Impact of different substructures on turbine loading and dynamic behaviour for the DOWNVInD Project in 45m water depth

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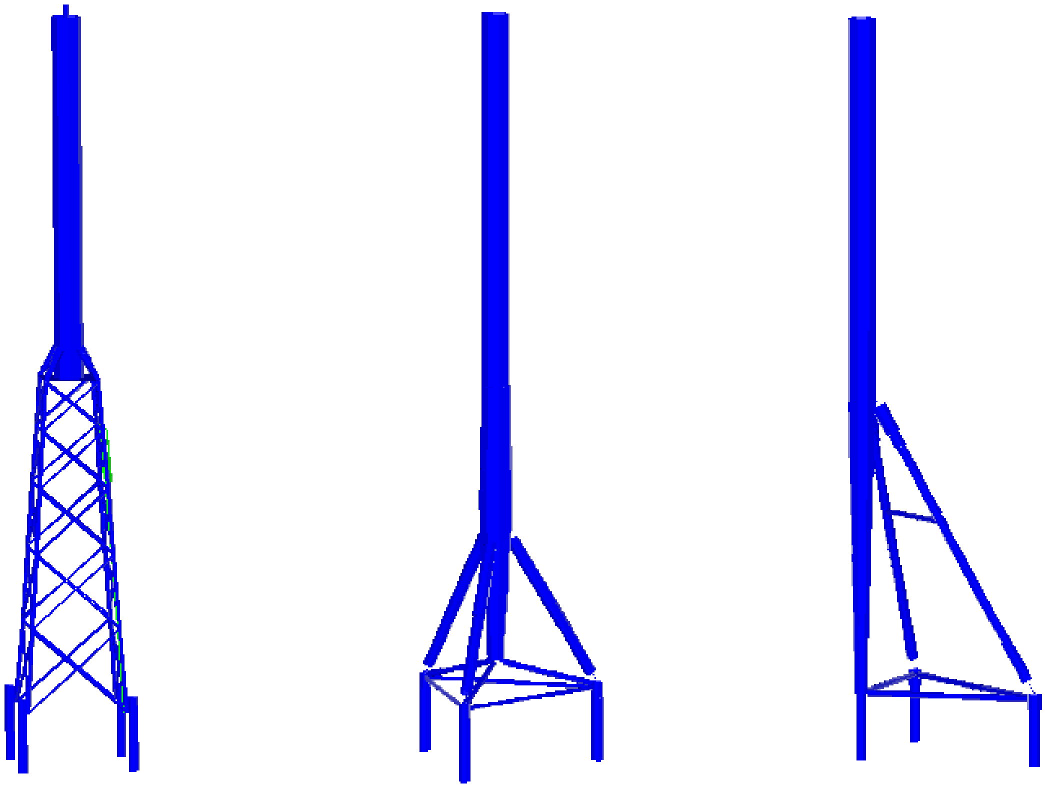
Summary

The DOWNVInD Demonstrator Project in Scotland will be the first Offshore Wind Project with a complex substructure as the water depth of 45m is not suitable for the simple Monopile or Gravity concepts. This paper addresses turbine loading and dynamic behaviour of the REpower 5M turbine when used together with different substructures. Three different concepts have been investigated, two Tripods and one Jacket.

The results show that careful consideration of dynamic behaviour is necessary. Substantial differences for the tower and substructure loads can be found depending on eigenfrequencies, wave loading and structural layout in the wave loaded zone. These influence parameters can only be addressed in an integrated analysis which takes account of turbine, substructure, wind and wave loading. Early involvement of the turbine manufacturer is thus strongly recommended to arrive at the best design possible.

1. Introduction

The DOWNVInD Demonstrator Project (http://www.beatricewind.co.uk) comprises two REpower 5M wind turbines in 45m water depth (design water depth 50m) close to the Beatrice platform 22km offshore in Scotland's Moray Firth. Extensive studies have been initiated by Talisman Energy to determine the best substructure for this demanding project. Based on studies performed by Atkins, Kellog Brown & Root, REpower and OWEC Tower, three substructures were considered for the final selection process: A Center Column Tripod (CCT), a Flat Faced Tripod (FFT) and the OWEC Jacket Quattropod (OJQ), a four-legged jacket solution (Fig. 1). A comprehensive substructure selection process was then conducted by AMEC, Talisman, SSE and REpower and finally the OJQ was selected for the project. This paper focuses on aspects related to the performance of the different substructures with respect to structural loads from wind and waves. Special attention is paid to the overall dynamic behaviour and influence of coupled wind-wave loading which has been assessed with the methodology presented in [1].



