Integrated analysis of wind and wave loading for complex support structures of Offshore Wind Turbines

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Summary

Offshore wind turbines are subject to combined wind and wave loading which must be taken into account for the structural assessment. While commercial software is available that allows for integrated wind/wave analysis of a Monopile foundation, programs which accomplish this task for complex structures are currently not available. REpower's version of Flex 5 ("REflex") has been enhanced for integrated calculations with ASAS(NL) which is a well-known standard package in the Offshore business for wave loaded structures to overcome this shortcoming. This enables design calculations for both fatigue and extreme conditions without the need for a substitute Monopile model, thus increasing confidence and accuracy in the design process.

1. Introduction

The new generation of large wind turbines, which is specifically designed for Offshore application, is now in the prototyping phase, the REpower 5M is in operation since autumn 2004. The majority of the existing Offshore projects with smaller turbines have been built with Monopile and gravity foundations, which are the simplest possible options. While these are still viable for the larger 5 MW turbines in some cases, other foundation types may be more interesting to optimise economic efficiency. This stipulates that sophisticated load calculation methods for complex structures must be adopted. This is the main focus of this paper.

2. Review of existing design methods

In a previous publication [1] the authors have presented a methodology which employs a substitute Monopile in Flex 5 and a more detailed model of the substructure in a specialised Offshore program. Although this "semi-integrated" methodology is workable for many substructures, there are some drawbacks:

- Stiffness representation with a Monopile is not good for all kinds of substructures. In many cases the diagonal elements of the generalized stiffness matrix can be fitted well, but the off-diagonal elements are often difficult to match. This leads to significant differences in overall stiffness and thus eigenfrequencies, which are an important parameter in the transient calculations. Furthermore, only force controlled superposition can be performed as the unavoidable differences in the stiffness matrix can lead to large errors for the deformation controlled superposition.

- Wave loading is calculated for a straight vertical member, thus the positive effect of distributed members in wave direction is not taken into account. Furthermore, finding equivalent hydrodynamic coefficients to take account of many members proves to be difficult in many cases.
- The use of foundation models in two different programs, which need to be harmonized e.g. in terms of wave loads, creates an additional interface with more possibilities for errors in the process.

The shortcomings of this approach lead to the development of a new solution with a higher degree of integration for the two programs used.

3. Structural modelling in Flex 5

In Flex 5 generalized coordinates (and associated system matrices) are used. The six generalized coordinates are:

- In vertical direction: Displacement z, rotation φ_z
- In longitudinal direction: Displacement x, rotation φ_y
- In lateral direction: Displacement y, rotation φ_x

Vertical displacement and rotation (torsion) are normally not used for the dynamic degrees of freedom. In REflex, these degrees of freedom have been activated for output of vertical deflection and torsional rotation of the substructure in order to enable the "deformation controlled" approach to work with substructures where these DOFs can not be neglected (as is the case for a Monopile).

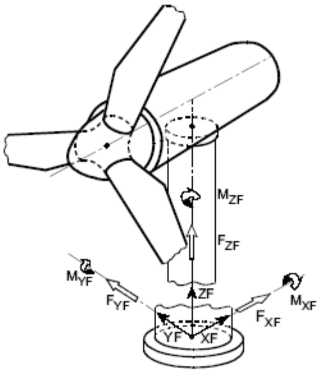


Fig. 1: Coordinate system as used in REflex

The set of differential equations (Coordinate system acc. to Fig. 1) which is solved in Flex 5 is:

$$\underline{K} \cdot \underline{u}(t) + \underline{D} \cdot \underline{\dot{u}}(t) + \underline{M} \cdot \underline{\ddot{u}}(t) = \underline{p(t)}$$

