Frequency domain calculation of offshore wind turbine response to wind and wave loads

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1. INTRODUCTION

The design of offshore wind turbine support structures at present very much resembles the installation method: the offshore contractor is responsible for the lower end; the turbine manufacturer supplies tower and turbine. The fact that the structure will behave as an integrated dynamic system is only covered superficially through crude combinations of simultaneous wind and wave responses. This separation in design has been instigated because of the following:

- onshore, turbine and tower are the design responsibility of turbine manufacturers, the foundation does not add design loads
- offshore structure design and design responsibility is preferably left to expert offshore contractors
- offshore contractors usually do not have expert turbine design programs or personnel qualified to use it
- turbine manufacturers are reluctant to share detailed information of their turbine and control system to improve the modelling capabilities for support structure design.

In offshore oil and gas, design of structures for fatigue loading is usually done in the frequency domain. Although the loads are not entirely linear, linearized models give sufficiently accurate results. For offshore wind turbines, current design practice prescribes time domain simulations with complete turbine dynamics and control and simultaneous wind and wave loading. But, as described above, these complete models are not always available. Furthermore, time domain simulations are still time consuming, especially when several support structure options are to be compared or when the support structure is to be optimised for every single location in the wind farm.

This paper describes a frequency domain approach for the fatigue load calculations of offshore wind turbine support structures. The method divides the offshore wind turbine in a turbine, clamped at hub height with no support structure dynamics and a support structure. The method enables easy, non-commercial data transfer between turbine manufacturer and offshore contractor and enables the offshore contractor to optimise the support structure in a quick and controllable manner without loss of detail.
The main steps of the frequency domain method are described in chapter 2. A comparison with traditional time domain fatigue is also given. In chapter 3, the steps are applied to a model of the Blyth turbines. The method is further applied to the more fatigue prone location off the Dutch coast of Egmond on a NEG-Micon NM92 turbine. The lifetime fatigue is calculated in both the time and the frequency domain. Chapter 5 gives the conclusions and an outlook.

2. SETUP OF THE FREQUENCY DOMAIN METHOD

As mentioned in the introduction, the analysis of wave loads in the frequency domain is already common practice. The focus of this chapter will therefore be primarily on analysing the wind load on the turbine.
The steps required to come to a fatigue calculation are depicted in Figure 2.1. In the time domain, on the left hand side, the wind characteristics are used as input to create a three-dimensional turbulent wind field. This field is then "shoved" through the rotor disk in a time domain model of the turbine. The program incorporates all specific details: wind shear, tip corrections, wake influence, tower shadow, etc. The program produces time series of bending moments and other response characteristics for different stations along the support structure.
To calculate fatigue damage at a specific location, the stress time series is post-processed. First, the bending moment is converted to bending stress, then the stress is rainflow counted (RFC) to find the stress range

variation histogram. With the proper *S-N* curve for the detail under consideration, the Miner sum gives the fatigue damage value D_{miner}.
The goal of the frequency domain method is to be able to optimise the design of the support structure. This requires complete separation between turbine and support structure in the calculation method. Figure 2.1 shows the separate calculation of the turbine loads in step 1 and the derivation of the transfer function between tower top load and support structure bending stress in step 3.
Previous studies have demonstrated the effect of the operating turbine on support structure dynamics. The rotor introduces aerodynamic damping, which should be taken into account in the further analysis of the structure, step 2.
Steps 1 to 3 result in a transfer function per wind class for turbulent wind field to support structure bending stress at any desired location along the structure. By multiplying the square of this transfer function with the input turbulent wind spectrum, the stress response spectrum can be found.
In a separate process, the stress response to the wave loading is determined, step 4. By linearly summing the ordinates per frequency of wind and wave induced stress response, the total response is found. This response spectrum can then be used to determine the stress cycles and find the fatigue damage in step 5.

