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Experimental validation of a dynamic mooring lines code with tension and motion measurements of a submerged chain

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ABSTRACT

This paper shows a complete study of the dynamics of a mooring line: first, a simulation code based on a lumped mass formulation was developed and tested under different setups and second, an equivalent experimental campaign was performed to compare against the numerical predictions. The tests consisted of a suspended chain submerged into a water basin, where the suspension point of the chain was excited with horizontal harmonic motions of different periods in the plane of the catenary. The code is able to predict the tension at the suspension point and the motions of the line with accuracy. For those cases where the line loses and subsequently recovers tension, the resulting snap load and motions are well captured with a slight over-prediction of the maximum tension. The added mass and drag coefficients for chains used in the computations have been taken from guidelines and, in general, predict correctly the hydrodynamic loads. In addition, sensitivity studies and verification against another code show that highly dynamic cases are sensitive to the seabed-cable contact and friction models. The results show the importance of capturing the evolution of the mooring dynamics for the prediction of the line tension, especially for the high frequency motions.

1. Introduction

The mooring system of an offshore floating structure consists of several lines attached to the structure by fairleads with their corresponding lower ends anchored to the seabed. The mooring system holds a floating structure in the desired location (station keeping) and, for certain platform designs, such as tension leg platforms (TLP), provides a restoring moment that contributes to counteract the overturning moment. Several studies relating floating wind turbines reveal that the dynamics of the moorings greatly affects the tension of the lines (see for example Kallesœ and Hansen, 2011 or Masciola et al., 2013); can influence the fatigue and extreme loads of the turbine components (Hall et al., 2014; Kallesœ and Hansen, 2011) and can affect the whole system motions (Masciola et al., 2013; Koo et al., 2014) including the global damping of the platform (Hall et al., 2014).

Due to the importance of these mooring systems in the simulation of floating structures and the necessity of an accurate description of their behavior, a new numerical tool, known as OPASS (Offshore Platform Anchorage System Simulator), was developed by CENER (the Spanish National Renewable Energy Centre) for the simulation of non-linear mooring dynamics. CENER and IFE (Institute for Energy Technology, in Norway) have been collaborating during the last years in the development of dynamic mooring lines models and in the experimental validation of models with scaled tests. A first verification of the OPASS code was successfully accomplished in Azcona et al. (2011) against computations of the dynamic mooring line module of the 3DFloat code (De Vaal and Nygaard, 2015), that is based on a finite element model (FEM) formulation. Afterwards, OPASS was coupled with the FAST V6.02 code (Jonkman, 2007), that was developed by NREL for the integrated simulation of offshore wind turbines. The resulting tool, where the mooring dynamics are computed by OPASS, was satisfactorily verified within the IEA Annex 30 benchmark (OC4) (Robertson et al., 2014b). Finally, an experimental validation has been completed against test data of a submerged chain generated at the Ècole Centrale de Nantes (ECN) wave tank in France. This paper describes the series of tests conducted at ECN by CENER and IFE and the results of the validation, comparing computations with experimental measurements for the chain suspension point tension, and for the motions of the line at different positions. For a highly dynamic case, the effect of seabed friction and damping was studied in more detail, also by verification against the 3DFloat code.

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2. Mooring lines modelling approaches

The equations of motion of a submerged line are non-linear and cannot be solved analytically, consequently numerical methods have to be applied. Some modelling approaches are simplified methods, such as the quasi-static or the force-displacement relationship. The quasi-static approach consists in the resolution of the static equations of the catenary at every time step of the simulation, given the position of the line-platform attachment. This method neglects the inertial effects and also the hydrodynamic drag produced by waves, currents or the movements of the line. In the force-displacement relationship model, non-linear spring stiffnesses are applied to the translational and rotational degrees of freedom (DOF) of the platform point where the line is connected. The force-displacement relationship has to be derived using a mooring line analysis code and the results obtained are similar to the quasi-static approach. Dynamic models consider effects as inertia, added mass or hydrodynamic drag, but they require higher computational effort. Several numerical formulations exist that can solve the dynamics of the line, such as the finite element method (FEM), the finite difference method or multi-body models. The lumped mass model can be considered a variation of the FEM approach, where the mass of the elements is concentrated in the element adjacent nodes. The OPASS code, that is validated in this paper is a lumped mass model.

The lumped mass method was first used to model a mooring line at the end of the 50's (Walton and Polacheck, 1960), though the model was simple and neglected the elasticity of the material, the hydrodynamic drag forces or the seabed-line contact and the model was not validated. This model was improved at the beginning of the 80's including elasticity, cable-seabed interaction and drag due to the relative motion of the cable with respect to the water and was validated with forced harmonic oscillation tests in Wilhelmy et al. (1981) and Nakajima et al. (1982). The agreement with computational models was good, though the tests only covered a limited set of cases that did not consider slack conditions.

