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Citation for the original published paper (version of record):
Moura Paredes, G., Eskilsson, C., Palm, J. et al (2019). Coupled BEM/hp-FEM Modelling of Moored Floaters. Lecture Notes in Civil Engineering, 18: 504-510.
http://dx.doi.org/10.1007/978-981-13-2306-5_71

Coupled BEM/*hp*-FEM Modelling of Moored Floaters

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Abstract. A coupling between a dynamic mooring solver based on high-order finite element techniques (MooDy) and a radiation-diffraction based hydrodynamic solver (WEC-Sim) is presented. The high-order scheme gives fast convergence resulting in high-resolution simulations at a lower computational cost. The model is compared against a lumped mass mooring code (MoorDyn) that has an existing coupling to WEC-Sim. The two models are compared for a standard test case and the results are similar, giving confidence in the new WEC-Sim-MooDy coupling. Finally, the coupled model is validated using experimental data of a spread moored cylinder with good agreement.

Keywords: mooring dynamics, coupled analysis, finite element method, high-order method, radiation-diffraction method

1 Introduction

The task of designing mooring systems for floating structures is a general problem in ocean and offshore engineering. With regard to station-keeping, there exist many solvers for simulating cable dynamics in the marine environment. The majority rely on first-order methods such as the lumped mass method (e.g. Orcaflex [1] and MoorDyn [2]) or second-order finite element methods (e.g. Riflex in DeepC [3]). The cubic splines finite element method used in ProteusDS [4] is the first work using higher order FEM modelling of cables. Higher-order models are typically more computationally efficient since the same error tolerance can be obtained with fewer degrees-of-freedom compared with low order methods. Recently, a high-order finite element method (*hp*-FEM) for mooring cable dynamics (MooDy) was presented [5]. MooDy uses elemental expansion bases of arbitrary order p to approximate the cable dynamics. In this paper, the coupling of MooDy to the open-source multi-body solver WEC-Sim, based on linear radiation-diffraction theory, is discussed. Here, an initial validation study is provided by comparing results from MooDy with a mooring cable solver based on the lumped mass method [2]. The WEC-Sim-MooDy coupled solver is also compared with experimental data, as well as with results obtained with a CFD-MooDy coupling [6], for a small scale model of spread moored cylindrical buoy.

2 Coupled Mooring Simulations

2.1 WEC-Sim: Boundary Element Model

WEC-Sim is a time-domain multi-body dynamics model. It is developed by the National Renewable Energy Laboratory (NREL) and Sandia [7, 8]. WEC-Sim solves Cummins equation [9] in Matlab/Simulink using hydrodynamic coefficients computed by any method (for example, the Boundary Element Method) for potential flow.

Of specific interest for the present study is the mooring force that goes into Cummins equation. In order to simulate non-linear mooring dynamics, WEC-Sim has to be coupled to external mooring simulation codes. The native mooring code coupled to WEC-Sim is the lumped-mass model MoorDyn [2]. The WEC-Sim-MoorDyn coupling is described in [10] where it was compared with industry standard lumped-mass model Orcaflex [1]. Although there were differences, the results showed an overall good agreement.

2.2 Mooring Models

Under the assumptions of negligible bending and torsion stiffness, the equation of motion for a cable of length L in terms of the unstretched cable coordinate $s \in [0, L]$ reads:

$$\frac{\partial^2 \mathbf{r}}{\partial t^2} = \frac{1}{m_\mathrm{l}} \frac{\partial \boldsymbol{\tau}}{\partial s} + \frac{1+\epsilon}{m_\mathrm{l}} \mathbf{f}_\mathrm{ext} \tag{1}$$

where $\mathbf{r}\left(s, t\right)$ is the global position vector, $\boldsymbol{\tau}\left(s, t\right)$ is the internal tension, ϵ is the strain, m_l is the cable mass per unit length and $\mathbf{f}_\mathrm{ext}$ represents all external forces acting on the cable.

MooDy: High-order Finite Element Method MooDy solves eq. (1) using an *hp*-adaptive discontinuous Galerkin (DG) model. In doing so eq. (1) is first reformulated to be cast in conservative form. The DG method allows discontinuities over the element boundaries and uses a numerical flux to couple elements together. This makes the DG method locally conservative and a good choice for problems involving shocks, such as snap loads. A DG cable is illustrated in Figure 1, where the elements are approximated using a basis made up of Legendre polynomials (top right corner), and the numerical flux is made up of an approximate Riemann solver (bottom right corner). The local Lax-Friedrich flux is used at present. MooDy exhibits convergence rates of $(p+1/2)$ for smooth solutions [5]. This allows for high-resolution solutions using few degrees-of-freedom. As the time step of the cable dynamics is smaller than for the body motion, MooDy does several sub-steps using the explicit third-order strong-stability-preserving Runge-Kutta (RK) scheme. The intermediate mooring boundary conditions for the fairlead positions are generated using a staggered quadratic interpolation as described in [6].