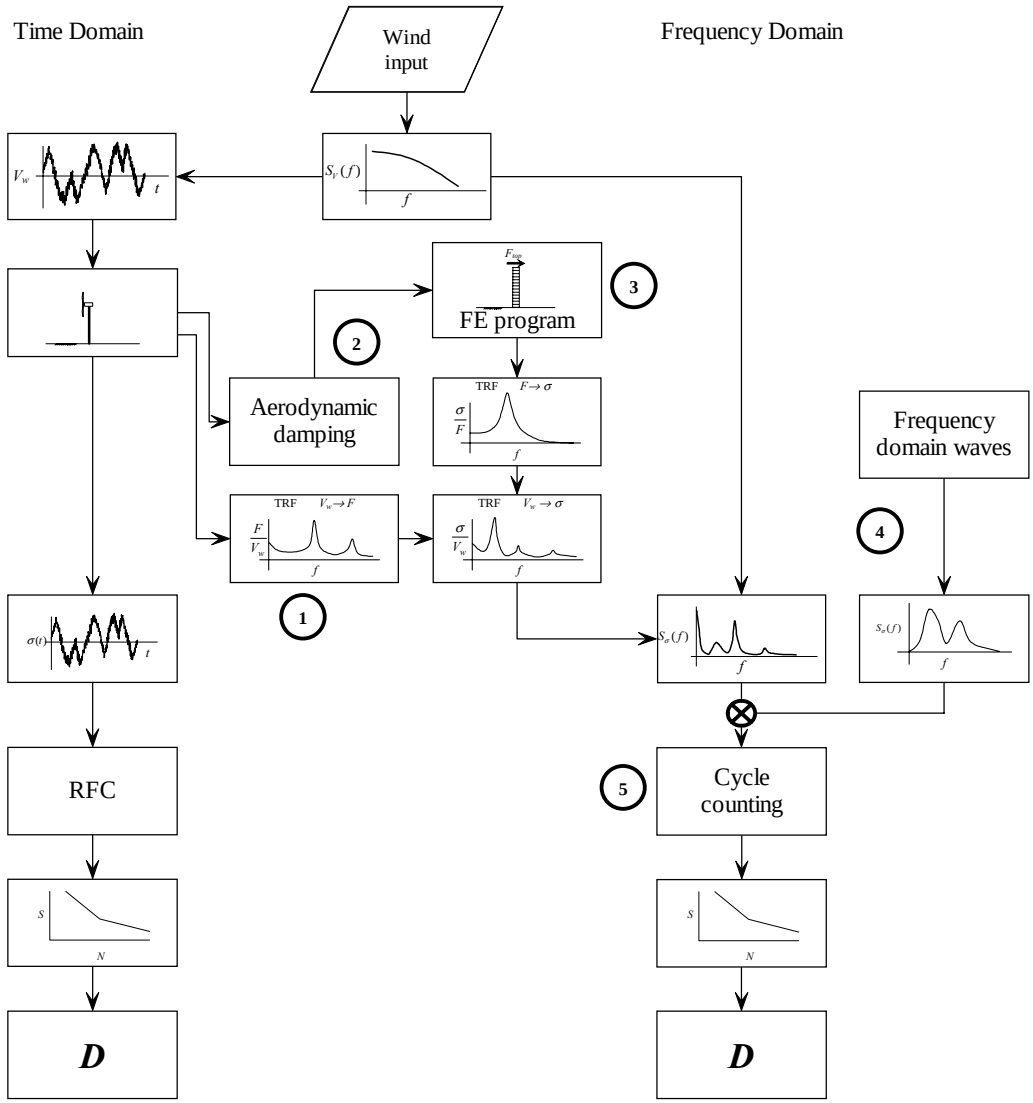

Figure 2.1 Fatigue calculation in time domain (left) and frequency domain (right)

Step 1: tower top loading

The non-linear behaviour of the wind turbine in different wind conditions cannot easily be linearized in an overall and direct manner. Some form of time domain simulation to solve the blade element momentum equations for different wind conditions will usually be required. This approach is used here in a pragmatic way.

During or preferably before the design of an offshore wind farm, a turbine manufacturer is selected. It can be assumed that the manufacturer has a working computer model of his turbine, capable of performing all typical design calculations prescribed for normal turbine design. To uncouple the turbine calculations from the behaviour of the support structure, the structure can be modelled as a rigid structure.

The computer model can now be used to calculate time series of the tower top load due to specific wind conditions with a mean wind speed, turbulence intensity and wind shear. As output, the tower top load is recorded. When the time series of both the input wind field time trace and the tower top load are converted to a spectrum, the transfer function can be derived by dividing both spectra and taking the square root as shown in equation 1:

$$TRF = \sqrt{\frac{S_{F_{top}}(f)}{S_{Kármán}(f)}} \qquad \text{(eq. 1)}$$

Step 2: Aerodynamic damping

For an operating turbine, support structure motion and turbine aerodynamics have a significant effect on each other. When the turbine moves forward (against the wind), the blades experience an increase in total wind speed. As a result of this increased wind speed, the instantaneous tower top load is increased through basic aerodynamic action of the blades. This load is acting against the tower top motion. For backward motion, the situation is analogous, now resulting in a reduced tower top load, also reducing the tower top motion. This effect is known as aerodynamic damping [1] [2]. To separate turbine and support structure calculations in the frequency domain approach, the aerodynamic damping needs to be calculated for each wind speed and must be incorporated through an equivalent viscous damping in the dynamic model of the support structure. To determine the aerodynamic damping, several methods exist. A dedicated paper on aerodynamic damping is also submitted to this conference to cover this topic [3].

