DESIGN AND LOAD CALCULATIONS FOR OFFSHORE FOUNDATIONS OF A 5MW TURBINE

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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 for a Monopile foundation, programs which accomplish this task for complex structures are currently not available. While the widely used Monopile is still an option for the REpower 5M with 126m rotor diameter, investigations regarding different substructures to develop the most cost efficient solution were conducted. This lead to the development of "semi-integrated" calculation methods for complex substructures which employ specialized programs from the Wind industry and the Offshore industry to combine these into a comprehensive load calculation package. Two different superposition approaches are explained and illustrated by an example which shows that excellent agreement compared to integrated analysis can be achieved.

1 Introduction

The new generation of large wind turbines, which is specifically designed for Offshore application is now in the prototyping phase.

The majority of the existing Offshore 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 many cases, other foundation types may be more interesting to optimise the economic efficiency. This stipulates that sophisticated load calculation methods for complex structures must be adopted. This is the main focus of this paper.

Fig. 1: REpower 5M in the erection phase

2 Monopile Design for the REpower 5M in North Sea Environment

Several Monopile foundations have been designed for the REpower 5M in North Sea conditions. The stiff sandy soils in the region are generally advantageous to achieve the required stiffness and thus a Monopile is not unthinkable even up to 30m water depth (it must be noted that the soil stiffness may be a problem for the pile driving – this has not been investigated in great detail, but it has been indicated by hammer manufacturers that a hydrohammer with a rated impact energy of 1200 kNm will probably suffice to reach target penetration).

The approximate dimensions of such a Monopile for 27m water depth are:

Length:	65m
Diameter:	7000mm
Penetration:	35m
Weight:	~775t

The transition piece weighs another 200t. A Monopile with 6000mm O.D. is also feasible, but at the expense of greater wall thicknesses and larger weight.

These dimensions are still within the viable limits for transport, lifting and pile driving as indicated by the leading contractors. Nevertheless, the overall weight in the region of 1000t makes other foundations with a more complicated geometry and smaller weight attractive to optimise economics.

3 Load calculations for Offshore wind turbines

Wind and wave loading influence the loading and behaviour of Offshore Wind Turbines. Specialized software packages exist in the wind sector and the Offshore Oil&Gas industry for the specific design approaches. Generally, at least the final calculations should be carried out in the time domain, although frequency domain may be attractive for conceptual design studies [1]. The focus of this paper is on time domain simulations. The investigations have been performed with Flex 5.

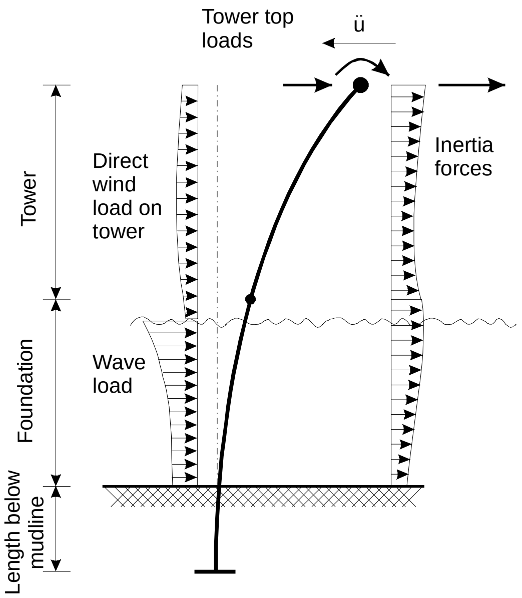

Fig. 2: Flex 5 integrated model (turbine not shown)

3.1 Wind load calculations

Wind loading is usually calculated with specialized software, Flex 5 and Bladed being the most popular design packages. Both are capable of integrated wind/wave load calculations for a simple Monopile (Fig. 2). Complex structures like Tripods or Jackets cannot be directly analysed with these programs.

3.2 Wave load calculations

Specialized software packages for wave load calculations are e.g. SESAM (from DNV) or ROSAP (from Rambøll). These programs are suitable for the time domain analysis of Jackets or Tripods with pure wave loading, but direct integration of wind loading poses several problems.