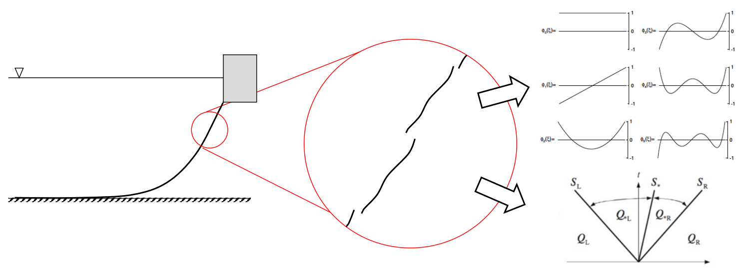


Fig. 1. Outline of the high-order DG modelling approach. The cable is discretized into finite elements of size h with approximation order p. The jumps are exaggerated for illustrative purposes.

MoorDyn: Lumped Mass Method MoorDyn solves eq. (1) using the lumped mass method [2]. The cable is split into discrete nodes of point masses where the mass is concentrated (lumped), see Figure 2. External forces act on the nodes and the nodes are connected by elastic segments (springs) which model elasticity and tension effects. Additionally, there are linear dampers at each segment in order to damp out unwanted oscillations. MoorDyn uses an explicit second-order RK scheme for the time-stepping.

Also included in Figure 2 is the ground model used for simulating the cables' interaction with the seabed. Both MoorDyn and MooDy uses a bilinear spring-damper approach for this.

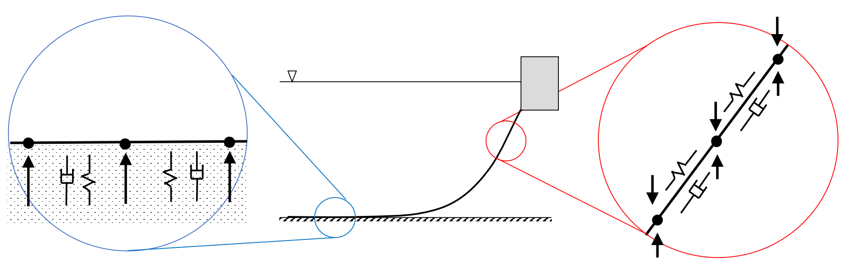
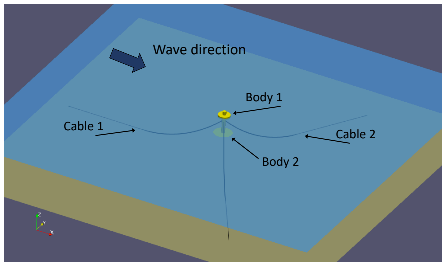


Fig. 2. Outline of the lumped-mass modelling approach.

3 RM3 Test Case: comparing MooDy and MoorDyn simulations

The RM3 case is part of the NREL model testing suite and has been applied before to validate numerical tools [7, 10]. The RM3 device is a heaving two-body point-absorber, Figure 3. The composite solution of chains and near-surface



Quantity	Value
Diameter (D_c)	0.144 m
Density (γ_c)	7736 kg m^3
Stiffness (EA)	583.376 MN
Normal drag coeff. (C_{dn})	1.6
Tangential drag coeff. (C_{dt})	0.5
Normal added mass coeff. (C_{an})	1
Cable length	280 m

Fig. 3. The RM3 case. Left: layout from WEC-Sim. Right: cable data.

floaters of the RM3 tutorial has been replaced with a single chain per mooring leg. This was done to remove the added dynamic effects of the floaters and thus allow a clearer comparison between the cable solvers. The hydrodynamic settings were those of the tutorial, and the mooring chain properties are shown in Figure 3.

Initially, the convergence of the models is evaluated using regular waves with $T = 10\,\mathrm{s}$ and $H = 0.5\,\mathrm{m}$. In lack of an analytic solution, high-resolution simulations were used as proxies for the exact solution (20 elements of 8^{th} order for *hp*-FEM; 1000 segments for lumped mass method). Figure 4 illustrates the obtained convergence in the l^2 norm. For *p*-type refinement MooDy exhibits the expected exponential convergence, illustrated by the straight line in the left plot of Figure 4. For the higher polynomial orders the convergence is sub-optimal. This is caused, in this specific case, by oscillations introduced by the ground model saturating the error. It is clear that MooDy requires few degrees-of-freedom for a given error value and well resolved solutions are obtained with around 50 degrees-of-freedom. The convergence of MoorDyn is evaluated to be of order 1 and the error is more monotone decreasing. Figure 4 also shows the actual recorded tension. It can be seen that MoorDyn predicts a lower mean value of the tension.

