | 689,40 | 693,60 | 1904,00 | 1841,00 |
| **5T6** | 115,40 | 5,04 | 503,00 | 0,79 | 771,30 | 776,80 | 1984,00 | 1916,00 |
| **7T1** | 149,60 | 5,18 | 526,10 | 0,84 | 883,20 | 900,10 | 2085,00 | 2046,00 |
| **7T2** | 149,00 | 5,21 | 525,60 | 0,83 | 808,90 | 818,40 | 2048,00 | 2002,00 |
| **7T3** | 154,00 | 5,19 | 534,20 | 0,82 | 776,70 | 792,20 | 2027,00 | 1987,00 |
| **7T4** | 153,60 | 5,19 | 527,50 | 0,82 | 824,20 | 842,00 | 2012,00 | 1980,00 |
| **7T5** | 155,00 | 5,18 | 525,00 | 0,84 | 784,60 | 810,30 | 2027,00 | 1977,00 |
| **7T6** | 156,70 | 5,21 | 537,10 | 0,88 | 926,80 | 942,30 | 2143,00 | 2112,00 |
| ***9T1*** | ***3477,00*** | ***68,61*** | ***3414,00*** | ***33,49*** | ***5578,00*** | ***5563,00*** | ***10690,00*** | ***10700,00*** |
| **9T2** | 165,60 | 5,36 | 553,60 | 0,84 | 833,70 | 875,90 | 2125,00 | 2115,00 |
| **9T3** | 157,90 | 5,36 | 546,50 | 0,85 | 832,00 | 863,40 | 2157,00 | 2150,00 |
| **9T4** | 163,80 | 5,36 | 546,90 | 0,84 | 838,60 | 872,90 | 2129,00 | 2121,00 |
| **9T5** | 160,10 | 5,33 | 541,20 | 0,83 | 903,70 | 941,00 | 2122,00 | 2106,00 |
| **9T6** | 155,10 | 5,35 | 531,70 | 0,82 | 792,80 | 803,80 | 2037,00 | 2009,00 |
| **11T1** | 229,80 | 5,65 | 606,20 | 1,02 | 1272,00 | 1329,00 | 2767,00 | 2803,00 |
| **11T2** | 229,80 | 5,65 | 606,20 | 1,02 | 1272,00 | 1329,00 | 2767,00 | 2803,00 |
| **11T3** | 228,70 | 5,69 | 608,60 | 1,01 | 1084,00 | 1137,00 | 2558,00 | 2580,00 |
| **11T4** | 224,60 | 5,64 | 602,90 | 1,03 | 1261,00 | 1320,00 | 2704,00 | 2746,00 |
| **11T5** | 225,60 | 5,64 | 626,10 | 0,99 | 1080,00 | 1141,00 | 2532,00 | 2553,00 |
| **11T6** | 223,40 | 5,65 | 607,30 | 1,04 | 1085,00 | 1129,00 | 2646,00 | 2672,00 |
| **13T1** | 273,90 | 5,92 | 658,70 | 1,17 | 1503,00 | 1578,00 | 2998,00 | 3042,00 |
| **13T2** | 282,40 | 5,93 | 662,40 | 1,20 | 1484,00 | 1555,00 | 3058,00 | 3113,00 |
| **13T3** | 282,30 | 5,99 | 670,20 | 1,20 | 1587,00 | 1661,00 | 3189,00 | 3238,00 |
| **13T4** | 280,00 | 6,07 | 655,00 | 1,22 | 1804,00 | 1892,00 | 3367,00 | 3430,00 |
| **13T5** | 277,60 | 5,95 | 648,20 | 1,18 | 1466,00 | 1523,00 | 3022,00 | 3056,00 |
| **13T6** | 277,90 | 5,95 | 658,20 | 1,23 | 1500,00 | 1556,00 | 3075,00 | 3109,00 |
| **15T1** | 322,30 | 6,26 | 693,90 | 1,21 | 1717,00 | 1791,00 | 3272,00 | 3315,00 |
| **15T2** | 323,30 | 6,22 | 692,30 | 1,31 | 1793,00 | 1864,00 | 3392,00 | 3442,00 |
| **15T3** | 314,90 | 6,23 | 684,80 | 1,29 | 1730,00 | 1800,00 | 3315,00 | 3351,00 |
| **15T4** | 302,80 | 6,33 | 676,40 | 1,28 | 1768,00 | 1849,00 | 3378,00 | 3412,00 |
| **15T5** | 326,10 | 6,24 | 690,60 | 1,27 | 1857,00 | 1948,00 | 3338,00 | 3379,00 |
| **15T6** | 327,10 | 6,31 | 708,60 | 1,28 | 1877,00 | 1959,00 | 3561,00 | 3628,00 |

| Filename | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **17T1** | 378,60 | 6,65 | 755,70 | 1,42 | 2152,00 | 2226,00 | 3855,00 | 3895,00 |
| **17T2** | 363,70 | 6,62 | 730,30 | 1,37 | 1978,00 | 2043,00 | 3712,00 | 3752,00 |
| **17T3** | 345,10 | 6,48 | 717,30 | 1,39 | 2036,00 | 2117,00 | 3590,00 | 3622,00 |
| **17T4** | 363,20 | 6,61 | 746,70 | 1,37 | 1900,00 | 1984,00 | 3601,00 | 3655,00 |
| **17T5** | 350,10 | 6,48 | 731,80 | 1,42 | 1937,00 | 1992,00 | 3722,00 | 3752,00 |
| **17T6** | 375,60 | 6,54 | 758,90 | 1,40 | 1879,00 | 1943,00 | 3625,00 | 3663,00 |
| **19T1** | 425,90 | 6,96 | 783,10 | 1,55 | 2327,00 | 2395,00 | 4181,00 | 4227,00 |
| **19T2** | 420,60 | 6,91 | 778,50 | 1,52 | 2270,00 | 2343,00 | 3999,00 | 4046,00 |
| **19T3** | 425,30 | 6,92 | 791,90 | 1,61 | 2237,00 | 2302,00 | 4043,00 | 4086,00 |
| **19T4** | 419,60 | 6,93 | 799,80 | 1,53 | 2170,00 | 2239,00 | 3919,00 | 3960,00 |
| **19T5** | 419,20 | 6,81 | 771,40 | 1,50 | 2044,00 | 2113,00 | 3893,00 | 3936,00 |
| **19T6** | 424,40 | 6,92 | 791,80 | 1,59 | 2354,00 | 2429,00 | 4217,00 | 4262,00 |
| **21T1** | 481,20 | 7,26 | 822,90 | 1,71 | 2347,00 | 2420,00 | 4151,00 | 4188,00 |
| **21T2** | 509,60 | 7,25 | 841,70 | 1,71 | 2764,00 | 2851,00 | 4569,00 | 4629,00 |
| **21T3** | 493,10 | 7,34 | 856,70 | 1,88 | 2894,00 | 2995,00 | 4872,00 | 4953,00 |
| **21T4** | 471,50 | 7,18 | 830,00 | 1,73 | 2559,00 | 2633,00 | 4375,00 | 4422,00 |
| **21T5** | 483,00 | 7,14 | 848,40 | 1,70 | 2344,00 | 2425,00 | 4458,00 | 4525,00 |
| **21T6** | 492,80 | 7,23 | 869,60 | 1,83 | 2870,00 | 2951,00 | 4986,00 | 5073,00 |
| **23T1** | 545,00 | 7,79 | 900,70 | 2,07 | 3112,00 | 3223,00 | 5132,00 | 5241,00 |
| **23T2** | 531,30 | 7,49 | 907,30 | 2,06 | 2897,00 | 2977,00 | 4989,00 | 5049,00 |
| **23T3** | 544,20 | 7,68 | 906,50 | 2,07 | 3242,00 | 3351,00 | 5238,00 | 5338,00 |
| **23T4** | 538,60 | 7,77 | 902,50 | 1,95 | 3147,00 | 3228,00 | 5226,00 | 5298,00 |
| **23T5** | 551,10 | 7,73 | 882,80 | 2,04 | 2829,00 | 2904,00 | 4974,00 | 5030,00 |
| **23T6** | 536,20 | 7,57 | 901,10 | 1,93 | 2688,00 | 2761,00 | 4680,00 | 4740,00 |
| **25T1** | 651,60 | 8,09 | 988,20 | 2,33 | 3193,00 | 3284,00 | 5394,00 | 5460,00 |
| **25T2** | 620,60 | 8,04 | 991,20 | 2,30 | 3161,00 | 3255,00 | 5278,00 | 5326,00 |
| **25T3** | 632,30 | 8,14 | 997,70 | 2,24 | 3128,00 | 3216,00 | 5249,00 | 5326,00 |
| **25T4** | 605,10 | 8,23 | 970,50 | 2,22 | 3242,00 | 3331,00 | 5392,00 | 5456,00 |
| **25T5** | 621,60 | 8,06 | 966,00 | 2,28 | 3600,00 | 3703,00 | 5777,00 | 5862,00 |
| **25T6** | 621,90 | 7,99 | 971,60 | 2,35 | 3206,00 | 3282,00 | 5429,00 | 5489,00 |