Step 3: Dynamic behaviour of the support structure

In step 3, the dimensions of the support structure are processed in a finite element model (FEM). To take the effect of aerodynamic damping into account, the structural damping factor is increased with the value derived in step 2. Solving the equations of motion for one or more specific points along the structure under time varying tower top loads will result in a transfer function between tower top load and bending stress at a specific location.

The total transfer function between the turbulent wind field and bending stress can now be found as the product of the derived transfer functions from steps 1 and 3. By multiplying the input wind spectrum with the combined transfer function squared, we find the total bending stress spectrum for the location under consideration.

The different steps to find the wind induced stress response in the frequency domain are shown in Figure 2.2.

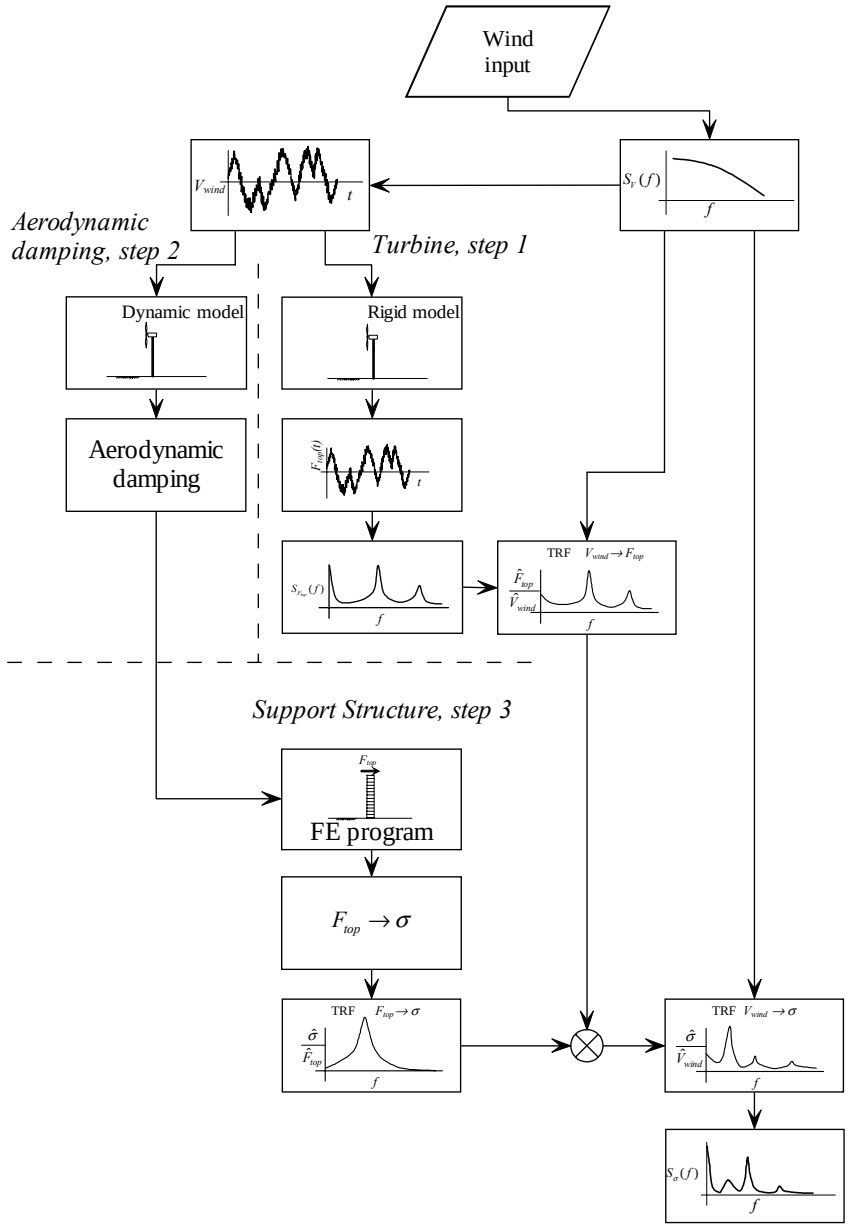

Figure 2.2 Flowchart for frequency domain calculation of the stress spectrum due to wind loading

Step 4: Incorporating stress response due to wave excitation

The previous section presented a method to derive the response spectrum for bending stress in the support structure due to wind loads on the rotor. For the design of offshore oil & gas structures it is common practice to use a frequency domain method for response calculations due to wave excitation. If the responses due to wind and wave response are assumed to be fully independent, the combined response can be determined by adding the respective response spectra. The effectiveness of this method was already shown in [4]. The only interaction between the wind turbine and the response of the support structure due to wave excitation is the aerodynamic damping. The flowchart in Figure 2.3 shows the steps to combine the stress response spectra due to wind and wave loading to obtain the spectrum of the total stress response.