If we fully write the stiffness portion for the substructure of this equation, then we get:

$$\underline{p} = \underline{K} \cdot \underline{u} = \begin{pmatrix} K_{xx} & K_{xy} & K_{xz} & K_{x\varphi_x} & K_{x\varphi_y} & K_{x\varphi_z} \\ K_{yx} & K_{yy} & K_{yz} & K_{y\varphi_x} & K_{y\varphi_y} & K_{y\varphi_z} \\ K_{zx} & K_{zy} & K_{zz} & K_{z\varphi_x} & K_{z\varphi_y} & K_{z\varphi_z} \\ K_{\varphi_x x} & K_{\varphi_x y} & K_{\varphi_x z} & K_{\varphi_x\varphi_x} & K_{\varphi_x\varphi_y} & K_{\varphi_x\varphi_z} \\ K_{\varphi_y x} & K_{\varphi_y y} & K_{\varphi_y z} & K_{\varphi_y\varphi_x} & K_{\varphi_y\varphi_y} & K_{\varphi_y\varphi_z} \\ K_{\varphi_z x} & K_{\varphi_z y} & K_{\varphi_z z} & K_{\varphi_z\varphi_x} & K_{\varphi_z\varphi_y} & K_{\varphi_z\varphi_z} \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ \varphi_x \\ \varphi_y \\ \varphi_z \end{pmatrix}$$

Due to the generalization only the following elements of the stiffness matrix are used:

$$\underline{p} = \underline{K} \cdot \underline{u} = \begin{pmatrix} K_{xx} & & & & K_{x\varphi_y} & \\ & K_{yy} & & K_{y\varphi_x} & & \\ & & K_{zz} & & & \\ & K_{\varphi_x y} & & K_{\varphi_x\varphi_x} & & \\ K_{\varphi_y x} & & & & K_{\varphi_y\varphi_y} & \\ & & & & & K_{\varphi_z\varphi_z} \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \\ \varphi_x \\ \varphi_y \\ \varphi_z \end{pmatrix}$$

This means that only the coupling between horizontal displacement and rotation around the corresponding axis is taken into account. All other coupling coefficients are neglected and no coupling is assumed. This is theoretically correct for a Monopile, but must be carefully checked for validity for other substructures.

4. Integrated analysis with Flex 5 and ASAS(NL)

The highest level of integration would of course be achieved in one integrated software package. As both wind and Offshore software is highly specialized and has been developed over many years, a solution which employs known and tested software was perceived as the preferred option though. Thus, ASAS(NL) as a well-known program was chosen for the "Offshore" part. In order to facilitate the calculation process, a sequential approach was chosen. The general idea of this **integrated, sequential approach** is to **completely substitute the Flex 5 foundation module** by a more complex model in ASAS(NL) while maintaining the general approach in Flex 5 which uses two generalized degrees of freedom for longitudinal and lateral movement of the foundation. An example of the deflection shapes for the generalized degrees of freedom is shown in Fig. 12 for a Tripod foundation. Generalized system matrices (stiffness, mass, damping) and loading history vector are then created in ASAS(NL) and imported into Flex 5. The results from Flex 5 (forces or displacements at foundation top) are transferred back into the more detailed model for recovery of the foundation member forces.

As the reduction of degrees of freedom is retained, simulations with Flex 5 are very fast. The retrieval run for the full model needs much more computation time, thus a selection of load cases can be made for ULS load cases based on the tower bottom loads and wave conditions to reduce total computational effort. An overview of the calculation procedure is shown in Fig. 2. The retrieval run to obtain member forces for the full model can again be performed as "force controlled" or "deformation controlled" superposition as discussed in [1]. The two methods are characterized by the following:

- The forces or deformations at the tower-substructure-interface are applied together with the same wave loading which was used to generate the generalized forces which where transferred to Flex 5 for the wind-wave-calculations.
- The "force controlled" superposition can only be performed statically. That is because the damping from the turbine (which is mainly aerodynamic damping) is not present in the ASAS(NL) model. This leads to exaggerated deformations in a transient run if a force time history is applied.
- The "deformation controlled" approach can be performed dynamically as the damping of the substructure itself is correctly described and the damping contribution from components above the foundation are of no influence for the local dynamics at this stage.