Attempts have been made in the past to take account of the wind/wave interaction by using wind load time series that were generated for a substitute onshore system with approximately the same eigenfrequencies and making new dynamic simulations in the Offshore design program using tower top or bottom load time series. Wave load was then added by the Offshore package, but was not present in the Flex 5 calculations. This may seem like a reasonable approach, but it has several drawbacks:

- Aerodynamic damping is only present in the full turbine model. Kühn [2] gives approximate constant aerodynamic damping values for different wind speeds that may be used in the simulations, but this is of course a coarse approach as the actual damping depends on many parameters, e.g. turbine controller, aerodynamic properties of the blades, stiffness distribution, etc.

- Both wind and wave loading influence the dynamic deformation of the system. Pure wind loading is associated with accelerations that cause part of the loading. The accelerations of the "combined" simulation in the Offshore package will not correspond to these values when the overall loading is not identical in both runs.

4 The equivalent Monopile foundation: Basis for semi-integrated approaches

Unless a software package exists that allows to conduct combined wind and wave analysis for arbitrary structures, two individual programs must be used to accomplish this task. The calculations performed with both programs must be tailored to each other, although the programs run individually. This is called a "semi-integrated" approach in this paper.

Basis for all semi-integrated approaches is an equivalent dynamic model (Fig. 3). The aim is to achieve identical kinematics at the foundation top for "real" and "substitute" model, thus also achieving identical member forces.

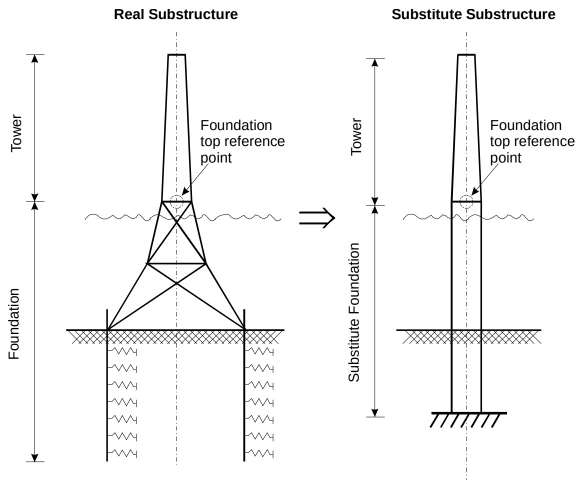

Fig. 3: Creation of the substitute model

The requirements for the substitute model are immediately obvious from the equations of motion:

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

As the aim is to receive identical vectors for acceleration, velocity and displacement, the system matrices for mass, damping and stiffness must be matched. Additionally, the global load vector must be equal in both cases to obtain identical system response.

It should noted that matching the eigenfrequencies alone is not sufficient – these depend both on stiffness and mass and errors in both may cancel out for the eigenfrequencies, but have significant impact on the results of the semi-integrated simulations.

4.1 Stiffness and mass equivalence

In Flex 5 a combined modal and static reduction methodology is adopted to reduce the number of degrees of freedom. The tower is treated with a (modified) modal reduction and the Monopile foundation is treated with a static reduction. Theoretical background for these reduction methods is e.g. given in [3] or [4].

The foundation is reduced with the displacement shapes for unit displacement and unit rotation at the foundation top.

The stiffness matrix at the foundation top is derived from the load cases depicted in Fig. 4:

$$K_{gen,ft} = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} 1/x & Mr/x \\ Fr/\varphi & 1/\varphi \end{bmatrix}$$

Stiffness equivalence is achieved when this foundation top stiffness matrix is identical for the real system and the substitute Monopile foundation. The authors are not aware of closed form solutions for this problem, thus iterative procedures must be adopted.