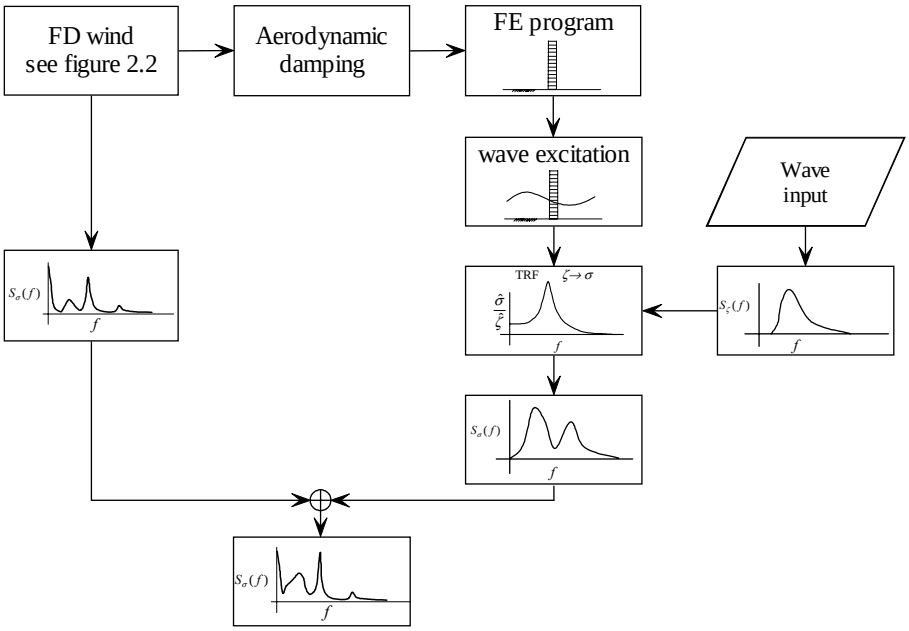

Figure 2.3 Flowchart for adding stress spectra due to wind and wave loading

Step 5: Fatigue damage calculation via spectra of the total stress response
The method presented in the previous sections will provide a response spectrum for the total stress due to wind and wave loading. The final step is to process this spectrum to obtain the cumulative fatigue damage D_{Miner}. Several solutions exist to derive the stress range distribution from the spectral moments of a stress spectrum. The Dirlik method is used here, which is an empirical method based on four moments of the spectrum. This method has been found to give results that compare best with time domain rainflow counting [5].

3. APPLYING THE FREQUENCY DOMAIN METHOD TO THE BLYTH TURBINES

To test the proposed method, an accurate model of an offshore wind turbine is needed. Within the OWTES project [6], a detailed model was created of the Vestas V66 turbines, which were installed in 1999 off the coast of Blyth, UK. The measurement and validation project assured that the model of the turbine is highly accurate compared with reality. The turbine is modelled in the time domain program *Bladed for Windows*.
To create transfer functions of the support structure, the offshore design program *SESAM* was used. Next to standard finite element modelling, this package incorporates all hydrodynamic modelling features required for offshore structure design.
For all simulations, the wind climate defined by Germanischer Lloyd was used [7]. GL prescribes a fixed turbulence intensity of 12% for all wind speed classes. Although higher turbulence intensity at lower wind speeds, as prescribed by other standards represents nature better, for the validation of the frequency domain method a fixed turbulence intensity is convenient and sufficient. For the wind shear the same standard was used, giving a shear factor $\alpha = 0.12$. This is again used for all wind speeds. Waves and currents are not included in these wind simulations.

Step 1: Transfer function for fluctuating wind speed to tower top load
First, a 3D turbulence field is created based on an improved Von Kármán spectrum for a mean wind speed of 10 m/s and a turbulence intensity of 12% in longitudinal direction. Then a simulation is carried out for the offshore wind turbine model at Blyth. The modal analysis of the support structure is set not to incorporate any modes, which effectively eliminates support structure dynamics. The blade modes are still active.
After the simulation, a spectrum estimate is determined for the wind speed at the hub. This results in the spectrum shown in Figure 3.1, when plotted on log-linear scale.

