Development of OPASS Code for Dynamic Simulation of Mooring Lines in Contact with Seabed

J. Azcona Armendáriz, X. Munduate Echarri, T. A. Nygaard, D. Merino Hoyos
1 National Renewable Energy Centre, CENER
Ciudad de la Innovación 7, 31621 Sarriguren, Navarra, Spain
Telephone: +34 948 252 800 Fax: +34 948 270 774
E-mail: jazcona@cener.com

2 Institute for Energy Technology, IFE, Norway

3 Acciona Energía, Spain

Abstract

The mooring system of a floating platform keeps the structure in the desired sea location and can also contribute to the system stability. It consists of several cables attached to the platform in a point called fairlead, and with the lower ends anchored to the seabed.

A new code for the dynamic simulation of mooring lines on wind turbines based on Finite Elements is presented. The code, called OPASS (Offshore Platform Anchoring System Simulator), includes effects as inertia, added mass, hydrodynamic drag, structural damping and contact and friction with seabed. The equations of motion are integrated in time using the Runge-Kutta-Nyström scheme. It has been loosely coupled with the FAST code for the simulation of offshore floating wind turbine dynamics. OPASS has been verified with semi-empirical expressions and with other codes as 3DFloat and SIMO-RIFLEX.

Simulations prescribing a harmonic horizontal motion with 5m amplitude at the fairlead with different periods were performed with the objective of evaluating the importance of dynamic effects. In these simulations, dynamic effects on the lines are more important at moderate line tensions and can increase the tension up to 60% in comparison with the static tension. For taut lines dynamic effects are smaller and the quasi-static model could be an acceptable approximation.

A comparison with FAST quasi-static mooring lines model has been also performed for a spar-buoy floating platform. The dynamic model predicts an important increase (30%) in the tension peaks of the cable with respect to the quasi-static approach and the consideration of dynamic effects can also have influence on the global motions of the platform. In particular, the quasi-static model can underestimate the surge damping.

1 Introduction

Wind energy continues growing at a high rate. During the first 6 months of 2011 the worldwide wind capacity rose 9.3% [1]. Offshore wind power is also increasing its relevance as an energy source. 9.5% of the total new wind power capacity in Europe during 2010 was offshore [2]. The main advantages of installing wind turbines in the sea are an increase in the wind quality and a decrease in visual and noise impact.

The average water depth of offshore wind farms has increased from 12.2m in 2009 to 17.4m in 2010 and it is estimated to be 25.5m during 2011 [2]. This increment in depth also means an increment in the cost of the bottom fixed structures as jackets, monopiles or gravity based foundations. For this reason, as depth increases, floating platforms emerge as an alternative for supporting wind turbines.

When a floating wind turbine is installed, the mooring system holds the structure in the desired location (station keeping) and for some platform types, provides a restoring moment that contributes to counteract the overturning moment due to the rotor aerodynamic thrust and the hydrodynamic loading. The mooring
system is made of several cables attached to the platform in a point called fairlead, and with the lower ends anchored to the seabed.

Several codes with capabilities for the simulation of offshore floating wind turbines have different mooring lines models [3]. Computational efficiency of these codes is important due to the high number of load cases that have to be simulated during the design and certification process. Some codes include the non-linear restoring forces from lines through user-defined force-displacement relationships. Some others use a quasi-static approach to calculate the forces caused by the mooring system, which is very economical in processing time, though it neglects effects as inertia, damping or hydrodynamic drag. Finally, there are codes, as the one described in this paper, that consider the full dynamics of the mooring lines. As these dynamic models require more CPU time, special attention to computational efficiency has to be paid when building the set of equations.

The development of OPASS started at the end of 2009. In the next sections the Finite-Element model (FEM) implemented in the code and the coupling with FAST will be described. Some data from the verification of the tool will also be shown. Finally, some conclusions about the importance of dynamic effects, and from a comparison of OPASS with a quasi-static model will be drawn.