OWEC Jacket Quattropod (OJQ)	**Centre Column Tripod (CCT)**	**Flat Face Tripod (FFT)**
f_0 = 0.33Hz (T_0 = 3.0s) f_1 = 1.64Hz	f_0 = 0.26Hz (T_0 = 3.8s) f_1 = 1.35Hz	f_0 = 0.30Hz (T_0 = 3.3s) f_1 = 0.86Hz

Fig. 1: Substructure alternatives for the DOWNVInD Project (with first and second global natural frequencies)

2. Dynamic characteristics with different substructures

2.1. Modal analysis and risk of 3p-excitation

Modal analysis results for the first two global support structure modes are included in Fig. 1. The operating range of the REpower 5M is 8.5rpm (at cut-in wind speed of 4m/s) to 12rpm (from rated wind speed to 30m/s), thus the excitation frequencies are:

- 1p-range: 8.5 – 12.0rpm → f_R = 0.141 Hz – 0.200 Hz
- 3p-range: 3·(8.5 – 12.0rpm) → f_R = 0.425 Hz – 0.600 Hz

The first natural frequency for all variants is thus not close to the excitation frequencies. If this is not the case, then significant dynamic amplification can occur as can be shown by the following simple considerations.

The dynamic amplification factor for a single degree-of-freedom system (SDOF) under harmonic loading is known as:

$$\chi = \frac{1}{\sqrt{\left(1-\left(\frac{f_R}{f_0}\right)^2\right)^2 + \left(\frac{\delta}{\pi}\cdot\frac{f_R}{f_0}\right)^2}}$$

where f_R: Driving frequency
f_0: Eigenfrequency
δ=0.28: Logarithmic damping (0.5% structural damping plus 4% estimated aerodynamic damping)

The 3p-excitation can be very significant as is shown in Fig. 2. A comparison is made in this chart for the tower bottom damage equivalent fatigue loads of the as-designed OJQ with f_0=0.33 Hz and a model where the tower stiffness (Young's modulus) has been increased such that the first natural frequency is at 0.38 Hz and thus only 10% from the 3p-range.

For low wind speeds the DELs increase about 130%. This increase can mainly be attributed to the increase in resonant vibration due to 3p-excitation. The ratio of dynamic amplification factors for a driving frequency of f_R=0.425Hz and eigenfrequencies of f_0=0.33Hz and f_0=0.38Hz is:

$$\frac{\chi_1}{\chi_2} = \frac{3.70}{1.50} = 2.47$$

This approximates to the increase of 130% which can be seen in Fig. 2. The actual increase is somewhat lower as the part of the wind loading on the rotor is not amplified by resonance.

Fatigue loads for higher wind speeds increase about 15% - which corresponds to the increase in eigenfrequency. This is logical as resonant excitation is not important for higher rotational speeds and the fatigue loads solely depend on the stochastic excitation and the admittance of turbine incl. substructure.