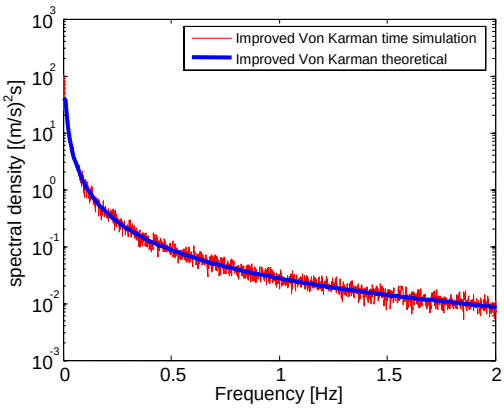

Figure 3.1 Wind spectrum, mean = 10 m/s, TI = 12%

For the resulting tower top load, the response spectrum is obtained by processing the time domain simulation of the axial load on the rotor axis to a spectrum using the same spectral settings; the result is presented in Figure 3.2. The effects of rotational sampling at 3P, 6P and 9P are clearly visible.

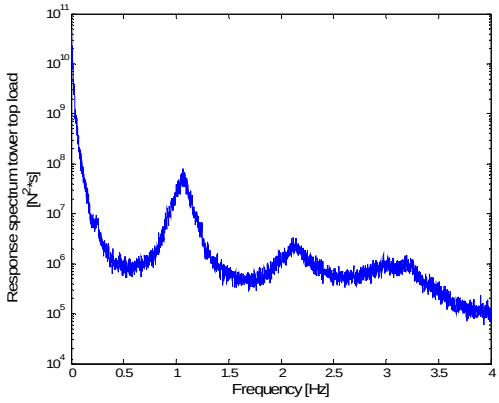

Figure 3.2 Response spectrum for tower top load

Now, the transfer function can be determined by taking the square root of the response spectrum divided by the wind spectrum at each frequency. Because the spectral estimates have been created with equal settings, the frequency intervals are the same, making the calculation of the transfer function very straightforward.

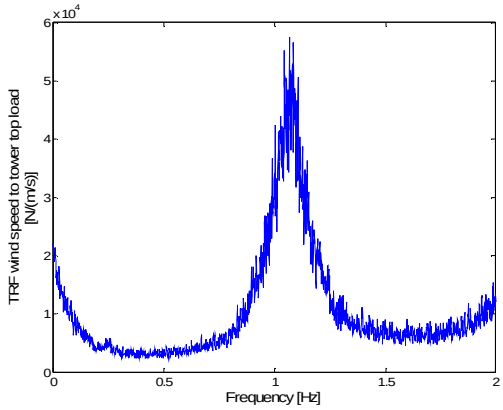

Figure 3.3 Transfer function between wind speed and tower top load

The mean rotor speed in this simulation is 21 RPM = 0.35 Hz. The 1P peak cannot be distinguished, the 3P speed at 1.05 Hz is clearly visible. It has to be noted that the 1st blade flapping frequency also lies in this range, which is, based on the "Campbell-diagram" approach, not entirely an ideal situation.

Step 2: Incorporating aerodynamic damping
The critical step in the frequency domain method is to incorporate the only interaction between turbine operation and structural dynamics: aerodynamic damping. To determine its magnitude, several options are available, which are detailed in [3]. For this paper, a damping of 4% of the critical damping is used for all wind speed ranges. Although this is not the most accurate figure, it approaches reality sufficiently for the frequency domain method to be demonstrated.

Step 3: Modelling the support structure
The finite element program SESAM was used to derive the transfer function for tower top load to mudline bending stress. A model of the offshore wind turbine was made and the natural frequency in SESAM was found to compare very well with the measured natural frequency and the natural frequency as modelled in Bladed. The structural damping was set to 1% and 1 + 4 = 5% of the critical damping, with and without aerodynamic damping, respectively. Then a sinusoidal tower top load was applied of 1000 N. This load was applied with increasing frequency from 0.01 Hz to 2 Hz in steps of 0.001 Hz, which resulted in the transfer functions shown in Figure 3.4. The effect of incorporating the aerodynamic damping is clearly very large.