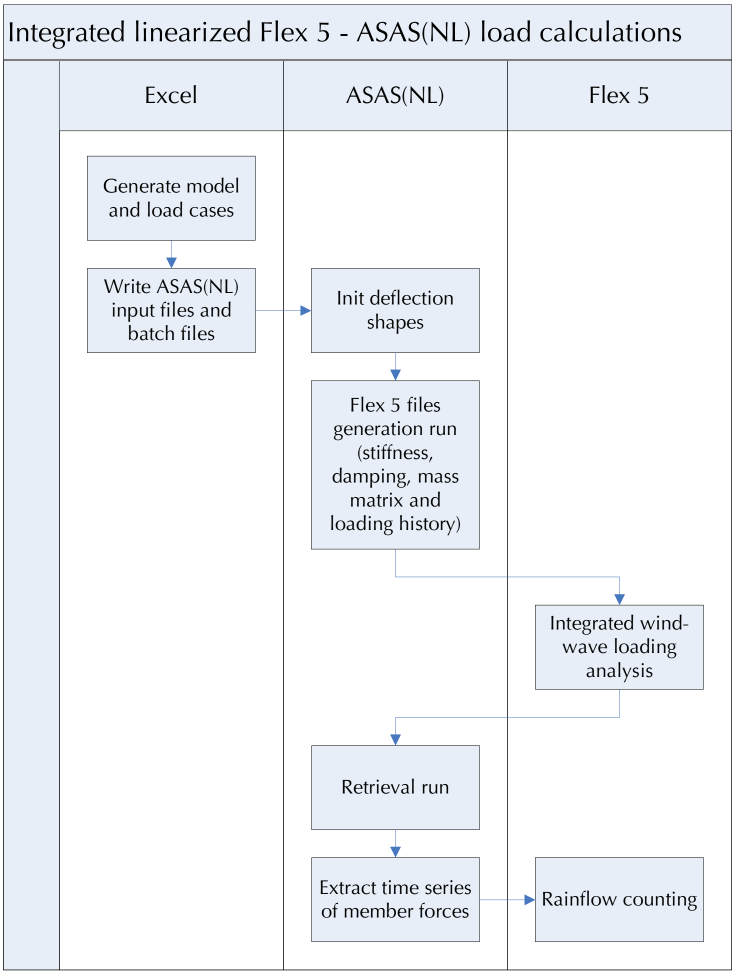


Fig. 2: Overview of calculation process

Deformation controlled superposition is preferred as the inertia forces of the foundation are included in case of a transient simulation. These are neglected in case of the force controlled superposition, which must be used for the semi-integrated approach with a substitute Monopile [1].

The limitations of this approach are as follows:

- Only linear foundations can be modelled. Any non-linear effects like soil-pile-interaction or second order bending can not be considered directly. This limitation applies to Flex 5 calculations in general and is not specific to this new approach for combined wind-wave calculations.
- As the generalization to two degrees of freedom is maintained, the overall solution will only be accurate if the global deformations can be represented well with the corresponding deflection shapes and if the directions are not coupled. This can e.g. be checked by comparing the modal analysis results from the full structural model in ASAS(NL) with the computation of Flex 5 which is based on the generalized matrices. Also, unit load cases or analysis of the system matrices can give insight on the degree of coupling between the DOFs.
- The wave loading time history which is passed to Flex 5 is calculated for a fixed structure as the structural movement is unknown at this stage. Relative kinematics can thus only be considered for the retrieval run, but not for the movement of the entire coupled structure. As the velocities and accelerations of the structure itself are typically very small, the error induced by this is negligible.

Apart from these limitations, no further drawbacks exist. The methodology is thus a very good compromise between theoretical accuracy and an economic calculation process.