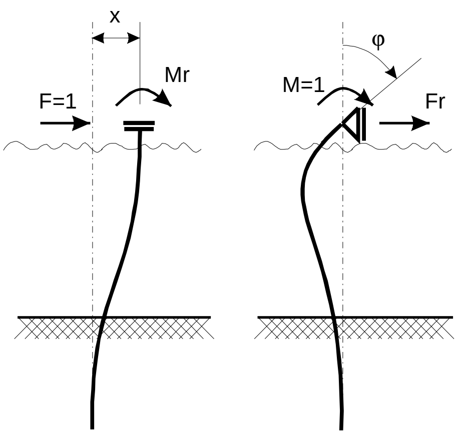

Fig. 4: Determination of foundation top stiffness matrix

Mass equivalence can easily be achieved by adjusting the structural masses with added lumped masses.

4.2 Hydrodynamic equivalence

The wave loading on small diameter members is calculated with Morison's equation:

$$F(t) = \frac{\pi}{4} \cdot \rho \cdot C_M \cdot D^2 \cdot \dot{u}(t) + \frac{1}{2} \cdot \rho \cdot C_D \cdot D \cdot u(t) \cdot |u(t)|$$

For a given wave (with given wave kinematics) the following must be achieved for the complex structure and the substitute Monopile to get equal loading for each vertical section for both systems.

For equivalence of the inertia term:

$$\sum_j C_{M,j}^{subst} \cdot \left(D_j^{subst}\right)^2 = \sum_i C_{M,i} \cdot D_i^2 \cdot \sin\alpha_i$$

For equivalence of the drag term:

$$\sum_j C_{D,j}^{subst} \cdot D_j^{subst} = \sum_i C_{D,i} \cdot D_i \cdot \sin\alpha_i$$

C_M^{subst} and C_D^{subst} can be arbitrary figures, which fulfil above equations (although values for C_M below 1 should be treated with care).

The use of $\sin(\alpha_i)$ with α_i being the member angle against the horizontal plane, is an approximation which yields good results for the global horizontal force compared to wave load calculations with inclined members.

The aim of this hydrodynamic equivalence is to ensure identical loading in horizontal direction, as this is the main direction that governs the vibrations of the system.

5 Semi-integrated load calculations for complex structures

Two paths have been followed to develop a design procedure. Both approaches involve the combined wind/wave simulation for a substitute system as described in the previous section. The investigations have been carried out with Flex 5 and specific comments are only valid for this package. Different considerations may be necessary for Bladed or other programs. In general, it can be stated that a very detailed knowledge about the implementation of structural dynamics in the wind simulation program is required to develop sound calculation procedures.

5.1 Deformation controlled approach

The member forces of the detailed foundation model are retrieved by applying foundation top displacement time series and wave loading on the foundation model simultaneously (Fig. 5).

It must be ensured that the wave loading (characterized by the wave surface elevation and hydrodynamic properties as described in section 4.2) is identical in both programs – this is crucial as the member forces and displacements at tower bottom (which are used as input) are only correct for a specific loading on the foundation! It is not sufficient to just apply wave loading which is characterized by identical wave spectra.

Different superposition strategies as shown in Table 1 can be adopted, depending on the capabilities of the software package which is used for modelling of the full foundation. Best accuracy is obtained with a transient simulation and local wave loading applied additionally to the prescribed displacements at the foundation top.

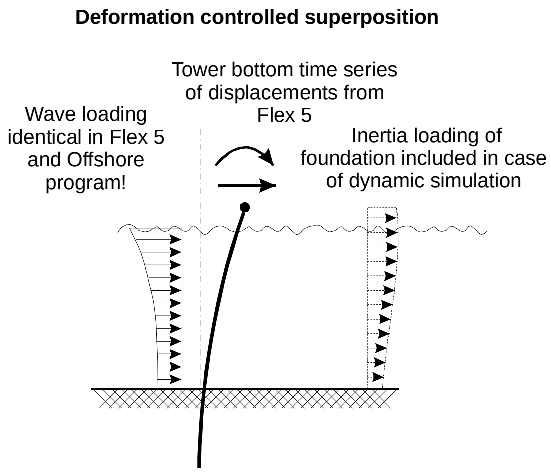

Fig. 5: Deformation controlled approach

	Static	Dynamic
Local wave loads not included for recovery of member forces	– –	–
Local wave loads included both in Flex 5 and for recovery of member forces in detailed model	+	++

Table 1: Accuracy of superposition strategies

If no other finite element package which is capable to include wave loading is at hand, local wave loading may be neglected when retrieving the member forces from the full model. The derived member forces are then theoretically only correct if the deformation of the entire foundation is correctly described by multiples of the unit deflection cases. This is typically not the case when local wave loading and inertia loading are present, thus an error is induced in the results. The magnitude of this error is depending on how much the actual deformation differs from the deformation derived by the unit deformation shapes.