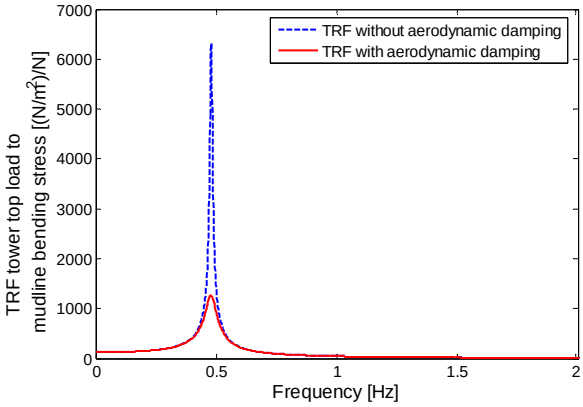

Figure 3.4 Transfer function of mudline bending stress per unit tower top load as function of frequency with only structural damping (1%) and 4% additional aerodynamic damping

By combining the transfer functions of Figure 3.3 and Figure 3.4, the combined transfer function as shown in Figure 3.5 is derived.

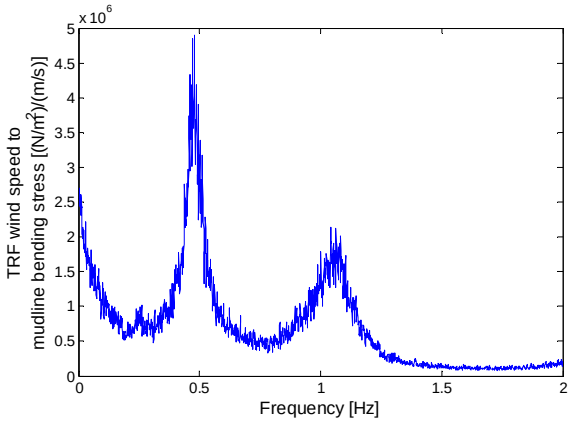

Figure 3.5 Combined transfer function of mudline bending stress per unit wind speed as function of frequency, including aerodynamic damping

By multiplying the combined transfer function squared with the input wind spectrum, we can determine the response spectrum for bending stress at the mudline, as shown in Figure 3.6. In the time domain, the time series of the mudline bending stress for the same conditions can be found by using a full dynamic model of

the offshore wind turbine (turbine and support structure). The resulting time series of the varying bending stress can next be transformed to a spectrum through Fast Fourier Transform (FFT). This spectrum is also shown in Figure 3.6.

Figure 3.6 shows that the results match very well. The shapes are identical and only the peak at 1 Hz, which corresponds with both the 3P-blade passing frequency and the first blade flap frequency, is slightly lower when calculated in the frequency domain. Apparently the overlapping of these frequencies influences the support structure when all dynamics are modelled in the time domain.

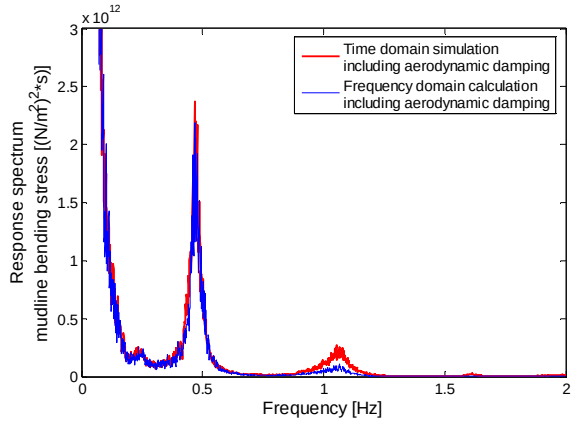

Figure 3.6 Mudline bending stress response spectra for frequency and time domain calculations

Step 4: Adding waves

Now that the stress response spectrum for turbulent wind has been found, the stress response spectrum for wave loading can be determined. Based on the assumption that wind and waves are completely independent (except for the aerodynamic damping) the wave response is calculated in the frequency domain program *SESAM*. Figure 3.7 shows the input wave spectrum with H_s = 1.75 m and T_z = 6 s and the resulting response spectrum for mudline bending stress. As no wave energy is present at the natural frequency at 0.48 Hz, only quasi static response is visible in the right-hand side plot.