## 7.7 Mlife Results: Mean DEL's for each wind speed

| 3m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 71,25 | 4,94 | 459,98 | 0,64 | 345,38 | 329,75 | 1597,50 | 1510,50 |
| **1,5stdev** | 75,63 | 4,94 | 462,65 | 0,66 | 410,32 | 398,00 | 1642,83 | 1554,83 |
| **2stdev** | 80,37 | 4,95 | 466,22 | 0,69 | 481,57 | 472,75 | 1691,33 | 1604,83 |

| 5m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 84,29 | 4,96 | 474,27 | 0,69 | 447,08 | 442,92 | 1680,33 | 1605,83 |
| **1,5stdev** | 96,91 | 4,99 | 486,15 | 0,73 | 567,22 | 567,38 | 1791,33 | 1718,33 |
| **2stdev** | 110,60 | 5,04 | 499,18 | 0,79 | 710,98 | 714,58 | 1924,83 | 1857,83 |

| 7m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 101,46 | 5,02 | 483,03 | 0,69 | 468,18 | 468,55 | 1700,50 | 1644,00 |
| **1,5stdev** | 126,25 | 5,11 | 505,03 | 0,76 | 655,07 | 663,10 | 1876,33 | 1825,17 |
| **2stdev** | 152,98 | 5,19 | 529,25 | 0,84 | 834,07 | 850,88 | 2057,00 | 2017,33 |

| 9m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 105,72 | 5,09 | 491,95 | 0,68 | 459,93 | 466,20 | 1712,33 | 1677,00 |
| **1,5stdev** | 134,82 | 5,23 | 518,07 | 0,76 | 662,40 | 683,98 | 1922,67 | 1898,50 |
| ***2stdev*** | ***713,25*** | ***15,89*** | ***1022,32*** | ***6,28*** | ***1629,80*** | ***1653,33*** | ***3543,33*** | ***3533,50*** |

| 11m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 136,80 | 5,23 | 527,22 | 0,78 | 650,78 | 680,15 | 1988,17 | 1976,50 |
| **1,5stdev** | 181,08 | 5,47 | 568,64 | 0,90 | 944,60 | 991,10 | 2344,00 | 2353,40 |
| **2stdev** | 226,98 | 5,65 | 609,55 | 1,02 | 1175,67 | 1230,83 | 2662,33 | 2692,83 |

| 13m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| **1stdev** | 160,73 | 5,41 | 543,98 | 0,86 | 885,02 | 915,68 | 2238,33 | 2236,67 |
| **1,5stdev** | 217,10 | 5,69 | 597,98 | 1,02 | 1178,20 | 1234,60 | 2606,80 | 2627,60 |
| **2stdev** | 259,58 | 5,88 | 639,98 | 1,14 | 1452,27 | 1515,35 | 2972,67 | 3012,00 |

| 15m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| 1stdev | 178,80 | 5,56 | 561,02 | 0,87 | 886,93 | 917,32 | 2274,17 | 2260,50 |
| 1,5stdev | 248,20 | 5,94 | 625,50 | 1,07 | 1335,17 | 1389,00 | 2812,17 | 2825,00 |
| 2stdev | 319,42 | 6,26 | 691,10 | 1,27 | 1790,33 | 1868,50 | 3376,00 | 3421,17 |

| 17m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| 1stdev | 193,72 | 5,68 | 577,42 | 0,91 | 981,98 | 1013,17 | 2420,00 | 2404,67 |
| 1,5stdev | 278,90 | 6,16 | 659,73 | 1,15 | 1480,17 | 1530,67 | 3061,33 | 3069,00 |
| 2stdev | 362,72 | 6,56 | 740,12 | 1,39 | 1980,33 | 2050,83 | 3684,17 | 3723,17 |

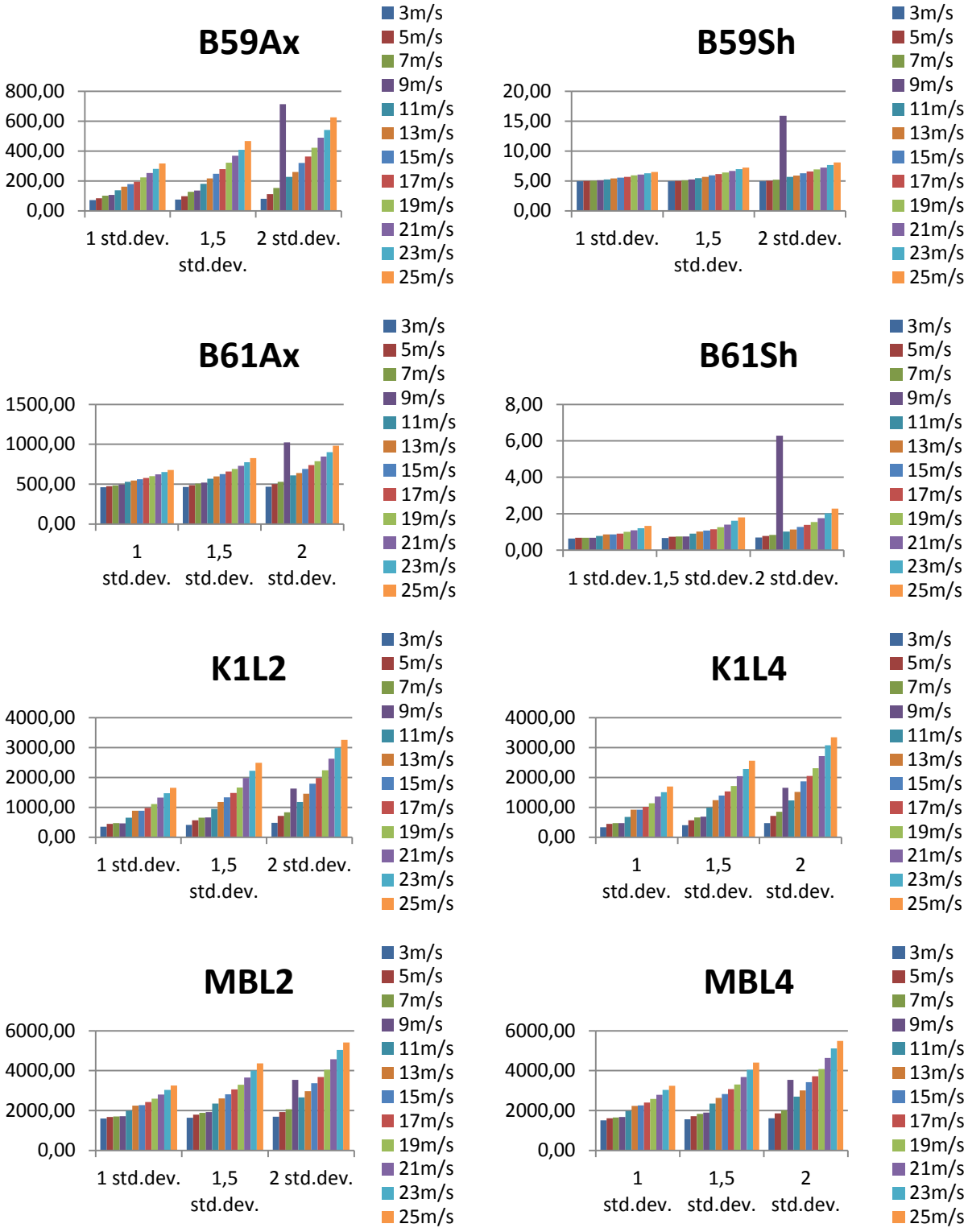
| 19m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| 1stdev | 223,78 | 5,92 | 601,22 | 1,01 | 1106,83 | 1136,83 | 2590,67 | 2577,00 |
| 1,5stdev | 321,08 | 6,40 | 689,62 | 1,27 | 1663,33 | 1714,67 | 3288,00 | 3302,67 |
| 2stdev | 422,50 | 6,91 | 786,08 | 1,55 | 2233,67 | 2303,50 | 4042,00 | 4086,17 |