The approach with dynamic calculation and simultanous wave loading is theoretically very accurate. The following has to be kept in mind:

- The substitute model must be modelled very carefully, esp. with regards to stiffness properties. The error in stiffness approximation is directly correlated to the error in member forces!
- Damping input influences the result of dynamic simulation, as well as the adopted time-stepping algorithm. If the implementation of both is different in the two programs, the quality of the results may suffer.

5.2 Force controlled approach

This approach uses the member forces at the foundation top instead of displacements. The member forces at the tower bottom, which include the forces and moments induced by the overall dynamic behaviour of the structure and (in the case of Flex 5) also the second order bending moments, are applied at the foundation top (Fig. 6). To complete the loading, wave loading must be applied again in the Offshore package. Again, the wave loading must be identical in both software packages to obtain good results.

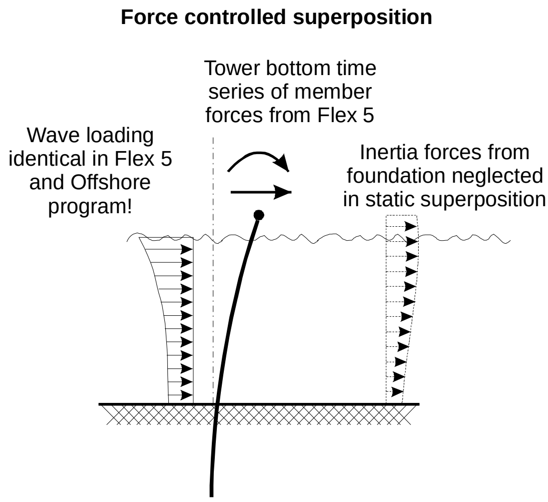

Fig. 6: Force controlled approach

The main advantage in this case is that accuracy demands to achieve a good approximation are less pronounced, esp. with regards to stiffness properties.
Loading from accelerated foundation masses is not included in this case, as the superposition must be performed statically; this leads to a slight underestimation of bending moments below foundation top (the error is increasing with larger distance to the foundation top and larger masses).

5.3 Example

To prove the accurateness of the proposed methods, a Monopile will be analysed and compared with the integrated solution from Flex 5. The main parameters for this calculation are:

Turbine:	REpower 5M, 126m rotor diameter
Hub height:	95.5m MSL
Water depth:	20m MSL (North Sea)
Tower:	Conical 5.5m – 6m O.D.,
Foundation:	Monopile, 6m O.D., 32m penetration
Interface level:	+22.7m MSL

In Flex 5, the Monopile extends to 17.5m below mudline and is clamped at that point (“fixity length” concept). For the substitute Monopile, a combination of independent horizontal and rotational springs has been used to achieve the same eigenfrequencies and foundation top stiffness matrix. This leads to good results for the overall stiffness, but is not totally acurate. This is due to the fact that the model in Flex 5 with a fixity length results in a full stiffness matrix with coupling terms between rotation and translation while the modelling with springs has independent stiffness properties (i.e. the stiffness matrix elements are zero except for the diagonal elements).

Results are compared for the fatigue load spectra for 20 years lifetime (assuming 100% availability).