2 Description of the Model

The equations of motion of the mooring lines dynamic model implemented in OPASS can be expressed as:

\[ \mathbf{M} \ddot{\mathbf{p}} = \mathbf{f}(\dot{\mathbf{p}}, \mathbf{p}) \]  

Three translational degrees of freedom per node are defined in the model. The mass matrix \( \mathbf{M} \) has contributions from the mass of the cable and also from the hydrodynamic inertia. This added mass is introduced through a coefficient and is considered only in the normal direction of the cable.

The term in the right hand side of equation (1) depends on the position and velocities of the nodal degrees of freedom and collects all the forces over the system: axial elasticity, structural damping, gravity, buoyancy, hydrodynamic drag, contact with seabed and line-seabed friction.

Axial elasticity is considered in the model assuming that the cable follows Hooke’s law. The structural damping is a Rayleigh model: the value of damping is proportional to the axial stiffness and is applied in the axial direction of the mooring line element.

Hydrodynamic drag is split into normal and tangential drag. They are calculated using the drag term of Morison’s equation with different coefficients in each direction.

Gravity and buoyancy forces are considered calculating the equivalent weight of the line in water.

Finite Elements Method discretizes the line in the space so that equations are defined in a certain number of nodes. Interpolation polynomials are used to integrate distributed forces along the elements and transfer them to the nodes. Explicit expressions for the nodal forces have been developed to increase efficiency of the code. Linear polynomials have been used to discretize most of the terms of the equations of motion that have been described above. In the case of normal drag forces there is not an explicit integral of the expression obtained when using linear polynomials. For this reason, constant basis functions have been chosen for this force.

Constant basis functions have been also used to obtain \( \mathbf{M} \) [4]. The use of these low order polynomials provides a global mass matrix that is formed by 3x3 sub-matrices centered on the diagonal. This way, the system of equations (1) can be solved inverting matrices of dimension 3x3, no matter the number of degrees of freedom. This can be done with very low computational effort.

The seabed is assumed horizontal for the contact and friction models. The line-seabed contact model is based on bi-linear springs. If an element has one or both nodes in contact with the seabed, a spring is added at the node position. This spring introduces a vertical reaction force that avoids the node to penetrate into the seabed.

The line-seabed friction model considers the interaction in the horizontal axial and the horizontal transversal directions independently. When a node in contact with the seabed is not moving, a horizontal spring is set at the node position to model static friction. If the resultant of the forces over the node starts moving it from its undisplaced position, the spring introduces a proportional horizontal force according to equation (2). This force is opposite to the displacement and tries to keep the node undisplaced. Since we are
modelling static friction (the node is not sliding) stiffness $k_f$ has to be set high enough so that distance $d$ is small.

$$F_{fs} = k_f d$$ (2)

The static friction force $F_{fs}$ has a maximum value depending on the friction coefficient and the vertical contact force from the seabed, as it is shown in equation (3).

$$F_{fs}^{\text{max}} = C_f F_v L$$ (3)

When the static friction force reaches this maximum value and the resultant of all the other forces over the node are higher, the spring will not be able to keep the node undisplaced and the node will start sliding. At this instant, the static friction force applied by the spring is substituted by a dynamic friction force. This dynamic friction force is always opposed to the node movement and it depends also on the friction coefficient and on the instantaneous vertical contact force as shown in Equation (4).

$$F_{fd} = C_f F_v L$$ (4)

The static friction springs are reinstated if the velocity of a sliding node becomes zero. They are also set if a node contacts the seabed and are removed if the node looses contact.