| 21m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| 1stdev | 252,18 | 6,06 | 623,93 | 1,09 | 1320,50 | 1359,33 | 2795,33 | 2782,33 |
| 1,5stdev | 368,40 | 6,67 | 730,38 | 1,41 | 1981,50 | 2042,83 | 3659,50 | 3685,17 |
| 2stdev | 488,53 | 7,23 | 844,88 | 1,76 | 2629,67 | 2712,50 | 4568,50 | 4631,67 |

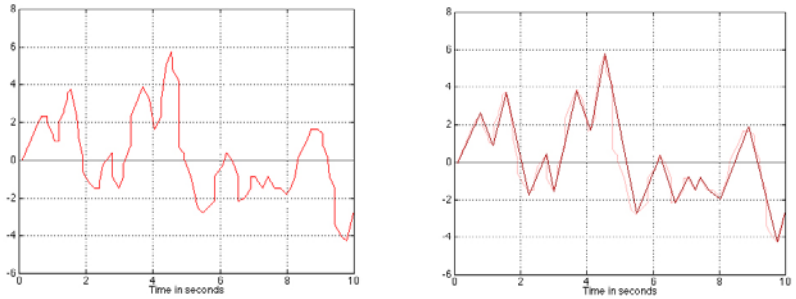
| 23m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| 1stdev | 280,57 | 6,27 | 650,07 | 1,21 | 1473,17 | 1507,33 | 3036,33 | 3030,67 |
| 1,5stdev | 407,05 | 6,97 | 773,13 | 1,61 | 2217,50 | 2277,00 | 4005,17 | 4038,83 |
| 2stdev | 541,07 | 7,67 | 900,15 | 2,02 | 2985,83 | 3074,00 | 5039,83 | 5116,00 |

| 25m/s | B59Ax | B59Sh | B61Ax | B61Sh | K1L2 | K1L4 | MBL2 | MBL4 |
|---|---|---|---|---|---|---|---|---|
| 1stdev | 317,12 | 6,47 | 677,38 | 1,33 | 1655,17 | 1698,50 | 3250,17 | 3243,33 |
| 1,5stdev | 466,37 | 7,24 | 824,93 | 1,79 | 2487,17 | 2554,83 | 4370,67 | 4401,83 |
| 2stdev | 625,52 | 8,09 | 980,87 | 2,29 | 3255,00 | 3345,17 | 5419,83 | 5486,50 |

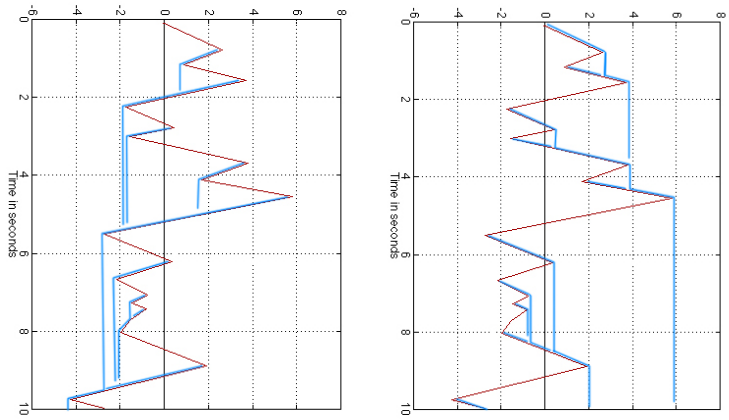
## 7.8 Mlife Results: DEL's versus increasing wind speed graphed



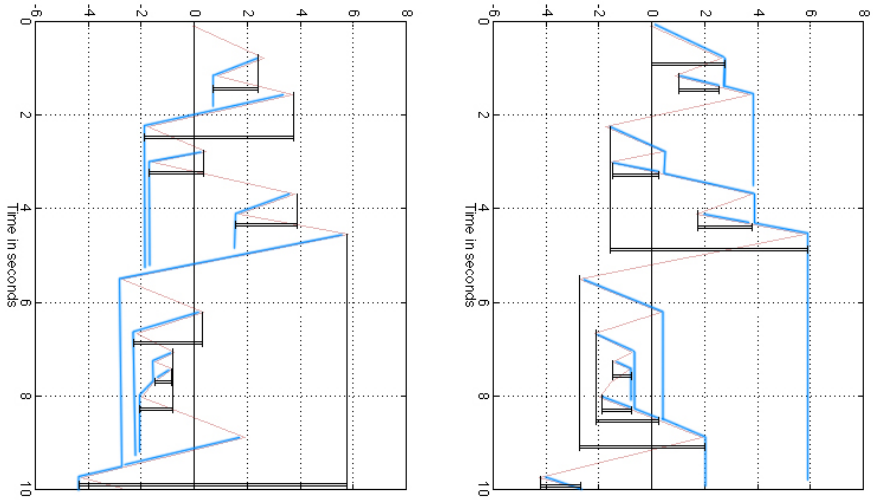
## 7.9 **Rainflow counting illustrated**