The methodology to perform the experimental tests was based in the work described a few years before in Pattison (1974). During these decades other lumped mass models were built, such as Khan and Ansari (1986) and Lindahl (1983) and new approaches based on finite difference method (Roussel, 1976) or finite element method (Johansson, 1976) were developed. More recently, other formulations based in linear finite element methods (Aamo and Fossen, 2000), higher order finite elements (Escalante et al., 2011) and mixed finite element formulations (Montano et al., 2007) have been presented. Some research on dynamic finite element models for polyester mooring lines has also been performed (Tahar and Kim, 2008).

A comparison between a computational lumped mass model and a submerged line with prescribed harmonic displacements at the suspension point is described in Van den Boom (1985). This reference shows a good agreement at the line end tension between the experimental results and the calculation, but comparisons of the cases including slack condition are not shown. In Suhara et al. (1981) the experimental results of the different line configurations are divided into four different states. In the Quasi-Static Condition the frequency of the excitation is low and the dynamic effects are negligible. The Harmonic Condition appears at a higher frequency and presents a tension signal in time domain that is close to sinusoidal. In the Snap Condition, the tension drops to zero when the fairlead moves towards the anchor. When the motion reverses, the tension is recovered, and the zero loaded chain links that are falling suddenly stop and a snap loading is produced. The fourth condition appears when the excitation frequency increases even more and the upper end of the chain completes a period before the whole chain is able to respond. In this case, a lower number of chain links loose tension and the snap load amplitudes start decreasing again. In the same reference, a lumped mass model is compared with tension experimental results with good agreement for the Harmonic Condition, but presents significant differences when the line loses tension.

The importance in the mooring lines dynamic modelling of the accurate identification of the cable elastic stiffness and the free falling velocity is highlighted in Papazoglou et al. (1989). This work also presents a comparison between the experimentally measured tension and numerical computations showing good agreement. In Simos and Fujarra (2004), dynamic simulations with Orcaflex (2014) are compared to experimental data of a mooring line with prescribed harmonic motion of the fairlead. The line tested consisted of a chain - steel wire rope - chain line and the Orcaflex numerical model included the bending stiffness for the wire rope. The experiments include cases with and without current. Good agreement between tension in computations and experiments is achieved except for the cases where the line loses tension. The computed results here show spikes of much higher tension than in the experiments due to a numerical perturbation. In Palm et al. (2013), the development and the experimental validation of a mixed finite element code for cable dynamics is presented, obtaining a good agreement of the computed tension with the experiments that include the slack of the line. The tests used for the validation had been previously published by Lindahl (1985), and consisted of a chain submerged in a wave tank with the upper end attached to a circular plate with a fixed rotation speed, that was located over the water level. Recently, a lumped mass mooring line code has been validated against tension measurements of a floating wind turbine mooring lines obtained with scaled tests in a wave tank (Hall and Goupee, 2015). The measured motions of the fairlead were imposed to the computational model and fairlead tension RAOs, maximums and fatigue loads were in most cases predicted within 10% of the experimental values.

3. Characteristics of the OPASS code

OPASS is a dynamic code based in the finite element method with three translational DOF defined at each node and the element mass lumped at the nodes. The code model consists of an slender line with constant circular section. It considers the effect of inertia, hydrodynamic added mass, gravity, hydrostatics, wave kinematics, tangential and normal hydrodynamic drag, axial elasticity and structural damping. The code neglects the bending stiffness, therefore, it is suitable for the simulation of chains. The contact of the line with the seabed is also included. The code can compute as a stand-alone tool for the simulation of one mooring line or coupled with the FAST V6.02 code (Jonkman, 2007), whose original mooring lines model is a quasi-static approach, for the integrated simulation of floating offshore wind turbines.

4. Basic dynamic equations

A mooring line has one of his ends fixed to the seabed by an anchor and the upper end is attached to the floating platform, usually using a fairlead. Part of the line can be in contact with the seabed. A coordinate system l_0 is defined in the cable as the distance along the unstretched length of the cable, from the anchor to the cable section to be considered.

The cable is a very slender structure and consequently shear forces can be neglected. If bending and torsion stiffness are low enough to also be neglected, the only internal forces are the tension T and the structural damping F_D, being both internal forces always tangential to the cable. The external forces acting on the cable are gravity, buoyancy and the hydrodynamic drag force. There is also an additional inertial force due to the volume of water displaced by the moving line (added mass).

Let us consider an infinitesimal element of cable dl, at point P, that is located at a distance l_0 along the unstretched length of the cable as it is shown in Fig. 1. The forces acting on the dl length of the cable are presented in Fig. 2. The resultant force from hydrostatic pressure and