Investigation of stability effects of an offshore wind turbine using the new aeroelastic code HAWC2

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Abstract
The objective of the present work is to investigate the effects on tower dynamics when mounting a turbine on a monopile foundation offshore compared to a similar onshore installation. Changes in frequency, modeshapes and damping are investigated including effects of hydrodynamics and nonlinear soil properties. The tool used for the investigation is the new aeroelastic code HAWC2, which is based on a multibody formulation. The multibody formulation used in the HAWC2 code is very generally formulated which means that it can handle any structural object (body) as well as large rotations between the bodies and their associated nonlinear effects. This means e.g. that complex foundation types as very flexible monopile foundations, tripod structures and floating support structures can be simulated in the code. In the present investigation the monopile foundation will be considered. It is possible to apply non-linear springs and dampers on the structure, which are used for soil properties. In the hydrodynamic module of the code the hydrodynamic forces are calculated using Morisons equation. The investigations performed are based on time simulations of a typical 2MW turbine during operation and standstill. Parameter variations are carried out to investigate the influence of wind speed, water depth, monopile length and diameter.

1. Introduction

During the last years more focus on the offshore wind turbines have forced the development in aeroelastic codes to include effects of tower foundation loading from waves, ice etc. This was also the case for the original aeroelastic code HAWC [1],[2] , developed at Risø, but due to limitations in the code at that time some simplifications were done which is now the keypoint for the present investigation. The old simplifications were that the water acceleration and velocity in the Morisons equation were neglecting the relative movement of the tower and that the soil suspension was modelled by extending the tower to an equivalent depth where it was fixed at the bottom. Now a completely new aeroelastic code HAWC2 has been developed at Risø, which among other improvements makes further extensions of the model easy and straightforward.
In this paper the influence of water and soil suspension on frequencies and damping is investigated.

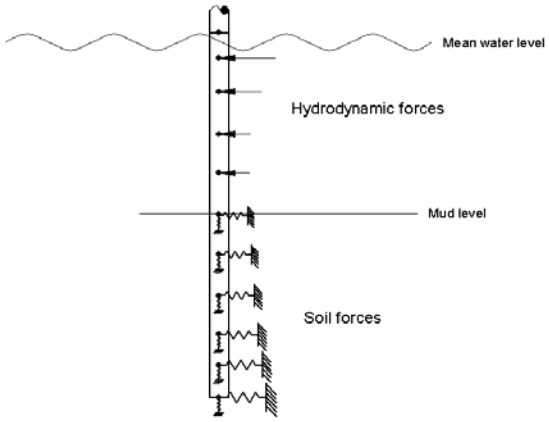


Figure 1: Illustration of external forces on the monopile foundation. The soil forces are illustrated as linear springs even though they are highly nonlinear. The stiffness increases with soil depth.

2. Symbols

A	[m^2]	Cross sectional area
C_m	[-]	Coefficient of inertia
C_d	[-]	Coefficient of drag
C_{1-3}	[-]	Coefficients as function of friction angle
D	[m^2]	Cross sectional diameter
G_0	[Pa]	Initial shear modulus of the soil
K	[Pa/m]	Initial modulus of subgrade reaction
U	[m/s]	Velocity of water
U_{rel}	[m/s]	Relative velocity between water and pile
$\dot{U}_{rel}$	[m/s^2]	Relative acceleration between water and pile
V	[m^2]	Volume of construction pr. length
V_R	[m^2]	Reference volume of construction pr. length
P_u	[N/m]	Ultimate lateral soil strength
Y	[m]	Lateral deflection
X	[m]	Height above mud level
Z_{IF}	[-]	Radius of influenced soil zone divided by pile radius
ρ	[kg/m^3]	Density of water
γ'	[N/m^3]	Submerged unit weight of soil

3. Model

The present investigation was made by use of Risø's newly developed aeroelastic code, HAWC2. HAWC2 is primarily aimed for time simulations of the aeroelastic response of wind turbines. However, the model is continuously extended to fulfil the demands for new features e.g. when the wind turbines move offshore. For the present investigation HAWC2 is extended to include hydrodynamic loading and soil support as well.
The main parts of HAWC2 are the structural part, the external loading part, and the control part. The structural model of HAWC2 is based on flexible multibody dynamics [3]. The wind turbine structure is modelled by a number of bodies, e.g. a tower body or a shaft body, and these bodies are then connected by a set of constraint equations. The flexibility of the structure is modelled by Timoshenko beam elements with 6 degrees of freedom for each node. Normally, the tower and shaft are modelled by a single body each, while the blades are divided into several bodies in order to capture geometric non-linear effects [4]. Further, all inertia forces and external loading are based on the deformed shape of the structure. The equations are solved using the Newmark beta method.