5. Verification

In order to verify that the proposed calculation procedure and the implementation in ASAS(NL) and Flex 5 are accurate, comparison between the fully integrated analysis with Flex 5 / WaveKin and the sequential approach with Flex 5 / ASAS(NL) is made. A Monopile foundation for a site with 20m water depth is used for this exercise. The Monopile is assumed clamped at mudline level – this does of course not reflect true boundary conditions, but is chosen in order to simplify the model as much as possible.

5.1. Eigenfrequencies

First of all the eigenfrequencies are compared:

	ASAS(NL)	Flex 5
f_0	0.293 Hz	0.294 Hz
f_1	2.414 Hz	2.360 Hz

Agreement between the model in ASAS(NL) – which includes the tower and the nacelle (simplified as a point mass with inertia) – and Flex 5 is very good. Small differences for the second mode are due to the limitations of defining accurate mass inertia values for the nacelle in the ASAS(NL) model with a point mass element.

5.2. System matrices and loading vector

Stiffness, mass and damping matrices have been compared directly with differences found to be less than 1%. The same is true for the loading vector, except for very small wave heights. This is due to the fact that Wavekin uses a correction for small amplitude waves to account for diffraction of large diameter members. This is not incorporated in ASAS(NL) and thus the wave forces are overpredicted.

Fig. 3 shows an example of the computed time history of the horizontal force at mudline. Excellent agreement between the different calculations is found.

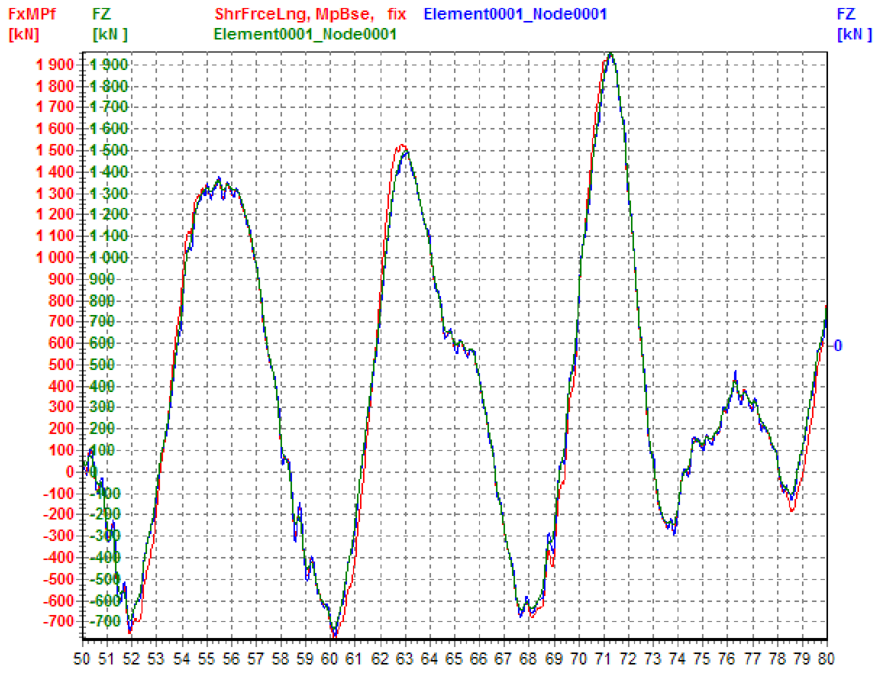


Fig. 3: Comparison of horizontal force at mudline for Hs=4.6m, Tp=8.84s (Flex 5: red line; ASAS deformation controlled superposition: blue line; ASAS force controlled superposition: green line).