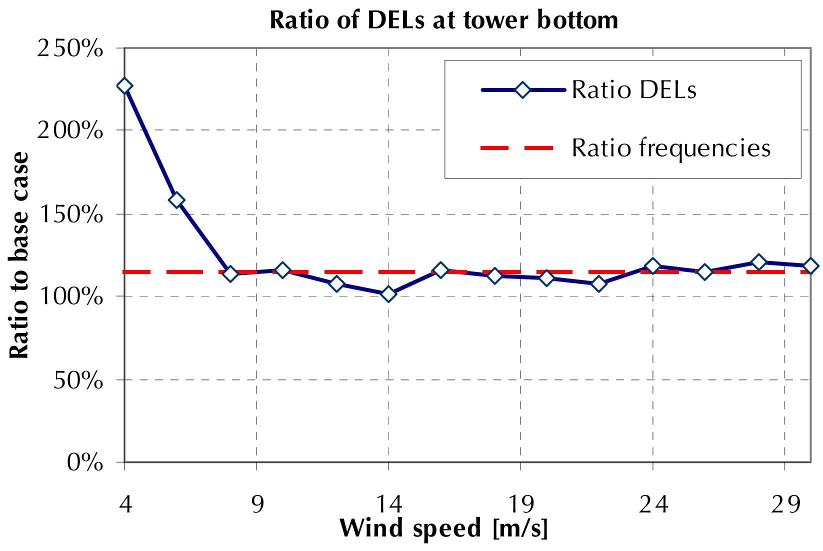


Fig. 2: Ratio of tower bottom fatigue loads for two structures with f_0=0.33 Hz (base case) and f_0=0.38 Hz

3. Impact of substructure selection on tower loads

In order to investigate the impact of substructure selection on tower loads, the effect of wind loading alone versus wind loading combined with wave loading has been investigated.

3.1. Impact of substructure with pure wind loading

The results of wind loading alone are compared graphically in Fig. 3 (tower top) and Fig. 4 (tower bottom). The following can be seen:

- Tower top loads for all components are within a tolerance of 5%. The differences arise from the different dynamic behaviour (number of cycles and amount of inertia loading), but as no critical frequencies (like the 1p- or 3p-excitation ranges) are hit, the results are quite similar.
- The same is true for tower bottom, except for the vertical force only which has a slightly higher difference of up to 12% for the FFT. This is due to a modal coupling between the blade edgewise frequency and a vertical eigenmode for the FFT.

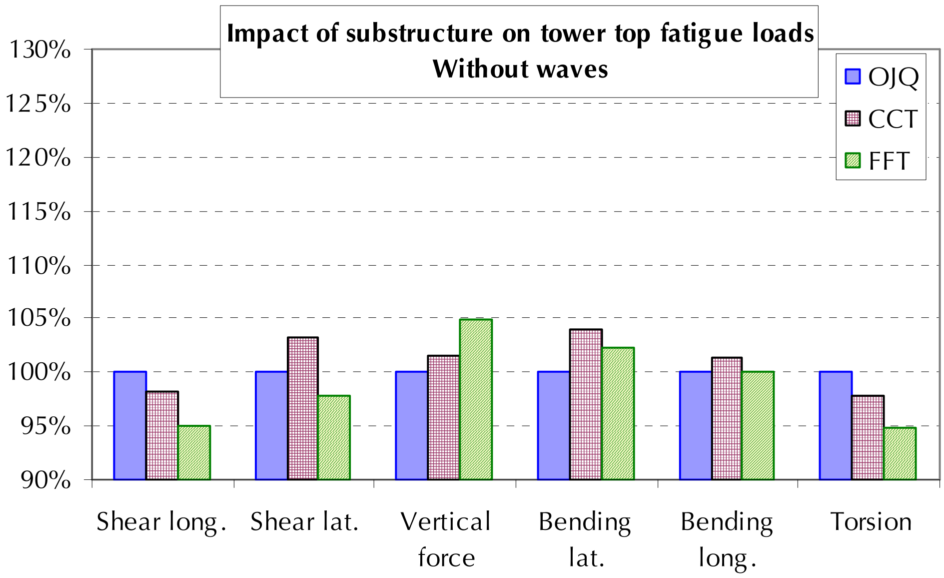


Fig. 3: Impact of substructure selection (excluding waves) on tower top fatigue loads (DELs)