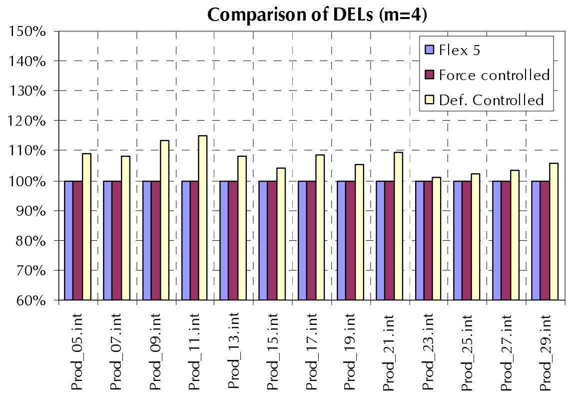

Fig. 7: Comparison of DELs (m=4) for individual time series at tower bottom (=foundation top)

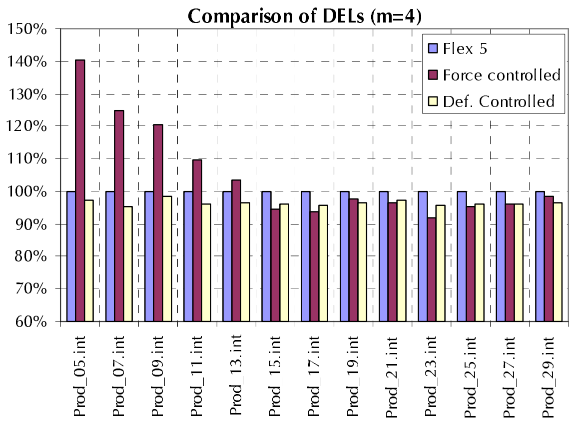

Fig. 8: Comparison of DELs (m=4) for individual time series at mudline

Fig. 7 and Fig. 8 show the comparison based on individual time series for tower bottom and mudline. The following can be observed:

- For the “force controlled” method, results are identical at tower bottom – this was to be expected as the load time series from Flex 5 are used as input here.
- The “force controlled” method yields higher results at mudline for small wind speeds with associated small wave heights. This is due to the fact that the used Offshore code does not include McCamyFuchs-correction for small amplitude waves (diffraction theory) while WaveKin for Flex 5 does have a correction and therefore smaller wave forces are computed.
- This increase is not observed for the “deformation controlled” approach, though. This can be explained by the boundary conditions which are applied as prescribed displacements in each time step at the foundation top. The load “moves upwards” instead of creating large bending moments from the cantilever action in the force controlled approach. This explanation is confirmed by the fact that the bending moments at tower bottom increase against the Flex 5 results for the “deformation controlled” approach (Fig. 7).
- For larger wind speeds, the “force controlled” method slightly underestimates the results at mudline. This is due to the missing inertia loads from the foundation in the static superposition approach. The error is relatively small (<5%), although the modelled monopile is very heavy (structural mass plus trapped water).
- For the “deformation controlled” approach it can be seen that for all wind speeds an increase of loading against Flex 5 results exists at tower bottom while the loads at mudline are slightly too small. On average, the mean value of the relative loads for wind speeds above 11 m/s is 100% - the different member force distribution is thus a result from slightly different stiffness distributions along the structure as explained before. This confirms that good stiffness representation for the substitute system is required for the “deformation controlled” approach.

In general good agreement can be seen. As low wind speeds contribute less to the overall loading, the total error resulting from the overestimation of loads from small waves for the “force controlled” method is relatively small.

The good agreement is also reflected in the fatigue life spectra which are shown in Fig. 9 for tower bottom and Fig. 10 for mudline. For tower bottom, the spectra from Flex 5 and the “force controlled” method are coincident. The spectrum from the “deformation controlled” approach is slightly higher due to the reasons explained before.

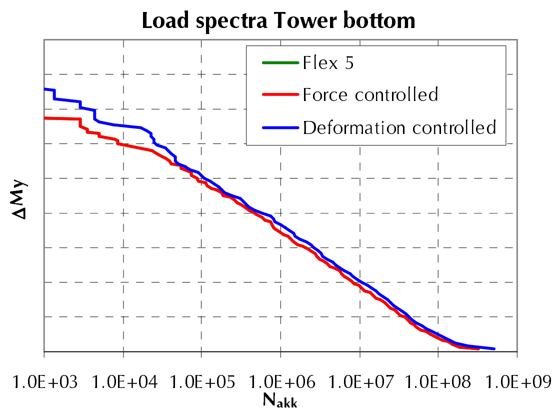

Fig. 9: Fatigue load spectrum My at tower bottom (20 years lifetime, 100% availability)