The aerodynamic part is based on the BEM principle with input data from Cl, Cd, Cm, alfa curves. The calculation points on the blades are positioned independently of the structural node/element discretization to provide an optimal distribution of these points, which normally differs from the optimal structural discretization. The spacing between aerodynamic calculation points are closest at the tip and root where the large aerodynamic force gradients normally occur. The BEM method used for calculation of the induced velocities is modified to handle dynamic inflow, large yaw errors. The dynamic stall model by Stig Øye is implemented.

Control of the wind turbine is handled by external DLLs so that the actual control algorithm needs not be linked directly with the programme. However, HAWC2 includes standard control DLL algorithms for common ways of controlling wind turbines. For controlling the rotational speed and the pitch position two methods exist. One is by specifying constraints for the current body which acts as a bearing (free to rotate in one direction) and controlling the position, speed and acceleration by servo forces. The other method is by specifying constraints that fix the body to a neighbouring body and control the angle between the bodies by external demands. Both methods provide full update of all inertia forces etc. within the iterations.

The soil and hydrodynamic loads are applied as external distributed loads on the structure varying in time and through the internal iterations.

The hydrodynamic forces are based on Morison's equation for drag and inertia loads as written in (1)

$$dF_{hydro} = \rho V\dot{U} + \rho V_r C_m \dot{U}_{rel} + \tfrac{1}{2}\rho D C_d U_{rel}\left|U_{rel}\right| \qquad (1)$$

Since Morison's equation includes a large force component in phase with the acceleration, the added mass part, the solver in HAWC2 had some troubles with the iterations at each time step. The reason for this is that the external forces are implemented as explicit formulations exactly as in (1). Since the added mass of the water is app. 10 times larger than the steel of the monopile the solver will not predict the accelerations well. This problem which also occurs when external forces acts as large stiffness (e.g. for the soil stiffness) was solved by adding the equivalent mass and stiffness to the prediction part of the solver.

The soil spring forces are as for the hydrodynamic forces modelled as external forces which enables the possibility of using the exact non-linear spring characteristic as stated in the standards for pile foundations [5],[6]. Since the current monopile for the investigation is mounted in sand, the lateral spring stiffness p-y curves are based on the expression in (2). Such a p-y curve is normally intended for static analysis of the pile. This means that information regarding hysteresis effects and effects of how the p-y curve shall be when soil previously has been submitted to large deflections are lacking. These effects that could very well increase the structural damping on the construction has therefore not been considered.

$$p(y) = AP_u \tanh\left(y\,k\,\frac{X}{AP_u} \right) \qquad (2)$$

P_u is the ultimate lateral resistance of soil based on the expression (3). The p-y characteristics for several soil depths are illustrated in .

$$P_u = \min\begin{cases}(C_1X + C_2D)\gamma' X \\ C_3D\gamma' X\end{cases} \qquad (3)$$

In the present investigation the coefficients chosen are for sand with a friction angle of 40°: C_1=4.5, C_2=4.2, C_3=100, γ' =2000N/m^3

The vertical spring stiffness is based on a t-z curve assuming small vertical shears. This stiffness causes the total turbine to move app. 2 mm downwards due to gravity.

$$t(z) = \frac{2G_0}{D\ln(Z_{IF})} z \qquad (4)$$

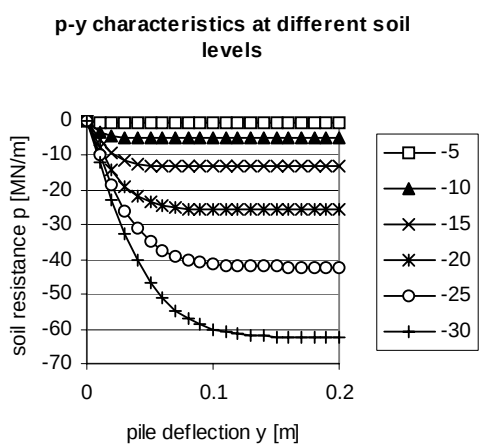


Figure 2: Relation between soil resistance and lateral deflection for a monopile in sand.