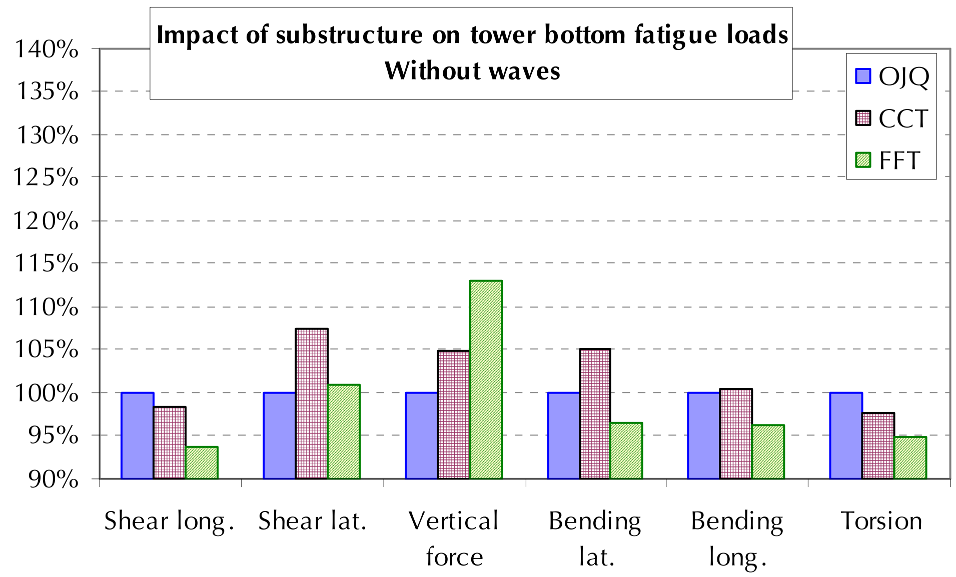


Fig. 4: Impact of substructure selection (excluding waves) on tower bottom fatigue loads (DELs)

4. Impact of wave loading for FLS assessment

4.1. Impact of wave loading on tower loads

A comparison for the fatigue loads at tower top including waves is provided in Fig. 5. All components except the longitudinal shear are not significantly affected by the wave loading. Fig. 6 shows the overall impact of substructure selection on the tower bottom fatigue loads. The following can be seen:

- Vertical force and torsional moment only vary by less than 5% between OJQ and CCT. This is because these components are primarily affected by the aerodynamics. As the tower top velocities are typically about only 1% of the wind speed, the effect for these components is small. The vertical force fatigue loads are larger for the FFT because an eigenfrequency with a vertical movement in the mode shape is close to the blade edgewise frequencies. This causes some dynamic excitation, leading to increased fatigue loads.

- Lateral shear force and bending moment increase up to 12% for the CCT/FFT compared to the OJQ. This is due to larger accelerations at tower top for the CCT/FFT, caused by the greater flexibility of the structure. The tower top displacements are about a factor of 2 larger for the CCT/FFT compared to the OJQ and this causes additional inertia forces which increase tower bottom loads.

- Longitudinal shear force and bending moment are also affected by the increased tower top dynamics. Additionally the deformations and hence accelerations are further increased by the wave loads. These are much larger for the CCT and the FFT and thus overall difference for these components is about 20% for the CCT and even 35% for the FFT!

In case of the FFT, larger fatigue loads do also occur because the second global mode at 0.86 Hz contributes significantly to the overall fatigue loading. This is different to the other substructures where the second global mode does not contribute significantly at tower bottom.

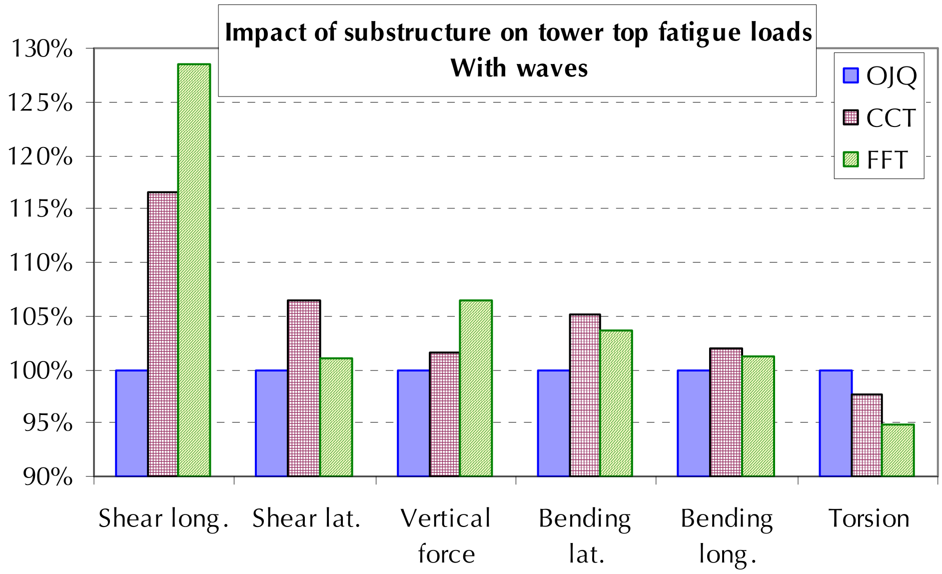


Fig. 5: Impact of substructure selection (including waves) on tower top fatigue loads (DELs)