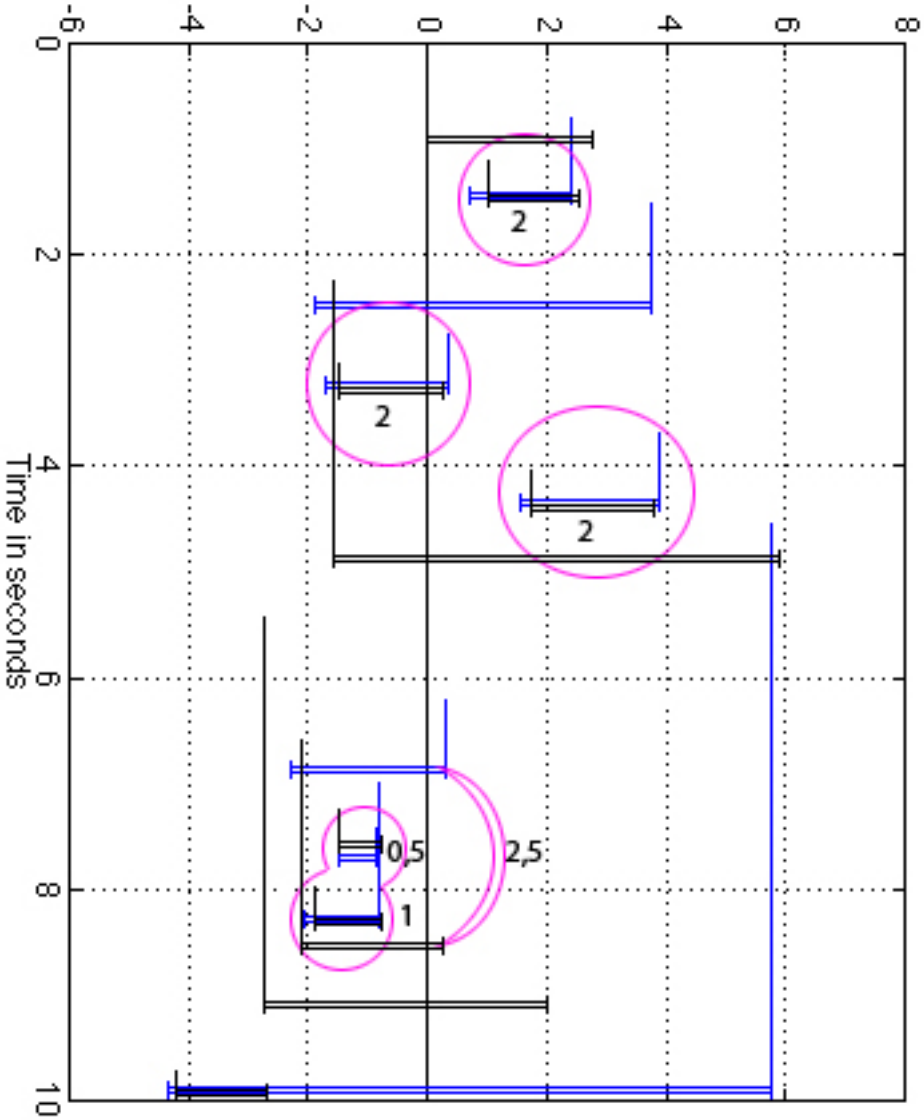



The recorded dataset is optimized by converting to peaks and troughs.




Rainflow analysis is made to categorize half cycles on each side of the pattern.






The halfcycles are paired to create full cycles with amplitude and mean.

## 7.10 **Matlab codes**

The following codes were used in Matlab to help process and generate data:

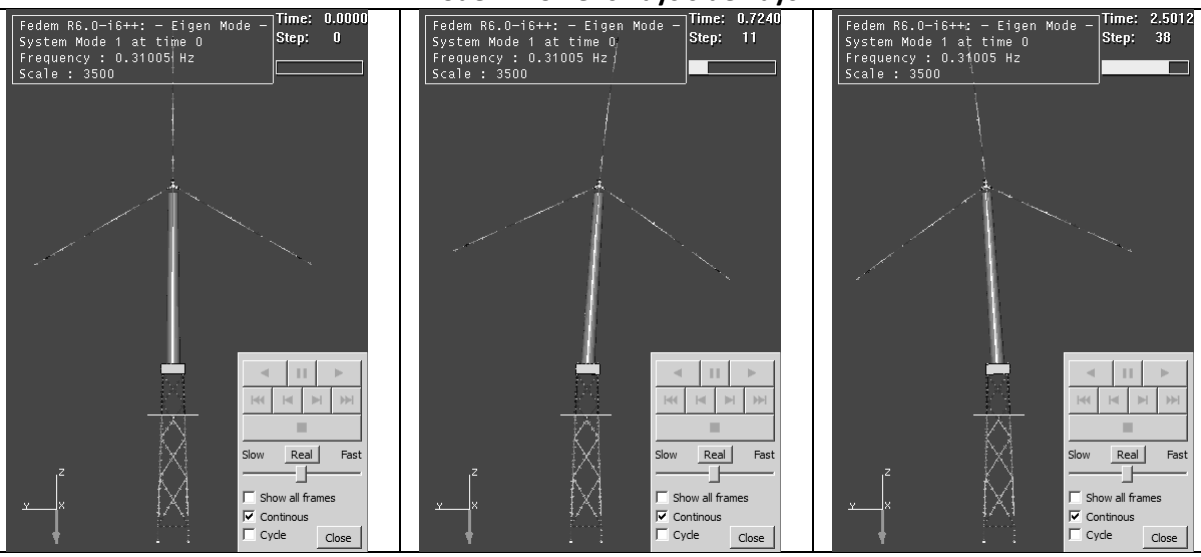
```
%Random generation of numbers:
%This code was made to generate a times b matrices with 6 digit random numbers.
%Numbers with less than 6 digits was manually filled with zeroes.
%The number with 7 digits was never encountered.

a=%number of rows
b=%number of columns
Round(1000000*rand(a,b))
```

```
%Generation of sample dataset:
%This code was made to generate a dataset from a 10Hz wave and a 23Hz wave with noise applied.
%Further it creates the power spectral density graph of the function. The plot have peaks at 10 and 23Hz as
%expected

fs = 100;                       % Sample frequency (Hz)
t = 0:1/fs:10-1/fs;             % 10 sec sample
x = (1.3)*sin(2*pi*10*t)+3*sin(2*pi*23*t)+(2.5)*rand(size(t));% one 10Hz and one 23Hz
m = length(x);                  % Window length
n = pow2(nextpow2(m));          % Transform length
y = fft(x,n);                   % Discrete Fourier Transformation
f = (0:n-1)*(fs/n);             % Frequency range
power = y.*conj(y)/n;           % Power of the DFT
```

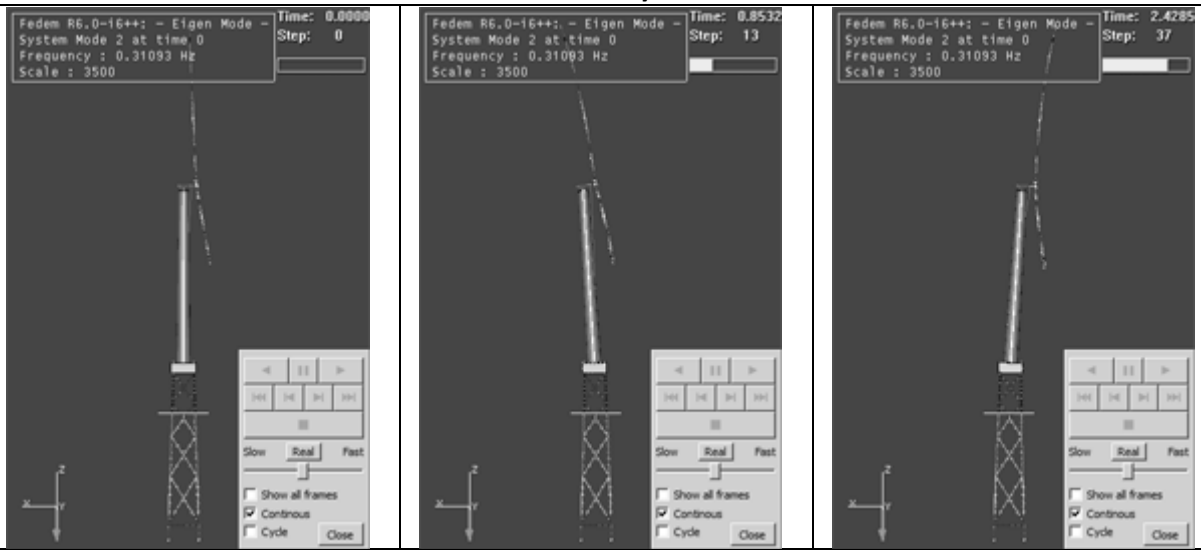
```
% Spectra for vindsimuleringer gjort i turbsim.   Written by Ph.D. Student Lene Eliassen
% ------------------------------------------
clc; clear all
%
% loading the FEDEM exported result file;
 A = importdata('9T1.rsp','\t',7);
 colN=2;                % column containing wind speed
 windX=A.data(:,colN);
 L=length(windX);
 dt=A.data(2,1)-A.data(1,1);
 t=A.data(:,1);
 % computing power spectral density
 fs=1/dt;                   % sampling ferquency in Hz
 fN=fs/2;                   % Nyquist frequency
 noFFT = 2^nextpow2(L);     % Next power of 2 from length of y
 df=fN/(2*noFFT);
 f=0:df:df*noFFT;
 % using the matlab function spectrum
 P1=1/fN*spectrum(windX,noFFT*2);
 subplot(212)
 plot(f,P1(:,1))
 axis([0 1 0 max(P1(:,1))+5])
 varSpec=sum(P1(:,1))*df
 y=windX-mean(windX);
 U_nav=mean(windX);
 %% Kaimal - onesided nondimensional spectra
 L1k=170.1*2;
 specKaimal=(4*f.*L1k/U_nav)./(1+6*f.*L1k/U_nav).^(5/3);
 %% FFT
 Y=fft(y,noFFT*2);
%  FY=abs(Fft).^2;
 Pyy=Y.*conj(Y)/((noFFT*2)*2);
 Sft=Pyy(1:noFFT+1);
%  Sft=1/(noFFT*2)*FY(1:noFFT/2+1);
 'variance from FFT='
 varP=sum(Sft)*df
 figure(2)
%  plot(f2,Sft)
 semilogx(f,Sft)
 axis([min(f) 0.5 0 max(Sft)])
 xlabel('Frequency [Hz]')
 ylabel('Wind Power Spectrum')

 Ti=round(std(windX)/U_nav*100*100)/100
 figure(3)
%  semilogx(f,f'.*Sft(1:noFFT+1)/varP)
 semilogx(f,f'.*Sft(1:noFFT+1)/varP,f,specKaimal)
%  semilogx(f2,f2'.*Pyy(1:noFFT+1)/varP,f2,specKaimal)
 xlabel('Frequency [Hz]')
 ylabel('Normalized Spectra [f*S_k/\sigma^2_k]')
 axis([min(f) max(f) 0 1.4])
%  axis([min(f) max(f) 0 max(f'.*Sft(1:noFFT+1)/varP)+0.1])
%   legend(['Simulated wind,  TI=' num2str(Ti) '%'])
 legend(['Simulated wind, \sigma^2=' num2str(round(var(y)*100)/100)...
     ' (m/s)^2   TI=' num2str(Ti) '%'])
 %,['Kaimal, L_k=' num2str(L1k) ' m'])
 title('Normalized Spectra')
```