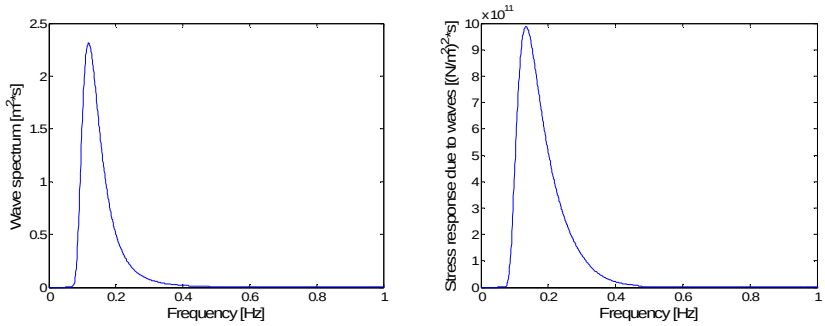

Figure 3.7 Input wave spectrum with H_s = 1.75 m and T_z = 6 s and the resulting response spectrum for mudline bending stress

The combined stress response spectrum can now be found by combining the wind and wave response spectra: per frequency step, the spectral ordinates are added to find the combined response as shown in Figure 3.8 where the frequency domain spectrum is compared to the time domain spectrum.

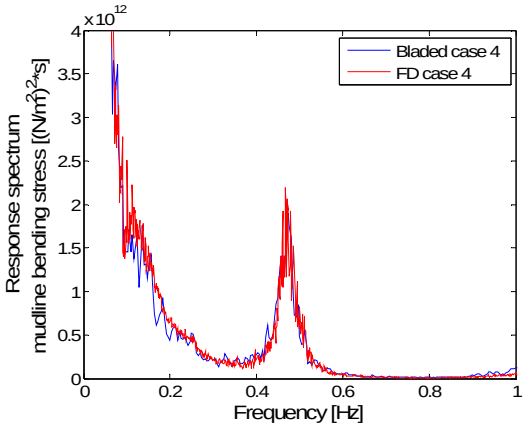

Figure 3.8 Mudline bending stress response spectra for combined wind and wave loading compared to time domain simulations

The combination created in Figure 3.8 is designated case 4 in table 1. This table is a selection of typical environmental states at Blyth. These 5 states were modelled in both the time and the frequency domain and their resulting mudline bending stress response spectra are plotted in Figure 3.9

Table 1. Selection of 5 typical states for testing the frequency domain method against the time domain method from [8]

case	H_s	T_z	V_w	% of occurence
1	0.25	2.0	5.0	20.47
2	0.25	4.0	11.8	21.76
3	0.75	5.3	5.8	13.25
4	1.75	6.0	9.9	4.83
5	3.3	9.7	18.7	0.14

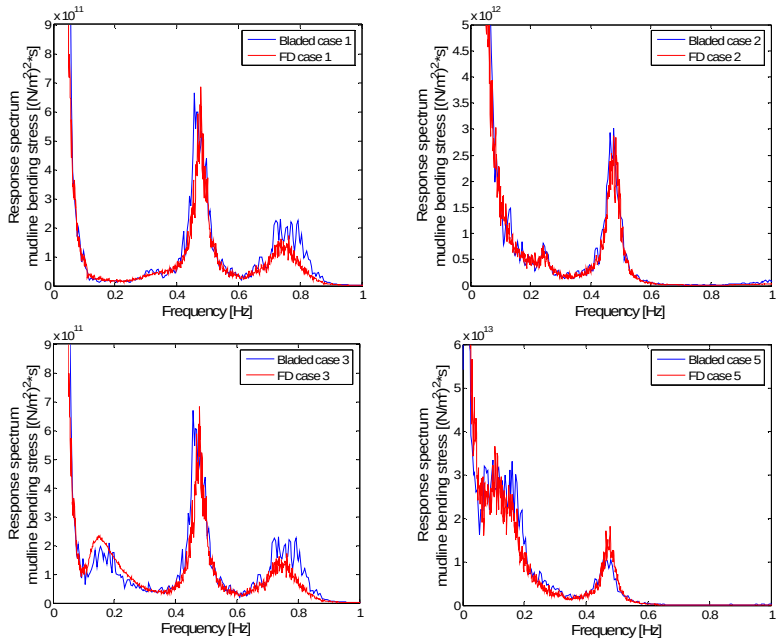

Figure 3.9 Comparison for 4 wind and wave load cases between frequency domain and time domain response spectra for the mudline bending stress

The figures prove that the frequency domain method works, at least when looking at the graphic representation. The aerodynamic damping of 4% is a functional estimate making the resonance peak at 0.48

Hz match between both methods. Furthermore, the superposition of separate wave and wind induced stress results in a realistic combined response spectrum. For Blyth the influence of waves on the bending stress is relatively small. This is of course to be expected as the site is only 6 m deep. Furthermore, the waves do not have any energy in the range of the structure's natural frequency, which means that no significant wave induced resonance is to be expected.