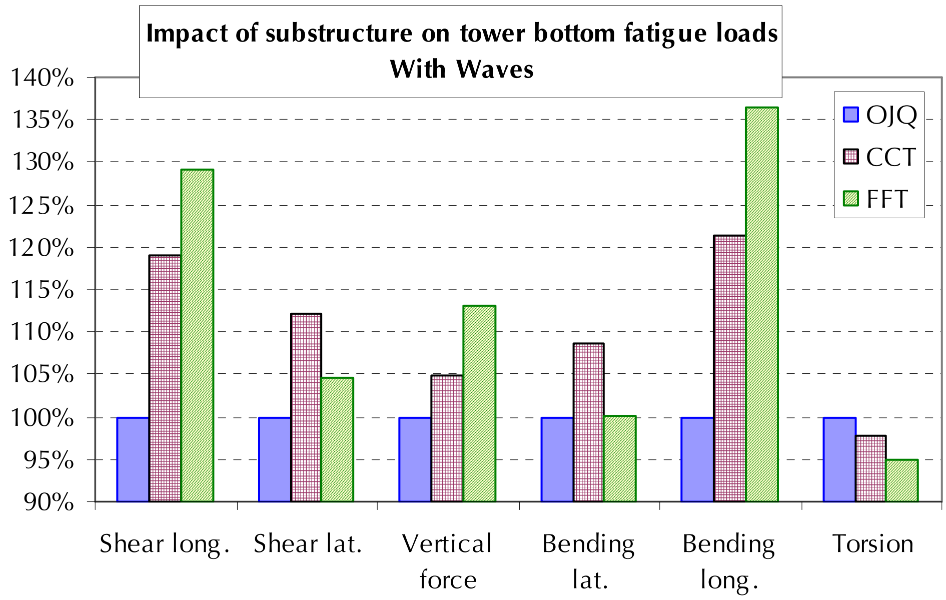


Fig. 6: Impact of substructure selection (including waves) on tower bottom fatigue loads (DELs)

A more detailed analysis can be based on Fig. 7, which shows the damage equivalent loads at tower bottom for different mean wind speeds for the three substructures. Additionally, the ratio of the wave spectral peak frequency f_p to the first global eigenfrequency f_0 is shown.

- The largest differences occur for small wind speeds. This is due to the fact that the chosen correlation between wind speeds and wave heights/wave periods has spectral peak periods close to the fundamental eigenfrequency of the system for CCT and FFT. For both structures it can clearly be seen that this resonant excitation greatly increases the fatigue loading.

- The DELs are becoming more similar for higher wind speeds. The loads for the CCT are even smaller than for the OJQ at very high wind speeds. This is due to the fact that the higher eigenfrequency of the OJQ leads to a higher number of cycles and hence to larger fatigue loads. This effect balances the increased wave loading for the CCT.