### 3 Coupling with FAST

The FAST code [5] is a code developed by NREL for the simulation of wind turbines considering the aerodynamics, the structural dynamics, the control and the hydrodynamics. FAST can simulate offshore wind turbines with fixed substructures and also floating platforms. To evaluate the equations of motion of a floating wind turbine, the FAST code needs a mooring lines model that provides the force produced by the mooring system on the platform. The original FAST mooring lines model uses a quasi-static formulation. In order to introduce new dynamic capabilities into the FAST code for the simulation of moored floating platforms, OPASS has been coupled with FAST using a loose scheme. FAST uses an Adams-Moulton-Bashforth predictor-corrector integrator. The solution at each time step is achieved by evaluating twice the equations of motion. In the first one, called predictor, accelerations are obtained from the equations of motion of the turbine and then, they are used to calculate the positions and velocities of the turbine’s degrees of freedom at the next time step. In a second stage, called corrector, this solution is refined using the next step positions and velocities to obtain more accurate accelerations for the next step. A final estimation of positions and velocities from these accelerations is performed and one time step is advanced. OPASS equations of motion are integrated in time using a Runge-Kutta-Nyström scheme [6]. Each time the FAST equations of motion are going to be evaluated either in the predictor or corrector step, the positions and velocities of the platform’s six degrees of freedom are sent to OPASS and this code provides FAST with the forces at the fairleads of each mooring line. Once the predictor and corrector steps are completed, both time integrators advance one time step.

### 4 Verification

#### 4.1 Natural Frequencies

A first verification of the stand alone code was performed comparing free oscillation simulations of a line with the properties of Table 1 with out of plane natural frequencies of the line calculated according to semi-empirical expressions from [7]. The line length was 113m. The anchor was located at a horizontal distance of 100 m from the fairlead, and 45 m below.
Table 1: Line Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass/Unit Length</td>
<td>135.35 kg/m</td>
</tr>
<tr>
<td>Density</td>
<td>7800 kg/m³</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.076 m</td>
</tr>
<tr>
<td>Axial stiffness</td>
<td>5e8 N</td>
</tr>
<tr>
<td>Number of Elements</td>
<td>15</td>
</tr>
</tbody>
</table>

The agreement was good: differences between predicted (0.1336 Hz) and simulated (0.1333 Hz) frequencies were below 0.2%.

4.2 Comparison with SIMO-RIFLEX

A comparison of OPASS simulation results with the commercial code SIMO-RIFLEX was performed to further verify the tool. A model of a 71.5m line with the same characteristics as defined in Table 1 was constructed. In this case, the anchor was located at a distance of 50 m from the fairlead and 30 elements were used to discretize the line. To test a general case, including seabed contact and friction, both anchor and fairlead were located at the same z coordinate: the sea surface. The central portion of the line lies on the seabed, at a depth of 20 m. A normal friction coefficient between cable and seabed of 0.2 was specified. There was also defined an added mass coefficient of 3.8 and a normal drag coefficient of 2.5 that were taken from reference [4]. An oscillatory force was introduced in the fairlead of SIMO-RIFLEX’s model, producing a displacement of 8 m amplitude in the x direction (out of mooring line plane) with a period of 10 s. The same movement was introduced in the fairlead of OPASS model and displacements at different nodes were compared. Figure 1 shows a comparison between displacements of several nodes predicted by OPASS and SIMO-RIFLEX. Lower nodes numbers means that they are closer to the fairlead. Node 9 is not in contact with the seabed and its movements have the higher amplitude. Nodes 14 and 16 are already laying over the seabed. The amplitude of their movements is reduced by friction and peaks are smoother. Node 19 has small displacements and, as simulation progress, it nearly sticks due to friction.

![Figure 1: Comparison of Displacements in x-Direction](image-url)
4.3 Comparison with 3Dfloat

Results from OPASS were also compared with 3Dfloat calculations. 3Dfloat is a code based on FEM that has been developed by IFE [8]. The mooring lines of the OC3-Hywind platform [9] were modelled to perform these verification simulations. The line length was 902.2m and the water depth was 320m. An added mass coefficient of 0.97 and a normal drag coefficient of 0.6 were defined. Tangential drag was neglected. Contact with the seabed was considered, but no friction. The line was divided into 64 elements. Resolution checks doubling the number of elements were run for both models. The results were essentially the same. Resolution checks were also carried out for the time step length.