## 7.11 **Vibration modes printed from Fedem**

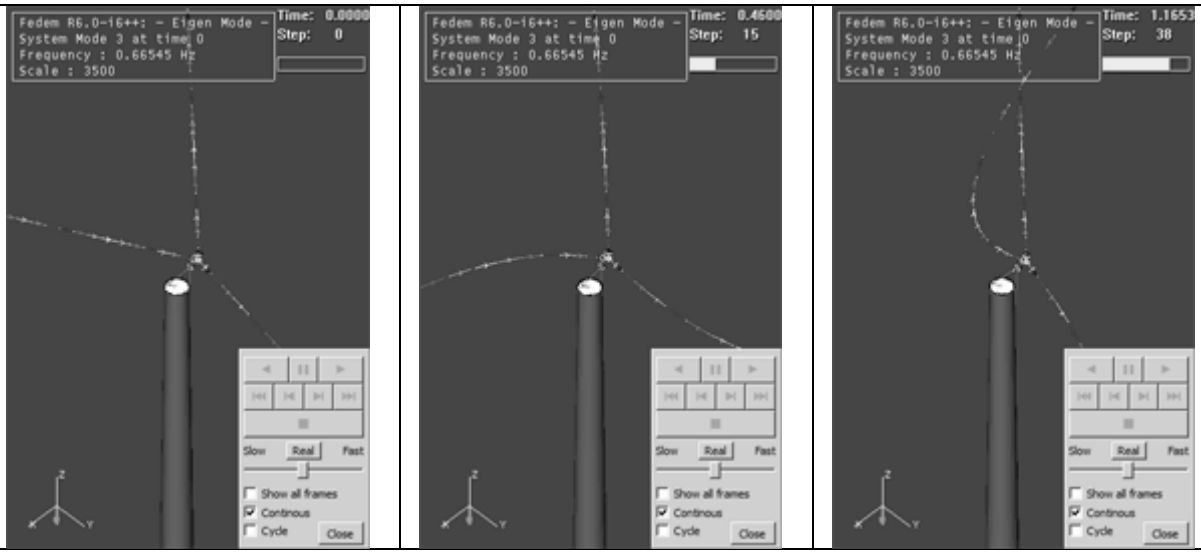
**Mode 1: Tower sways sideways**



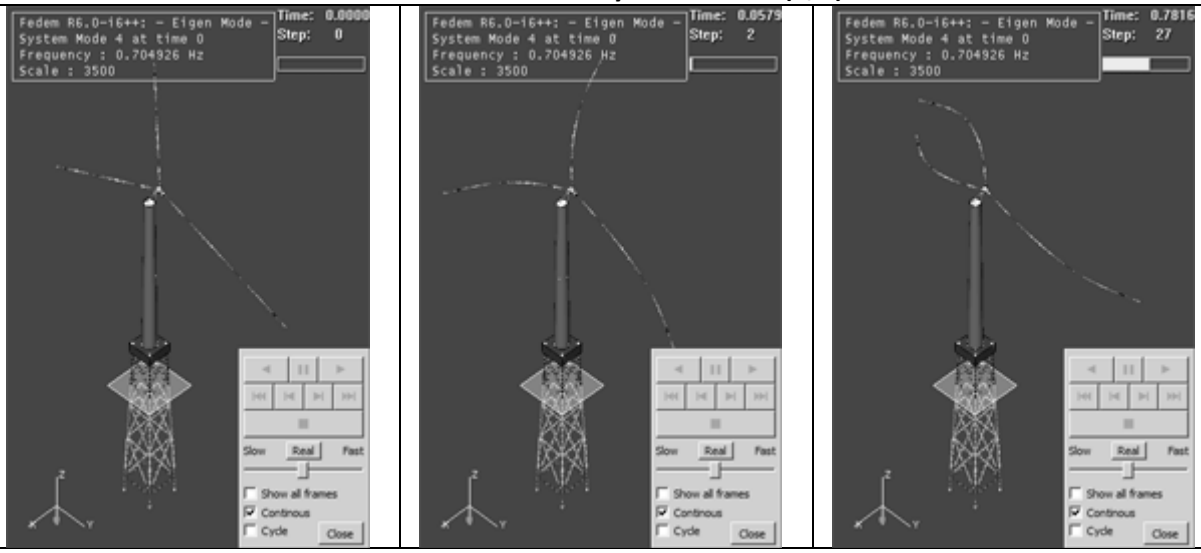

**Mode 2: Tower sways fore and aft**



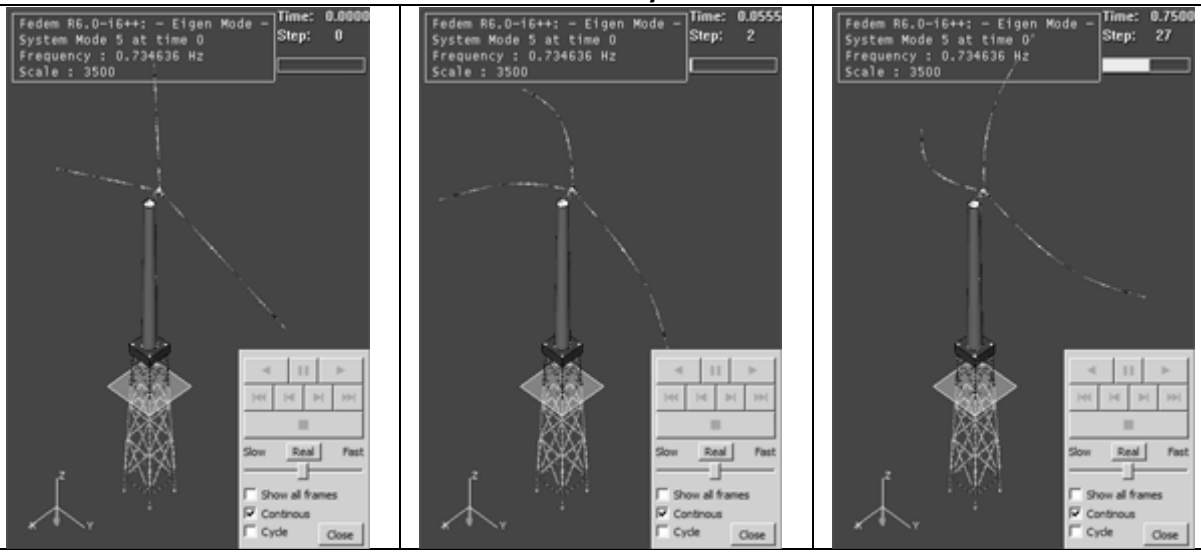

**Mode 3: Tower twists**



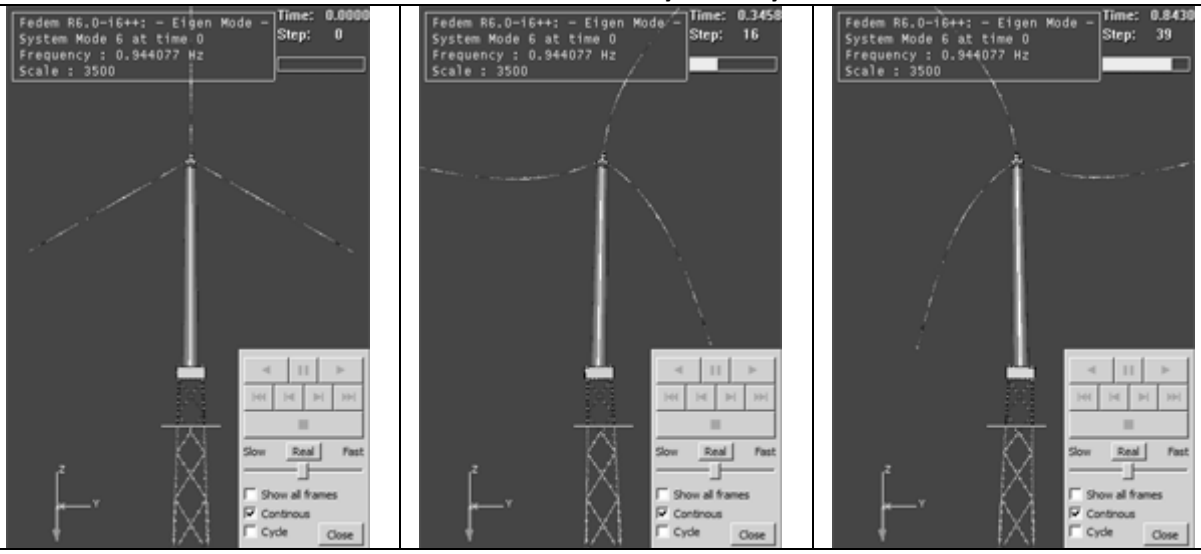
**Mode 4: Blades sway fore and aft (2/1)**