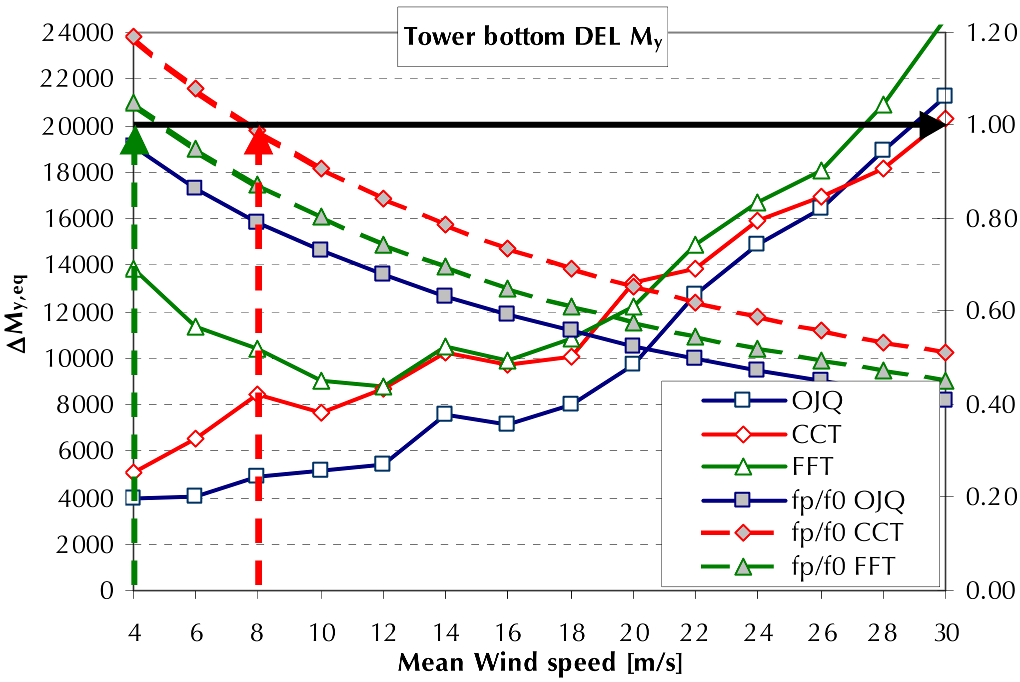


Fig. 7: Damage equivalent tower bottom loads at different wind speeds and ratio of spectral peak frequency to first natural frequency for OJQ and CCT

4.2. Impact of wave loading on other components

A comparison of fatigue loads for other components which are important for the design of the turbine is given in Fig. 8. It can be seen that only the rotor thrust is increasing due to higher inertia loading for the Tripods compared to the OJQ. The other components are only marginally different, thus assessing the turbine suitability for a specific site without knowing the substructure is feasible.

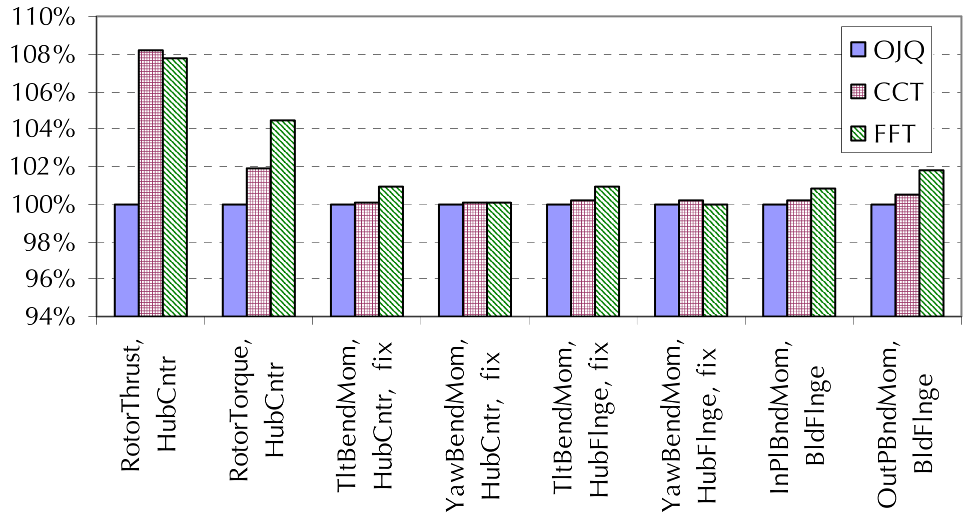


Fig. 8: Impact of different substructures on fatigue loads of other components

5. Impact of wave loading for ULS assessment

A comparison of extreme loads (global overturning moment and base shear) is shown in Fig. 9. For this comparison, identical tower bottom "wind" loads for all substructures have been assumed, as full extreme load calculations have not been evaluated for all variants. It should be noted that this is probably not conservative for the Tripods – it can be assumed that the tower bottom loads are also increased for extreme load situations due to increased inertia loading from the nacelle.