5.3. Damage equivalent loads and load spectra

Fig. 4 shows the comparison of Damage Equivalent Loads (DELs) for the longitudinal bending moments at tower bottom. The following can be seen:

- The results of the sequential, integrated analysis with ASAS(NL) are slightly lower than the Flex 5 results. This is solely due to the fact that a time step of 2ms was used for the Flex 5 simulations while the ASAS(NL) retrieval runs were performed with a time step of 5ms. This leads to smaller fatigue loads as the peaks are smoothened.
- The results of the deformation controlled and force controlled superposition are virtually identical.
- Overall, the ratio of results is 0.997, thus the larger time step underestimates fatigue loading by 0.3%.

The comparison of bending moments at mudline is given in Fig. 5:

- The ratio of "Deformation controlled" results to the integrated Flex 5 solution is 0.99 on average. Thus, only a very small difference, which can e.g. be due to slightly different treatment of wave loading near the waterline, exists.
- The ratio for the "Force controlled" superposition is 0.976 on average. The difference to the "Deformation controlled" approach is due to the neglect of inertia loading from the Monopile.

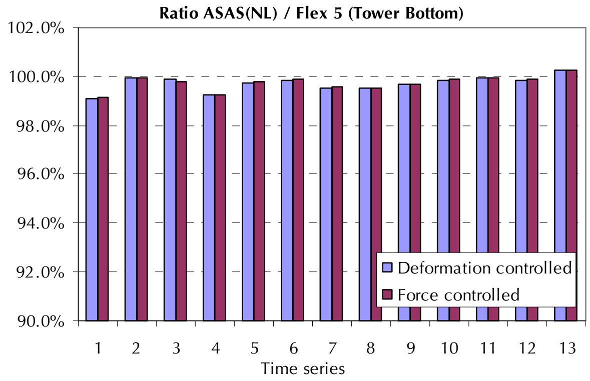


Fig. 4: Comparison of bending moments DELs at tower bottom

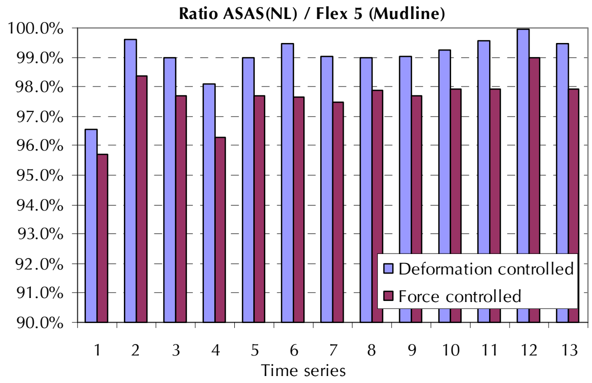


Fig. 5: Comparison of bending moments DELs at mudline

The excellent agreement is also reflected in the load spectra, e.g. the spectrum for bending moment at mudline (Fig. 6). The difference between the Flex 5 integrated results and the deformation controlled superposition is within the line thickness in the chart.