A horizontal harmonic displacement of amplitude 5m in the in-plane direction was applied in the fairlead with two different periods: 10s and 30s. The curves for Tension-Displacement obtained by both codes are shown in figures 2 and 3. In figure 2, the initial position of the fairlead is 0m. In figure 3, the fairlead is initially displaced 20m in the horizontal in-plane direction and then tension is higher. Results show a good agreement between both codes.

Figure 2: Initial Position of the Fairlead: 0m

Figure 3: Initial Position of the Fairlead: 20m
5 Influence of Dynamic Effects

The simulations performed in the previous paragraph for verification (oscillation of 5m prescribed at the fairlead) were extended for an additional period of 20s and also for fairlead initial positions of -30m and +30m. The properties of the mooring line model were the same. Figure 4 shows the Tension-Displacement dynamic loops generated in these calculations in comparison with the static Tension-Displacement curve (in gray). Tension is increased by dynamics up to 60% (relative to the static) for the simulation with fairlead initial position of 0m and period of 10s. Dynamic effects are smaller when the fairlead initial position is 30m (and thus the tension at the line is higher), even for the 10s period simulation. This suggests that for taut lines a quasi-static model may be an acceptable approximation. Dynamic effects are also smaller at position -30m, where tension is low.

![Figure 4: Dynamic Effects in a Mooring Line](image)

6 Comparison of OPASS with the Quasi-Static Approach

As described in section 3, OPASS has been coupled with the FAST code, providing an alternative to the quasi-static model originally implemented in FAST. Results from FAST with both mooring lines models: quasi-static and OPASS were compared.

The wind turbine used for this simulations was the NREL 5MW Baseline turbine, described in [10]. The turbine was attached to a spar-buoy floating platform composed by two cylinders with different diameters, joined by a transitional cone. Characteristics of the platform are described in Table 2.

Mooring system had three lines at 0, 120 and 240 degrees with respect to the nominal downwind direction. Mooring lines properties are shown in Table 3.

An added mass coefficient of 1.2, a normal drag coefficient of 1.4 and no tangential drag were defined in this model. The values of these coefficients are suitable for wire rope and were obtained from [11]. The line was divided into 60 elements. A resolution check with 120 elements gave essentially the same results. A resolution check on the time-step length was also carried out. Switching from the quasi-static to the dynamic mooring line model with the time step unchanged increased the computational effort with 10%.
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft</td>
<td>90</td>
<td>m</td>
</tr>
<tr>
<td>Freebord</td>
<td>10</td>
<td>m</td>
</tr>
<tr>
<td>Length lower cylinder</td>
<td>78</td>
<td>m</td>
</tr>
<tr>
<td>Diameter lower cylinder</td>
<td>12.16</td>
<td>m</td>
</tr>
<tr>
<td>Length upper cylinder</td>
<td>16</td>
<td>m</td>
</tr>
<tr>
<td>Diameter upper cylinder</td>
<td>6.24</td>
<td>m</td>
</tr>
<tr>
<td>Transition length</td>
<td>6</td>
<td>m</td>
</tr>
<tr>
<td>Mass</td>
<td>8798.728</td>
<td>Ton</td>
</tr>
</tbody>
</table>

Table 2: Spar-Buoy Characteristics

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor radius</td>
<td>600</td>
<td>m</td>
</tr>
<tr>
<td>Anchor depth</td>
<td>200</td>
<td>m</td>
</tr>
<tr>
<td>Fairlead radius</td>
<td>6.5</td>
<td>m</td>
</tr>
<tr>
<td>Fairlead depth</td>
<td>12</td>
<td>m</td>
</tr>
<tr>
<td>Line length</td>
<td>658</td>
<td>m</td>
</tr>
<tr>
<td>Line diameter</td>
<td>0.1468</td>
<td>m</td>
</tr>
<tr>
<td>Mass per unit length</td>
<td>131</td>
<td>kg/m</td>
</tr>
<tr>
<td>Axial stiffness</td>
<td>6.72E+8</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 3: Mooring Lines Characteristics