4. Investigation of soil support

Normally the soil support is not taken into consideration or simply taken into consideration by extending the tower down to an equivalent fix point. This is clearly a simplification of the boundary conditions from the soil, which is mainly due to limitations in the aeroelastic codes so far.

The monopile chosen for the investigation is a pile with a diameter of 4.5m, wall thickness of 0.05m and a length of 24 m in the soil. The deflection shape of tower and monopile when the tower is submitted to a lateral force of 1MN at the tower top can be seen in Figure 4. The more correct way of modelling results in a deflection shape of the pile where the lower part moves in counter phase with the tower motion.

The size of the pile is essential for its support of the wind turbine above. The natural frequencies of the tower were excited at standstill by applying a lateral external random force on the tower top. In Figure 3 the influence of pile diameter and length can be seen. A constant wall thickness of 0.05m is used. It is seen that the frequency increases with increasing diameter and pile length. When the pile is longer than a certain length, which in this case is app. 20m, the frequency is no longer affected by further pile elongation and only the pile diameter influences the frequency.

The first natural frequency of the tower is 0.347Hz when the tower is fixed at the mudlevel. This is decreased to 0.328 Hz for a pile of 24m and a diameter of 4.5m. However if we assumed the pile to be fixed at –11m, which is the zero crossing for the static deflection in Figure 4 and skips the soil forces the natural frequency decreases to 0.336 Hz. However if the equivalent fix point was –16m, which corresponds to the first deflection tangent the tower frequency decreases to 0.323Hz. A rule of thumb could be that the equivalent fix point for a monopile is between the static zero cross point and the first deflection tangent. For this turbine the equivalent fix point seems to be in –14m This approach also seems to give good results regarding the higher order tower vibrations for the turbine which is shown in Figure 5 when the turbine operates at 8m/s.

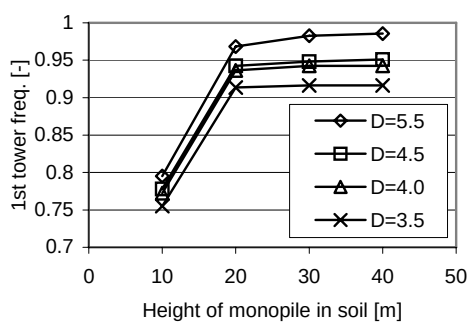
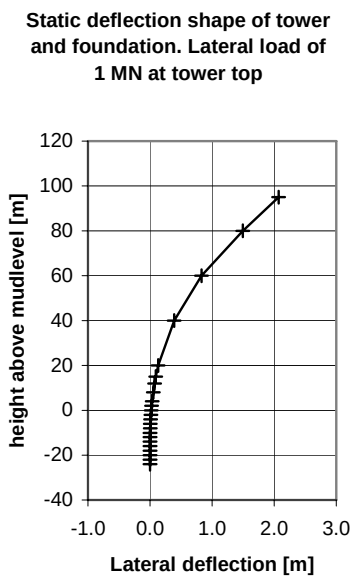


Figure 3: Influence on first tower frequency by changes in monopile lenght and diameter. The frequency is normalized with the tower frequency for a tower fixed at the mudlevel.



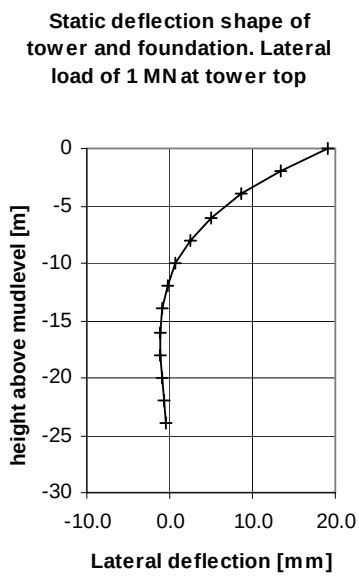


Figure 4 Static deflection of tower and monopile when applying a single static lateral force on the tower top.

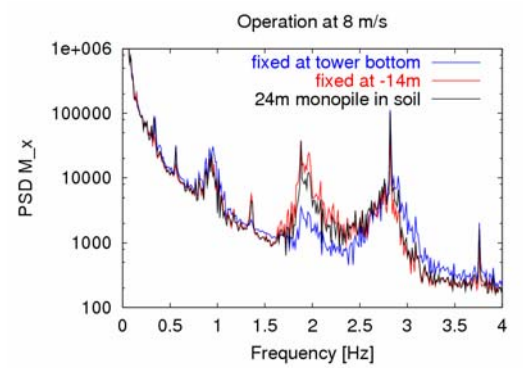


Figure 5: PSD of tower moment at midlevel of tower for three configurations of tower suspension. The monopile in soil and the tower fixed at an equivalent depth of 14 m are almost identical, where the configuration with the tower fixed at mudlevel has less energy at 2 Hz.