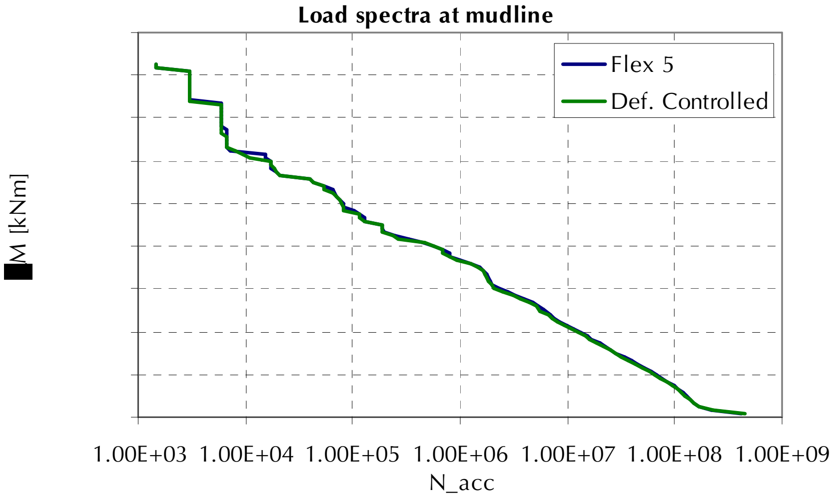


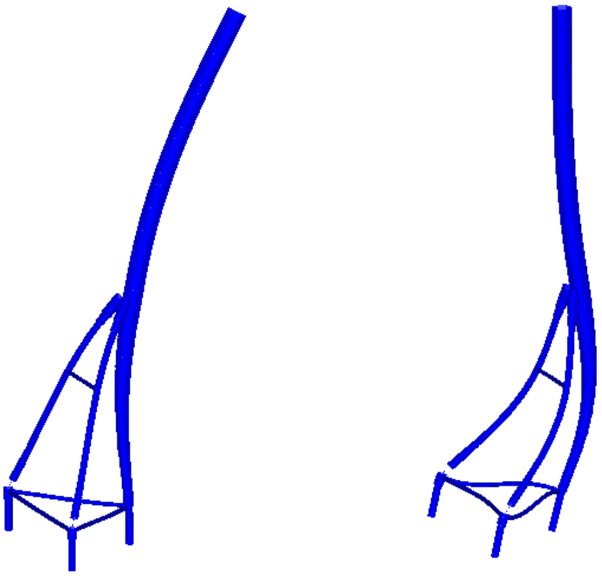
Fig. 6: Comparison of bending moment load spectra at mudline

6. Example 1: Flat Face Tripod

A substructure with a Tripod in 45m water depth is chosen as an example to show some results. This example also serves to highlight limitations of the approach for unsymmetrical substructures.

6.1. Modal analysis

The first two mode shapes as calculated with ASAS(NL) are shown in Fig. 7. The agreement for the eigenfrequencies is less perfect than for the Monopile in this case as the unsymmetrical Tripod is difficult to represent with two generalized DOFs. Nevertheless, agreement is acceptable within the limits of expected accuracy.



f_0 = 0.316 Hz
Flex 5: f_0 = 0.325 Hz

f_2 = 0.953 Hz
Flex 5: f_1 = 1.14 Hz

Fig. 7: Modes shapes for the example

1.19E+08	7.10E+06	-2.25E+08	2.39E+06	**-9.88E+07**	-3.36E+07
7.10E+06	**1.19E+08**	-2.25E+08	**9.89E+07**	-2.33E+06	3.36E+07
-2.25E+08	-2.25E+08	**2.05E+09**	6.26E+08	-6.26E+08	-7.98E+04
2.39E+06	**9.89E+07**	6.26E+08	**2.39E+10**	3.51E+08	1.31E+09
-9.88E+07	-2.33E+06	-6.26E+08	3.51E+08	**2.39E+10**	1.31E+09
-3.36E+07	3.36E+07	-7.98E+04	1.31E+09	1.31E+09	**3.31E+09**

Relative contribution per degree of freedom

100.00%	5.97%	-189.08%	2.01%	**-83.21%**	-28.28%
5.97%	**100.00%**	-189.08%	**83.27%**	-1.96%	28.31%
-10.96%	-10.96%	**100.00%**	30.54%	-30.55%	0.00%
0.01%	**0.41%**	2.62%	**100.00%**	1.47%	5.49%
-0.41%	-0.01%	-2.62%	1.47%	**100.00%**	5.49%
-1.02%	1.02%	0.00%	39.62%	39.62%	**100.00%**

Fig. 8: Stiffness matrix for Flat Face Tripod (Units: N, m, rad)

Analysis of the stiffness matrix (Fig. 8) reveals significant coupling between the degrees of freedom, though. The coefficients in bold type are taken into account in Flex 5, the other coefficients are neglected and should thus be small to avoid errors in the calculation. There is, however, strong coupling e.g. between the vertical z-displacement and the x- and y-displacements. Also, there is coupling between the horizontal displacements and rotations with rotation around the vertical (torsion).