The following conclusions can be drawn from the figures:

- The wave load portion of the overall bending moment differs significantly for the three substructures, the extreme bending moment from wave action alone is app. 40% larger for the FFT compared to the OJQ. For all three substructures the wave loading is significant for ULS, but the wind loading is dominant.

- The base shear is dominated by the waves and again large differences exist for the different structures. The shear for the CCT is even larger than for the FFT which is due to the larger diameter columns which extend down to seabed. The FFT has the larger overturning moment as more members are near the wave crest and thus have a larger lever arm.

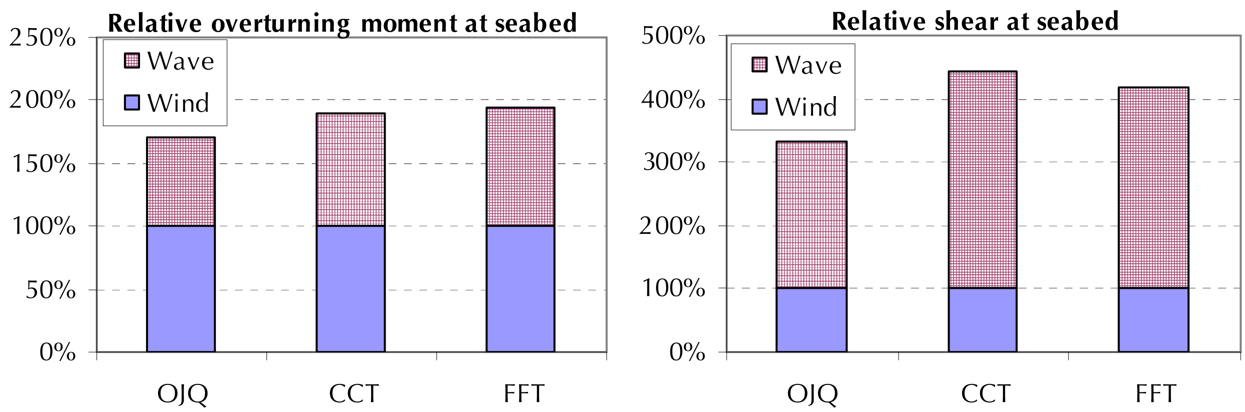


Fig. 9: Comparison of extreme loads (global overturning moment and shear) at seabed

6. Benefit of integrated wind-wave calculations

Integrated analysis of wind and wave loading including a reasonably detailed model of the support structure is required for a safe and economic design. It has already been demonstrated that integrated analysis is important for the loads at tower bottom, which can be considered as "global" loads, but it is even more important for local problems. This is illustrated in Fig. 10 which shows a mode shape of a high frequency mode at 3.45 Hz. This mode is primarily a blade mode (flapwise direction), but it can be seen that the bracings in one of the lower bays are also part of this mode shape. In the integrated analysis it turns out that the governing loading for these bracings is the out-of-plane bending moment which is caused by this and other local vibration modes. These local vibrations can only be identified in an integrated analysis!