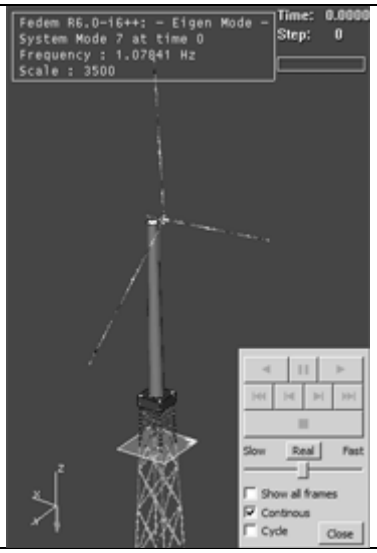

**Mode 5: Blades sway fore and aft**

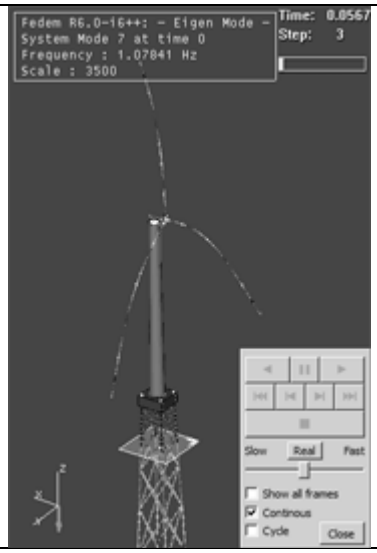


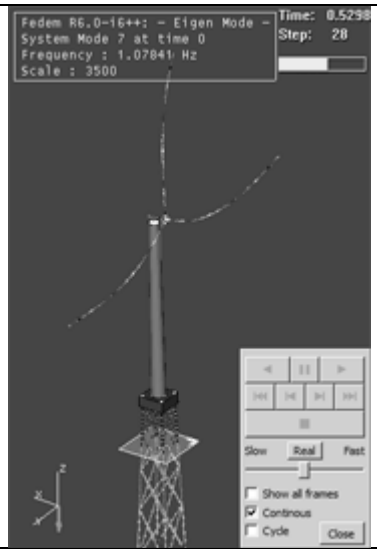

**Mode 6: Blades sway sideways**



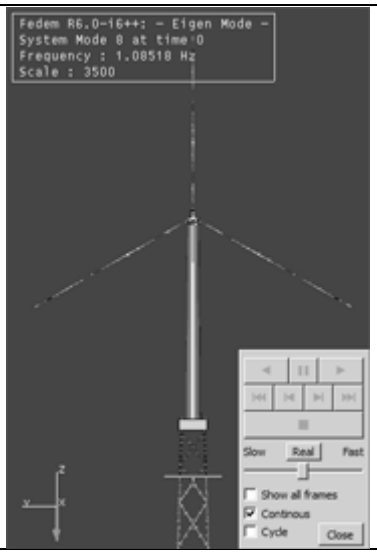
**Mode 7: Blades**

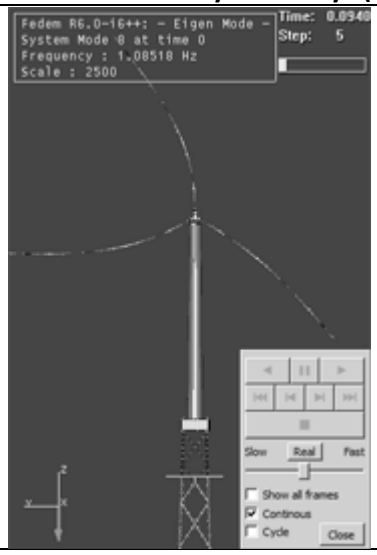


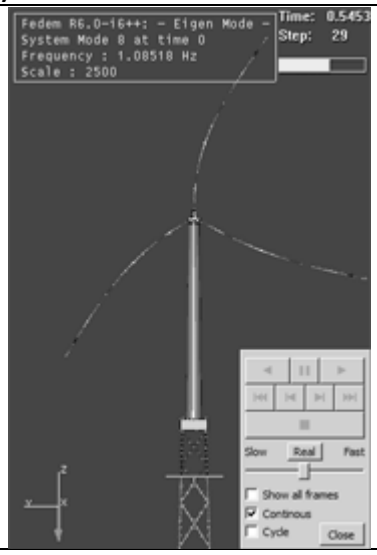



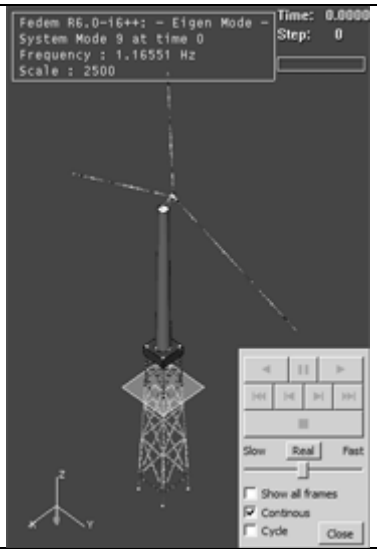

**Mode 8: Blades sways sideways (2/1)**

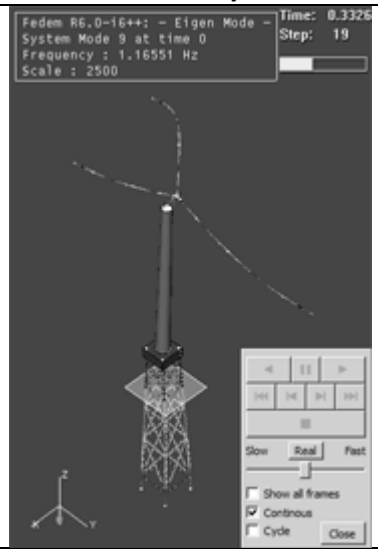