This behaviour can be visualized by applying unit loads to the structure. Fig. 9 shows displacement shapes for vertical force (left part) and torsion (right part) at hub height. It can clearly be seen that horizontal displacements and rotation occur simultaneously due to the unsymmetrical layout of the substructure. The effect of neglecting the coupling coefficient must thus be carefully evaluated before applying the proposed methodology to this structure.

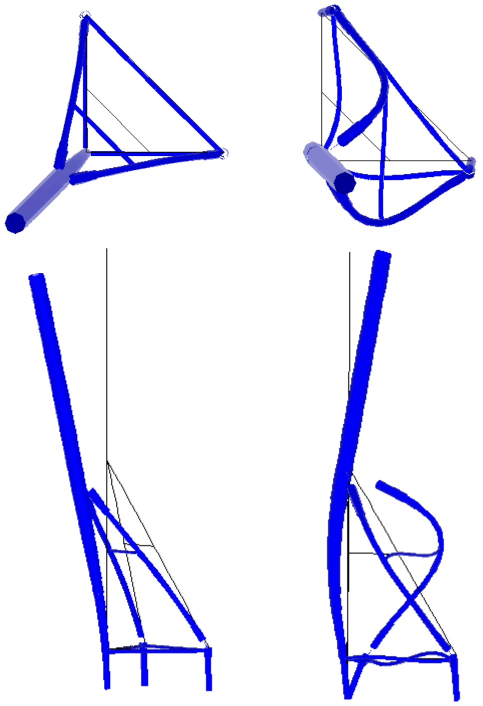


Fig. 9: Deformation shapes for vertical force (Fz) and torsional moment (Mz) at hub height

7. Example 2: Center Column Tripod

Another model for a Tripod in 45m water depth is chosen as a second example (Fig. 11). In this case, the stiffness matrix reveals only marginal coupling between the generalized degrees of freedom (Fig. 10). This structure is thus an example for a very well suited substructure where the use of generalized, decoupled degrees of freedom will have a high degree of accuracy.The generalized deflection shapes for this Tripod are shown in Fig. 12.

7.96E+07	5.94E+03	-6.67E+04	8.48E+04	**-1.29E+09**	-8.35E+03
5.94E+03	**7.96E+07**	4.81E+04	**1.29E+09**	-6.72E+04	4.24E+04
-6.67E+04	4.81E+04	**1.92E+09**	7.31E+05	1.12E+06	-1.22E+05
8.48E+04	**1.29E+09**	7.31E+05	**3.91E+10**	-9.62E+05	4.45E+05
-1.29E+09	-6.72E+04	1.12E+06	-9.62E+05	**3.91E+10**	9.84E+04
-8.35E+03	4.24E+04	-1.22E+05	4.45E+05	9.84E+04	**6.15E+09**

Relative contribution per degree of freedom

6.18%	0.00%	0.01%	0.01%	**100.00%**	0.00%
0.00%	**6.18%**	0.00%	**100.00%**	0.01%	0.00%
0.00%	0.00%	**100.00%**	0.04%	0.06%	0.01%
0.00%	**3.29%**	0.00%	**100.00%**	0.00%	0.00%
3.29%	0.00%	0.00%	0.00%	**100.00%**	0.00%
0.00%	0.00%	0.00%	0.01%	0.00%	**100.00%**

Fig. 10: Stiffness matrix for Center Column Tripod

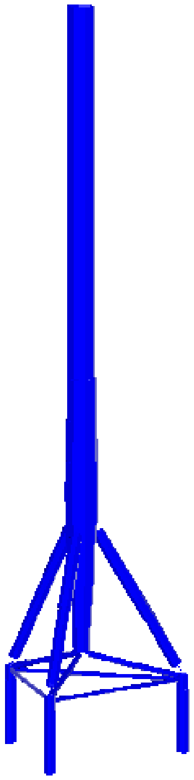


Fig. 11: Centre Column Tripod (with tower up to nacelle)