4. LIFETIME FATIGUE ASSESSMENT IN TIME AND FREQUENCY DOMAIN FOR NSW SITE

To assess the effectiveness of the frequency domain method with regard to lifetime fatigue calculations (step 5), another turbine and site were selected where wave induced resonance will make fatigue a critical design issue. In 2006 the Near Shore Windfarm off Egmond in the Netherlands will be constructed. Although for the eventual site the Vestas V90 turbines will be used, previous designs were based on the NEG-Micon NM 92 turbine. Since the merger of both companies though, this model has been discontinued. A model of this turbine in *Bladed* was available for this paper and, as the site coincides with previous studies [1] [9], the site conditions are known to a high degree of detail. The design under consideration has a 2.75 MW turbine, a hub height of 70 m above mean sea level and stands in 20 m of water. Furthermore, an 8 m deep scour hole is anticipated in the design. The structure has a natural frequency of 0.31 Hz, making it susceptible to wave induced resonance.
The wind and wave data for the site comprise 7 full years of hind-cast data. These have been processed to a 3 dimensional scatter diagram where per wind speed interval of 2 m/s for the operational range of the turbine (so 4, 6, 8, .. 24 m/s) a wave scatter diagram for significant wave height (H_s) and zero-crossing period (T_z) was produced. This resulted in 112 environmental states. All wind and waves are assumed to come from only 1 direction. Directionality was neglected for these tests. The 112 states were all simulated for a 1 hour period in the time domain in *Bladed* and directly through the frequency domain method. To find the cycles to perform the Miner sum fatigue damage check in the frequency domain, the Dirlik method was used. At present, the Dirlik method matches the outcome of time domain rainflow counting most precisely and is therefore the best method to be used for this typical comparison. Current developments in this field have seen the arrival of new and improved methods based on more theoretical foundations [10], but for this paper these have not yet been implemented.

The outcome of the time and frequency domain lifetime fatigue checks is presented in table 2. The value given in the Miner sum fatigue damage, which must be less than 1 for the structural detail to satisfy the fatigue limit check. In the frequency domain, two wave transfer functions were created: with and without diffraction correction. As the diameter of the support structure is 4.75 m, small waves with higher frequencies will be influenced by the presence of the structure, causing diffraction. This phenomenon makes the wave load calculation method of Morison less valid. To correct the method, the MacCamy-Fuchs correction factor can be applied in the frequency domain, effectively reducing the inertia coefficient. In the *Bladed* wave modelling module, the correction is simulated by applying a frequency dependent cut-off of the input wave spectrum on which the wave time series is based.

Table 2. Results of lifetime fatigue check in the time and frequency domain, with and without diffraction correction for 112 uni-directional environmental states

	Bladed time domain with diffraction cut-off	Frequency domain without diffraction correction	Frequency domain with diffraction correction
D_{life}	0.56	0.70	0.52

5. CONCLUSIONS AND OUTLOOK

The frequency domain method for calculating the fatigue damage of support structures of offshore wind turbines delivers results which are very comparable to the outcome of time domain simulations, both graphically, when looking at the stress response spectra and in the final outcome of the fatigue check. The method severs the turbine at the yaw bearing and leaves support structure optimisation to the offshore contractor while the turbine manufacturer only needs to provide a set of tower top loading transfer functions to a turbine on a support structure without dynamics. The method enables rapid support structure optimisation. Simple adjustment of the finite element model of the support structure and recreation of

transfer functions are fed into the excel sheet and yield a lifetime fatigue damage within 2 minutes. A further advantage of the frequency domain is the direct graphic visibility of peaks in the input, transfer and output graphs. This makes it very clear which features need to be targeted to optimise the structure even further. For instance, the effect of aerodynamic damping is easily illustrated, an increase will drastically reduce the fatigue damage even further when the input load spectra contain energy in that area.

The functioning of the frequency domain method has only been proven for two structures at present. Research is ongoing to further optimise the method with respect to the more detailed estimation of aerodynamic damping. Further structures and sites will be studied in the near future to prove the general applicability. The method is also able to model other structures than just the monopile. Design studies in this area are ongoing. The execution of the method is currently done in an Excel sheet. This may be altered to make the method more robust for general use. A project to implement the method at the engineering department of a large offshore contractor has recently started.
The current status of the frequency domain method is that it can be used for preliminary design. Further development and standardisation of the different steps may eventually make it suitable for general application as a final design tool, as is already the case with frequency domain fatigue assessment for offshore structures subjected to waves only.

This paper is part of the PhD thesis "Design of support structures for offshore wind turbines" which will be available at the end of 2005 [11].

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