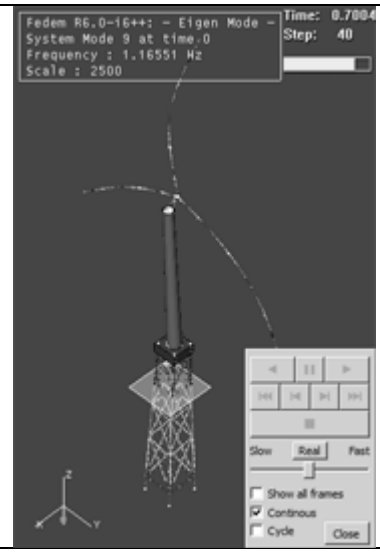



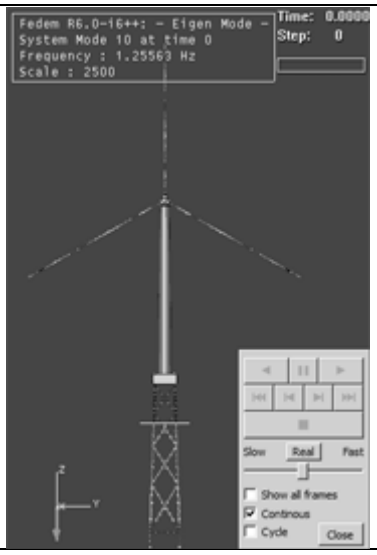
**Mode 9: Jacket sways fore and aft**

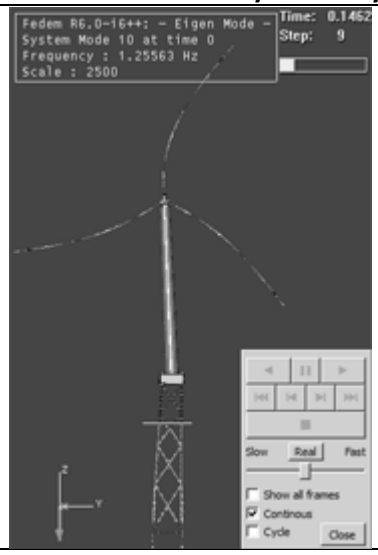


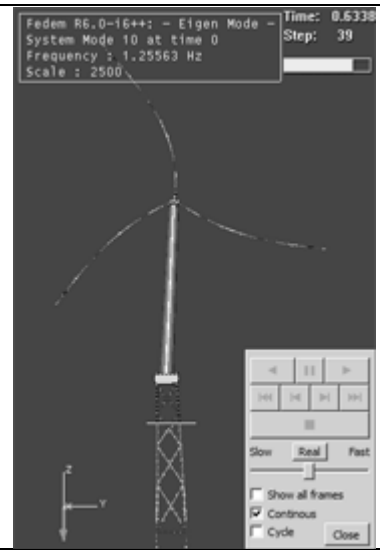




**Mode 10: Jacket sways sideways**

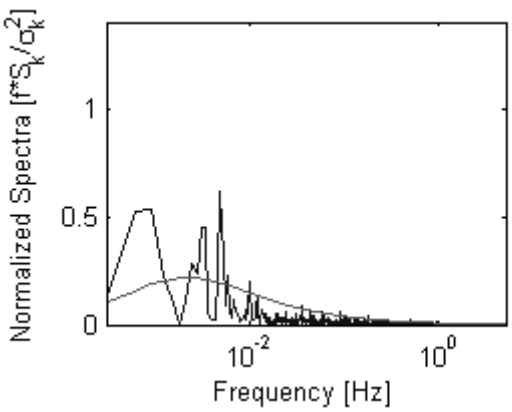
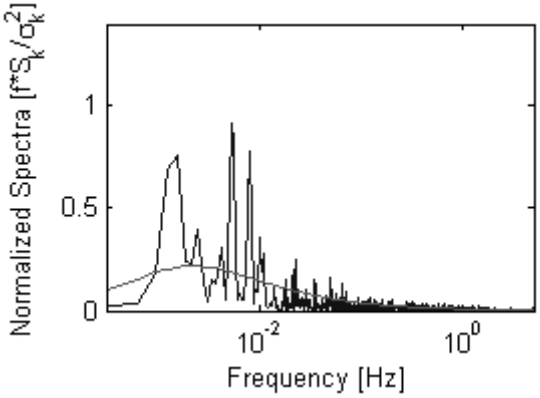
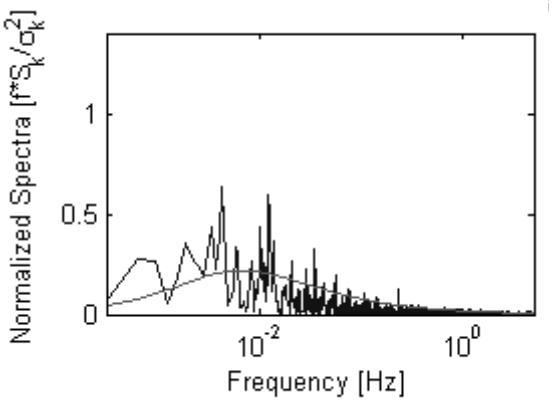
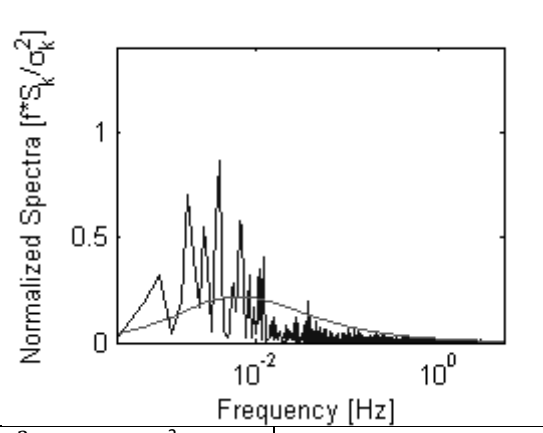
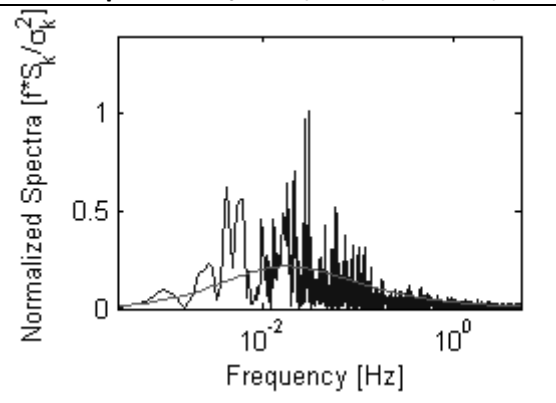
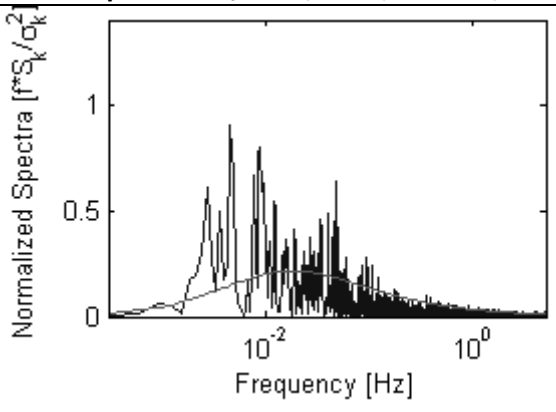