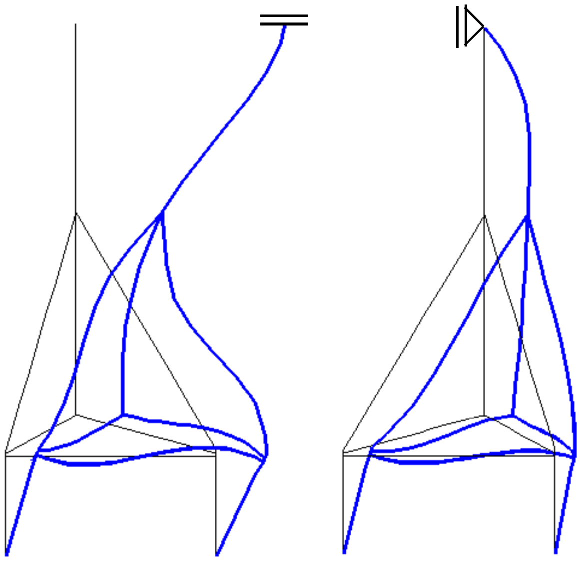


Fig. 12: Deflection shapes for generalized DOFs

Comparison for the fatigue loads is provided for two members in Table 1 and Table 2. It can be seen that the influence of wave loading varies substantially for the different components of each member. Quadratic superposition with static wave loading underestimates the total loading and can thus not be used for the design process. Superposition with wave loading only from a dynamic simulation (with 1% damping for the first and second global mode) leads to significant overestimation on the other hand.

The integrated calculation methodology does thus provide a suitable means to achieve the optimum design solution, avoiding unnecessary conservatism or uncertainty which result from the use of simplified methods.

	Wind only (Flex 5 / ASAS)	Wind & Wave (Flex 5 / ASAS)	Wave static (ASAS)	Wave dynamic (ASAS)	Quadratic superpos. (Wave static)	Ratio to integrated calculation	Quadratic superpos. (Wave dynamic)	Ratio to integrated calculation
Fx (axial)	1180	2550	2170	2600	2470	97%	2855	112%
Mz (IPB)	2300	3164	1904	3206	2986	94%	3946	125%
Mx (torsion)	325	325	0	0	325	100%	325	100%

Table 1: Damage equivalent loads at support leg close to central node for $N_{ref} = 2 \cdot 10^8$ cycles

	Wind only (Flex 5 / ASAS)	Wind & Wave (Flex 5 / ASAS)	Wave static (ASAS)	Wave dynamic (ASAS)	Quadratic superpos. (Wave static)	Ratio to integrated calculation	Quadratic superpos. (Wave dynamic)	Ratio to integrated calculation
Fx (axial)	72	72	0	0	72	100%	72	100%
My (bending)	18639	20368	3427	20176	18951	93%	27468	135%
Mx (torsion)	3952	3953	0	0	3952	100%	3952	100%

Table 2: Damage equivalent loads at vertical main leg above central node for $N_{ref} = 2 \cdot 10^8$ cycles

8. Summary and conclusions

Integrated wind-wave-calculations are an essential part of the design process for Offshore Wind Turbines, esp. for fatigue conditions. A new methodology has been presented to accomplish this task, using well proven software from the Wind and Offshore industries. The methodology has been validated and results have been shown to be in excellent agreement with the reference calculation.

In two examples, it has been shown that substantial benefits from integrated calculations can be achieved as superposition from separate calculations for wind and waves is not straightforward. REpower has thus made a major step towards optimised substructures for the Offshore application of the 5M turbine.

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References

[1] Seidel, M.; v. Mutius, M.; Steudel, D.: Design and load calculations for Offshore foundations of a 5 MW turbine. Conference Proceedings DEWEK 2004. Wilhelmshaven: DEWI 2004.