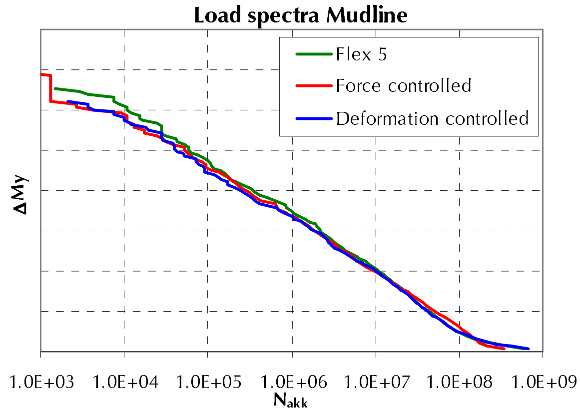

Fig. 10: Fatigue load spectrum My at mudline (20 years lifetime, 100% availability)

Summed up over all time series and weighted with the Weibull distribution for this North Sea site, the results compare as follows:

	Force controlled	Deformation controlled
Tower bottom	$\frac{\Delta M_{eq,fc}}{\Delta M_{eq,Flex5}} = 1.00$	$\frac{\Delta M_{eq,dc}}{\Delta M_{eq,Flex5}} = 1.06$
Mudline	$\frac{\Delta M_{eq,fc}}{\Delta M_{eq,Flex5}} = 0.98$	$\frac{\Delta M_{eq,dc}}{\Delta M_{eq,Flex5}} = 0.96$

Table 2: Overview of results from semi-integrated analysis compared to integrated solution with Flex 5

Overall, the difference of less than 2% for the force controlled method and 4-6% for the deformation controlled method to the results from the integrated simulations is deemed to be absolutely sufficient as other parameters, e.g. ambient and effective turbulence intensity, have much greater impact on the results of fatigue load calculations.

The “force controlled” method is judged to be more robust if exact stiffness representation for the entire length of the foundation can not be ensured. This will be relatively difficult for structures like Tripods.

6 Extreme load calculations

The described methodology can be used for both fatigue and extreme load calculations. For extreme loads, the following should be kept in mind:

- Large waves must typically be calculated with nonlinear wave theories. It should be checked whether the wave theories adopted in the wind and wave load calculation programms give the same results.
- Linear elastic behaviour is assumed in Flex 5 and Bladed, i.e. no non-linearities e.g. from soil reaction can be included. If these effects are not negligible for the load calculations, reasonable approximations must be adopted.

7 Influence of wave loading for the REpower 5M

In the course of these investigations it became apparent that the influence of wave loading is less pronounced for the 5M than for other turbines. This is easily explained as the fatigue loads from the 126m rotor are considerably larger compared to smaller turbines while the inertia driven hydrodynamic loading increases less drastically. Thus, computation of wave loads and the possible error from superposition methods as proposed are of smaller importance compared to other turbines. This should be kept in mind when these methods are used for smaller turbines.

8 Summary and perspective

Substructures for the REpower 5M (which comprises tower and foundation) need to withstand large loads. Even though the Monopile is still an option for harsh North Sea conditions, more complex structures may be economically beneficial.

Foundations other than a Monopile require advanced load calculation techniques that are not readily available in commercial software. Two methods that employ available software packages from the Wind and Oil&Gas industries have been presented that enable the calculation of both fatigue and extreme loads with reasonable accuracy while maintaining a practicable design procedure. The difference for fatigue load calculations has been found to deviate less then 5% from the integrated solution for a Monopile foundation which has been used as an example.

Thus, also complex structures can be analyzed with good accuracy. This leads to optimised foundation structures for large Offshore Wind turbines like the REpower 5M under all typical conditions.

The next step is integrated load calculation of wind and wave actions for complex structures. This requires either the extension of existing wind engineering software packages to include complex structures and wave loading or alternatively the integration of two existing packages. First steps in that direction have been made by REpower and will be further developed in the near future.

9 References

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