5. Investigation of influence of water level on tower frequency and damping at standstill

The influence of water level on tower frequency and damping was tested during standstill conditions with no aerodynamic forces. A constant force activated the tower motion over a short period from 100 to 120 sec., Figure 6. On basis of the tower response after time 120 sec. the first tower eigenfrequency and damping was derived for four water depth; 0m, 10m, 20 m and 30 m. The result is summarized in Table 1 and it is seen that the eigen-frequency is slightly decreased with increasing water level and the damping is almost unchanged.

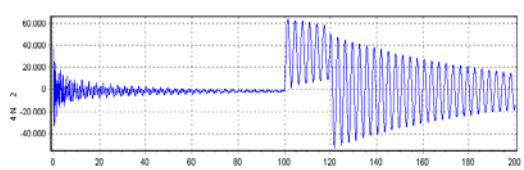


Figure 6: Tower activated by a constant force in axial direction in the period from 100 – 120 sec.

Water depth	*1st tower eigenfrequncy [Hz]*	*Damping Logarithmic decrement*
0	0.3208	0.0450
10	0.3206	0.0451
20	0.3192	0.0443
30	0.3142	0.0485

Table 1: Influence of tower depth on 1st tower frequency and damping during standstill.

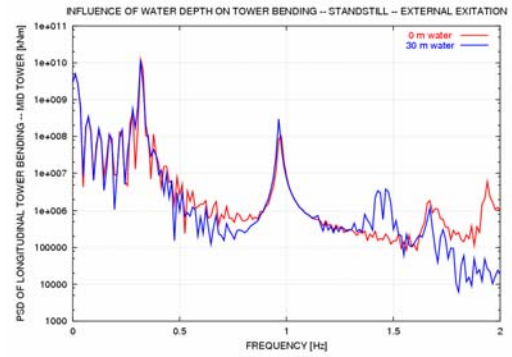


Figure 7: Spectrum of tower bending moment on the mid part of the part at standstill without aerodynamic forces. Tower activated as above with a constant force over a short period.

The investigation of influence of water depth on tower frequency is further illustrated by the power spectrum of the tower bending moment on the mid part of the tower, Figure 7

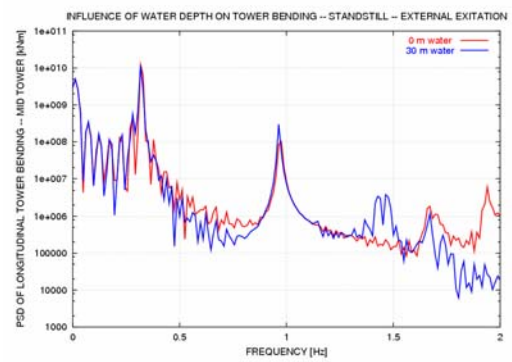


Figure 7. The second tower bending frequency is just below 1 Hz and it is seen that this frequency decreases slightly, Figure 7

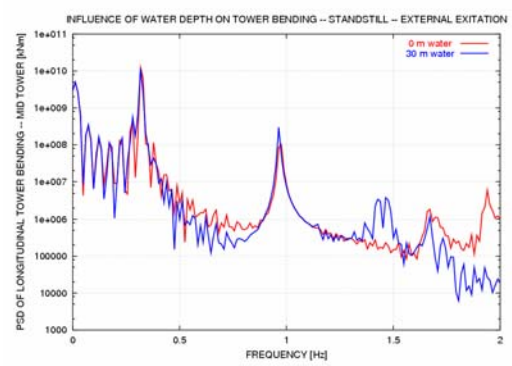


Figure 7. On the other hand there are two other frequencies in the range from 1.5 to 2.0 Hz, which are changed down to about 1.4 and 1.7 Hz, respectively. In these vibrations the 2nd tower bending mode is dominant in combination with edgewise blade bending.

6. Influence of water level of dynamic tower response during operation

Next the influence of water depth on tower dynamics during operation was investigated.