Figure 5 shows the surge displacements (nominal downwind direction) of the platform in a case with a regular wave of height 10 m, period of 17.63 s and downwind direction. Figure 6 shows the tension at the fairlead of the line aligned with the downwind direction for the same case. Results predicted by FAST coupled with OPASS and by the original FAST code with the quasi-static mooring lines model are compared in both figures.

![Figure 5: Surge Displacement with Regular Waves](image1)

![Figure 6: Fairlead Tension with Regular Waves](image2)
Figure 5 shows a transient in the surge movement of the platform during the first seconds of simulation. The surge displacement oscillates at the natural period of the platform (around 200 s) and also at the period of the wave. In the simulation performed with OPASS the natural frequency of the platform is more damped than in the quasi-static approach due to the influence of hydrodynamic drag over the mooring system of the platform. The quasi-static model predicts peaks of surge displacement up to 2m higher than in the OPASS simulation. This suggests that considering dynamics of the mooring system when simulating a floating wind turbine can have influence over the whole platform behaviour.

The comparison at figure 6 for the tension at the fairlead, shows that the dynamic model predicts higher peaks of tension: the amplitude of tension oscillations in the calculation with OPASS is around three times the amplitude of the quasi-static model. Therefore, dynamic effects as inertia, added mass or hydrodynamic drag seem to have an important influence on tension.

A different simulation under irregular waves with a significant height of 10 m, a peak period of 17.63 s and the same direction was run with the same model. A comparison of the results provided by FAST coupled with OPASS and FAST with the quasi-static model is shown in figure 7. As in the regular waves case, under irregular waves loading, the dynamic model also provides much higher tension peaks (up to 30%) than the values of tension from the quasi-static calculation.

7 Conclusions

A new stand alone code called OPASS for the dynamic simulation of mooring lines have been developed. The code has been coupled with FAST, improving its capabilities for simulating floating platform wind turbines. OPASS introduces new features as: damping, inertia, added mass, water drag and seabed friction. The code has been verified with semi empirical expressions for the natural frequencies and by comparison with the SIMO-RIFLEX and 3Dfloat codes.

Dynamic effects on lines are more important at moderate line tensions. Simulations performed prescribing a harmonic horizontal displacement at the fairlead have increased tension up to 60% with respect to the static value. In taut lines dynamic effects are smaller and the quasi-static model could be an acceptable approximation.

Comparison with quasi-static approaches for mooring lines modelling shows that important phenomena can be missed if the whole dynamics of the lines are not considered. In simulations with regular and irregular waves an important increase in the peaks of tension at the lines fairlead appear (up to 30%), when the dynamic results are compared with the quasi-static calculations.

The whole platform motions can be also affected when dynamic effects are considered. An increase in the surge damping has been observed in the case with incident regular waves.
8 Acknowledgements

We want to thank Ingemar Carlen from Teknikgruppen AB for his guidance and support at the beginning of this study. Part of this work has been performed within a project funded by Acciona Energía.

References


Nomenclature

\( \dot{p} \) vector with the accelerations of the nodal degrees of freedom
\( \dot{\rho} \) vector with the velocities of the nodal degrees of freedom
\( C_f \) line-seabed friction coefficient
\( d \) node distance to the spring origin
\( F_{fd} \) nodal dynamic friction force
\( F_{fs} \) nodal static friction force
\( F_{fs}^{\max} \) maximum nodal static friction force
\( F_v \) vertical reaction force due to contact with the seabed
\( k_f \) stiffness of the static friction spring
\( L \) element length
\( M \) system global mass matrix
\( p \) vector with the positions of the nodal degrees of freedom