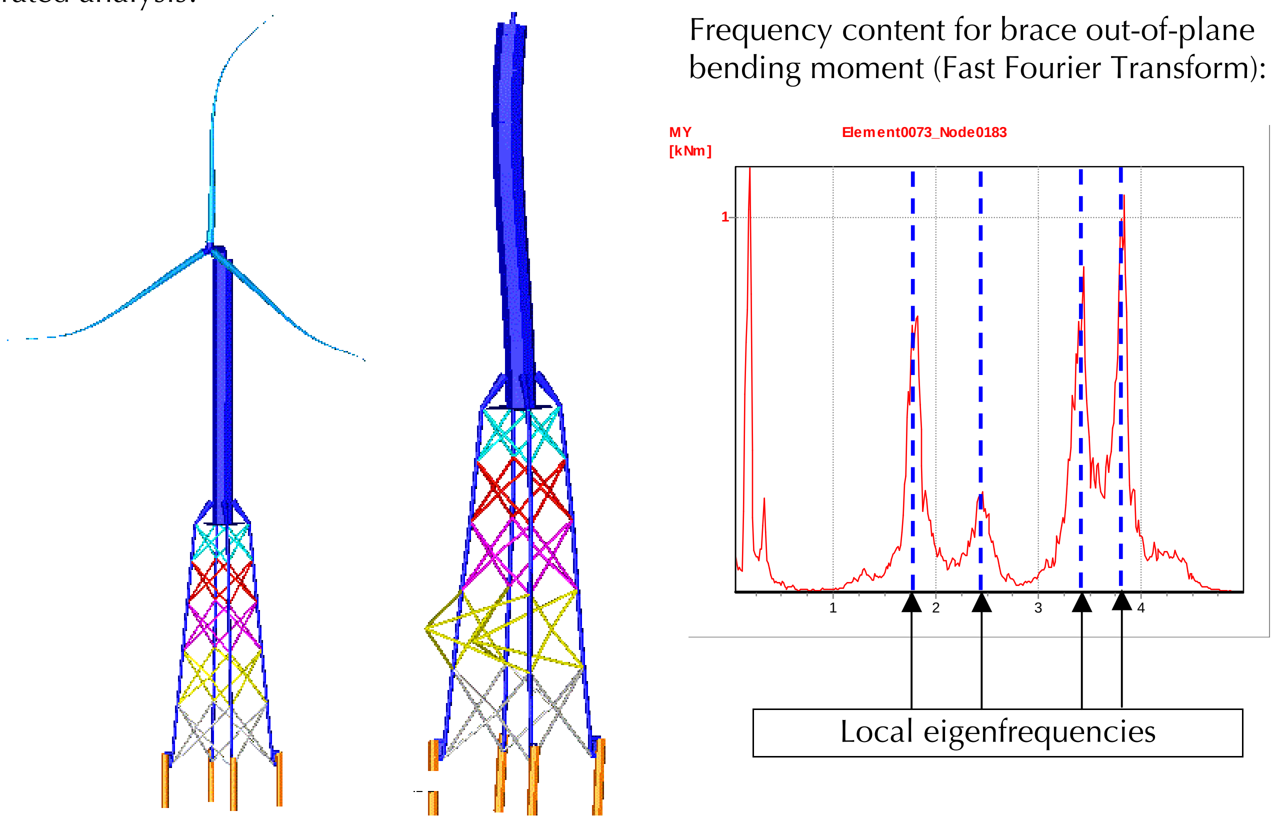


Fig. 10: Mode shape of coupled turbine-support structure (mode 25, f_{25}=3.45 Hz) and FFT of brace out-of-plane bending moment

7. Summary and conclusions

It has been shown in this paper that turbine and substructure must always be treated as an integrated system as they influence each other substantially. The magnitude of tower bottom and tower top loads is affected strongly by the overall dynamic characteristics which are in turn dominated by the substructure. The following conclusions can be drawn:

1) "The turbine loads" – which are normally requested for substructure design studies or even final design – do not exist as such. Tower top or tower bottom loads are only valid for a given substructure characterized by mass and stiffness distribution and for given site parameters. Global eigenfrequencies, wave loading and admittance of wave loading by the structure are the most important parameters.

2) Global and local vibrational phenomena can be important for the design. Both are affected by the turbine and can only be identified in an integrated analysis. Multi-member structures like Jackets or Tripods are of course more complicated to analyze with respect to local vibrations than Monopile or Gravity foundations and the importance of using an integrated load analysis is increasing for such substructures.

3) Components other than the tower top thrust force are only marginally affected by global dynamics and wave loading. This justifies that the rotor-nacelle-assembly (RNA) can be designed and certified for certain site conditions without detailed knowledge about the substructure and met-ocean data.

Project developers and consultants should thus be extremely careful when making decisions about substructure design without involving the turbine manufacturer. Severe misjudgement of suitability and/or cost can only be avoided in a joint design process involving turbine manufacturer and substructure designer.

References

[1] Seidel, M.; v. Mutius, M.; Rix, P.; Steudel, D.: Integrated analysis of wind and wave loading for complex support structures of Offshore Wind Turbines. Conference Proceedings Offshore Wind 2005: Copenhagen 2005.

Acknowledgment

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