A simulation at turbulent wind at 8 m/s has been run, Figure 8. A considerable less high frequent energy in the PSD spectrum is seen above 1.7 Hz for the 30 m water depth, however with a slight increase at 1.5 Hz. This is due to the change in frequencies as discussed above on basis of Figure 7

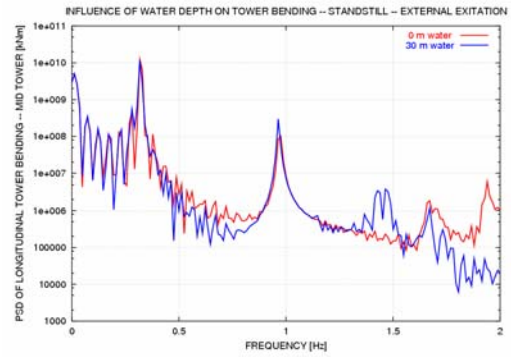


Figure 7, and a minor, but still present, damping effect from the water.

7. Results and discussion

In this paper the newly developed code HAWC2 was used to investigate some stability effects regarding the boundary conditions of a monopile foundation that is lacking in other codes. Nonlinear soil spring forces were applied as well as hydrodynamic forces based on Morisons equation. The problems that arised with the numercal solver due to the explicit formulation of soil and hydrodynamic forces were solved by adding equivalent mass and stiffness to the predictor part of the solver.

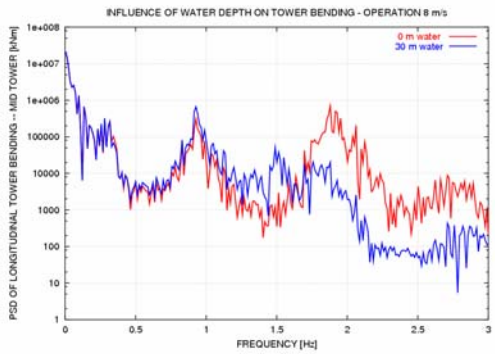


Figure 8: PSD of tower bending moment on the mid part of the tower during operation at 8 m/s.

The boundary conditions of the soil and the flexibility of the pile mainly reduce the first tower frequency with app. 5%. A parameter variation showed that when the pile length exceeds a certain minimum length any further elongation does not contribute to increased stiffness. The equivalent fix point for aeroelastic codes that does not include soil springs was right between the static zero crossing depth and the deflection tangent of the static deflection shape of the pile submitted to a lateral load in the tower top.

The influence of hydrodynamics showed only minor influence on the tower frequency and damping. The tendency was however that the 1st tower frequencies decreased slightly for increasing water depth. The influence of the water mainly appeared in a frequency change of some high order frequencies where the 2nd tower bending mode dominates, that was reduced from 1.7 and 2.0 Hz to 1.4 and 1.7 Hz, respectively.

The results of the investigations are that the hydrodynamics only affects the mode shapes where the 2nd tower bending mode is present by decreasing the natural frequency. The effective damping on the 1st tower vibration is not affected by the hydrodynamics, but slightly on the higher frequencies. It is verified that even though the soil support has a very nonlinear characteristic it is fully justifiable to simplify the model by modelling the monopile down to an equivalent depth where it is fully fixed.

The calculation time for a 600s time simulation with 38 nodes on the tower, 4 nodes on the shaft and 12 nodes on each blade is app. 1000s, which corresponds to a time ratio of 1.7 more than real time. The processor used is a 2.8GHz Pentium 4.

8. References

[1] Petersen, J.T. *Kinematically Nonlinear Finite Element Model of a Horizontal Axis Wind Turbine. Part 1: Mathematical Model and Results.* PhD thesis, Risø National Laboratory, 1990

[2] Petersen, J.T. *The Aeroelastic code HAWC – Model and Comparisons*. In 28th IEA Experts Meeting: 'State of the art of aeroelastic codes'. DTU, Lyngby, 1996

[3] Shabana, A. A., *Dynamics of multibody systems.* Cambridge University Press, University of Illinois at Chicago, 2nd edition, 1998

[4] Larsen, T.J., Hansen, A., Buhl, T. *Aeroelastic effects of large blade deflections for wind turbines*. Proceedings of the special topic conference "The Science of making Torque from Wind". Delft university of technology. The Netherlands 2004.

[5] Offshore standard DNV-OS-J101 *Design of offshore wind turbine structures.* June 2004.

[6] *Guidelines for Design of Wind Turbines 2nd edition*. Det Norske Veritas and Risø National Laboratory. 2002. ISBN 87-550-2870-5