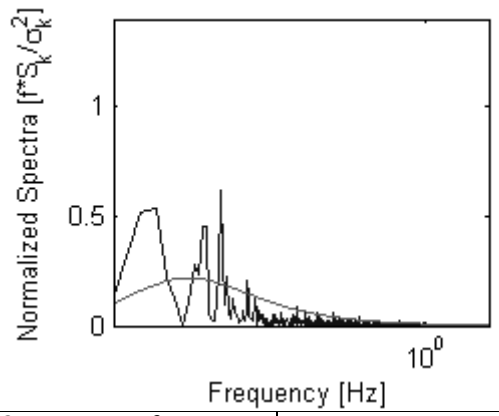
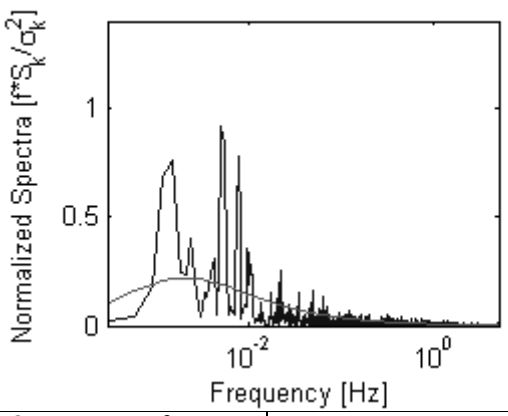
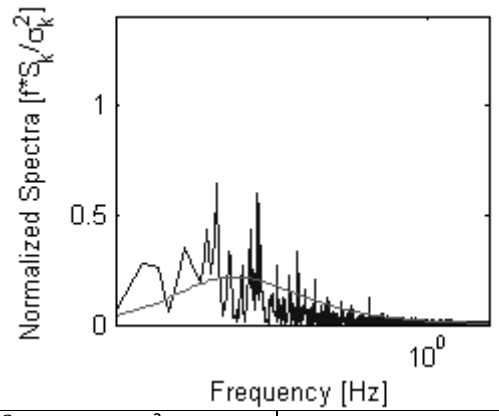
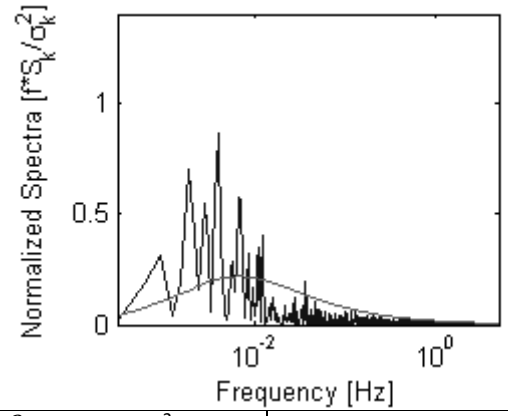
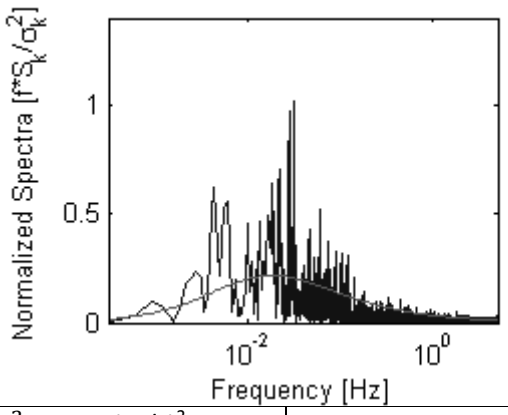
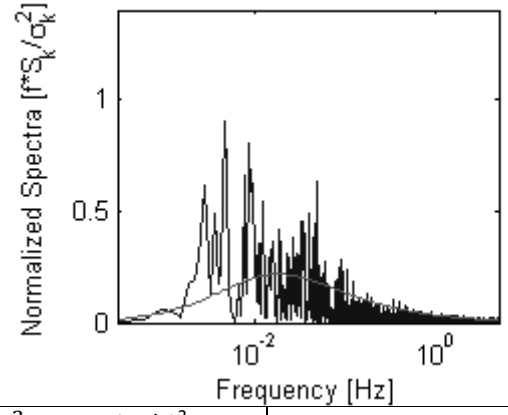



## 7.12 **Power spectral densities calculated by MatLab**

Power versus frequency (Hz). The green curve is the Kaimal spectrum. Notice how TurbSim generated wind gains lower values. The bold text resembles the input parameters. The information underneath represents the actual values calculated from the time series.

| **TurbSim param: $U_{10}$=3m/s σ=0,28 TI=9,3%** | | **TurbSim param: $U_{10}$=3m/s σ=0,28 TI=9,3%** | |
|---|---|---|---|
|  | |  | |
| $\sigma^2$=0,06 (m/s)$^2$ | TI=8,5% | $\sigma^2$=0,03 (m/s)$^2$ | TI=5,78% |
| **TurbSim param: $U_{10}$=9m/s σ=0,91 TI=10,15%** | | **TurbSim param: $U_{10}$=9m/s σ=0,91 TI=10,15%** | |
|  | |  | |
| $\sigma^2$=0,54 (m/s)$^2$ | TI=8,1% | $\sigma^2$=0,79 (m/s)$^2$ | TI=9,74% |
| **TurbSim param: $U_{10}$=25m/s σ=0,91 TI=11,2%** | | **TurbSim param: $U_{10}$=25m/s σ=0,91 TI=11,2%** | |
|  | |  | |
| $\sigma^2$=3,58 (m/s)$^2$ | TI=8,85% | $\sigma^2$=3,91 (m/s)$^2$ | TI=9,37% |

Power versus frequency (Hz). The green curve is the Kaimal spectrum. Notice how turbsim generated wind gains lower values. The bold text resembles the input parameters. The information underneath represents the actual values calculated from the time series.

| **TurbSim param: $U_{10}$=3m/s σ=0,56 TI=18,61%** | | **TurbSim param: $U_{10}$=3m/s σ=0,56 TI=18,61%** | |
|---|---|---|---|
|  | |  | |
| $\sigma^2$=0,25 (m/s)$^2$ | TI=17,23% | $\sigma^2$=0,12 (m/s)$^2$ | TI=11,74% |
| **TurbSim param: $U_{10}$=9m/s σ=1,83 TI=20,30%** | | **TurbSim param: $U_{10}$=9m/s σ=1,83 TI=20,30%** | |
|  | |  | |
| $\sigma^2$=2,18 (m/s)$^2$ | TI=16,01% | $\sigma^2$=3,15 (m/s)$^2$ | TI=19,26% |
| **TurbSim param: $U_{10}$=25m/s σ=5,61 TI=22,44%** | | **TurbSim param: $U_{10}$=25m/s σ=5,61 TI=22,44%** | |
|  | |  | |
| $\sigma^2$=18,93 (m/s)$^2$ | TI=17,6% | $\sigma^2$=23,92 (m/s)$^2$ | TI=19,39% |