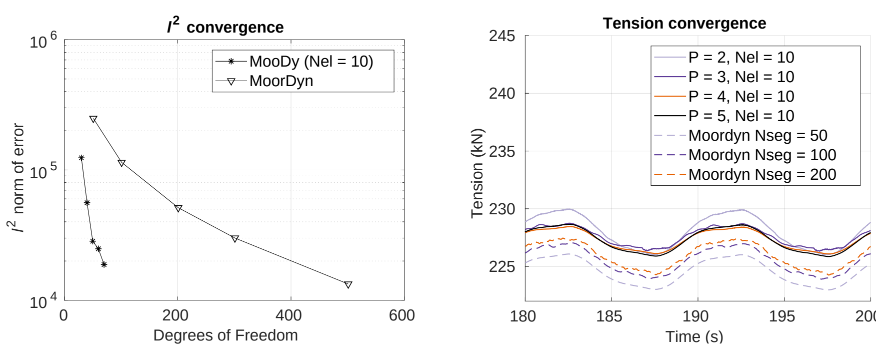


Fig. 4. RM3 case using regular waves. Left: convergence in the l^2 norm. Right: tension at fairlead cable 1.

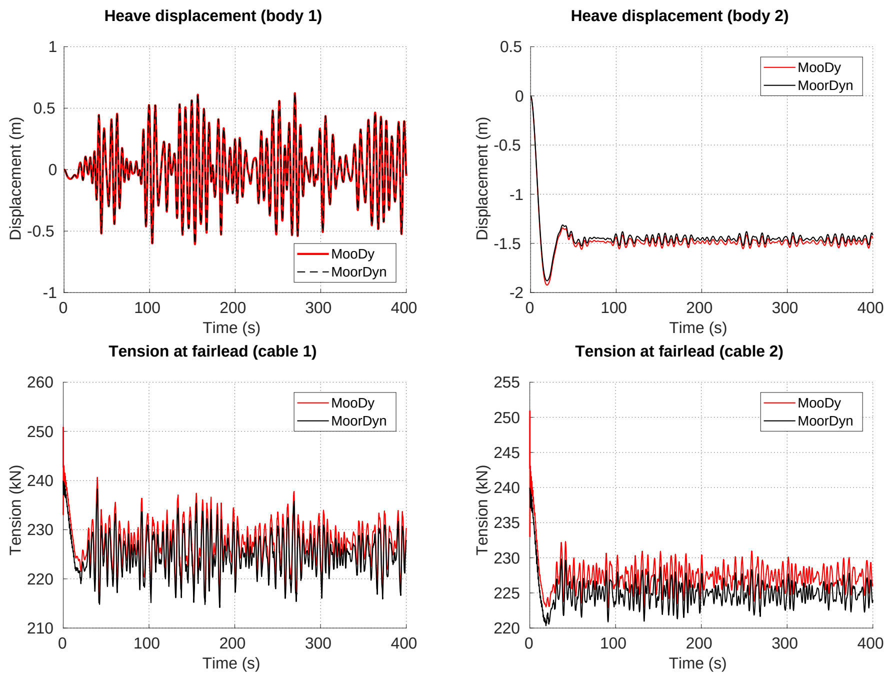


Fig. 5. Motion and tension in irregular waves for the RM3 case. Upper left: heave displacement for body 1. Upper right: heave displacement for body 2. Lower left: tension at fairlead in cable 1. Lower right: tension at fairlead in cable 2.

A comparison between MooDy and MoorDyn simulations in irregular waves (as found in the WEC-Sim tutorial) is presented in Figure 5. MooDy uses 10 elements of order 5, while MoorDyn uses 60 segments.

In the beginning of the simulation the large displacement in heave, of about 1.5 m, is due to the initial position of the RM3 device not being the static equilibrium position. Except for an offset in the mean position of body 2 and in the tension, there is no difference between the results obtained with MooDy and with MoorDyn. The slightly higher mean tension predicted by MooDy leads to a larger mean displacement of body 2 relative to the initial position when compared with MoorDyn. For body 1 the results obtained with MooDy match almost exactly those obtained with MoorDyn: the fairleads of the mooring system are at body 2, influencing the motion of body 2, while body 1 is free to move in heave relative to body 2, being largely unaffected by the mooring system.

4 Moored Cylinder Test Case: validation with MooDy

Experiments of mooring forces on wave energy converters were conducted in the wave basin of the Faculty of Engineering of the University of Porto [11], Figure 6. A truncated cylinder in regular waves is moored with a three-cable

Quantity	Value
Diameter (D_c)	4.786×10^{-3} m
Density (γ_c)	$0.1447\,\mathrm{kg\,m^{-3}}$
Stiffness (EA)	1.6 MN
Normal drag coeff. ($C_{\mathrm{d}n}$)	2.5
Tangential drag coeff. ($C_{\mathrm{d}t}$)	0.5
Normal added mass coeff. ($C_{\mathrm{a}n}$)	3.8
Cable length	6.95 m

Fig. 6. The moored cylinder case. Left: photo of experiment. Right: cable data.

spread catenary system (see Figure 6 for the cable data and [6] for the properties of the buoy). This case was used to validate a coupling between MooDy and the two-phase Navier-Stokes solver found in OpenFOAM [6]. The same wave conditions are investigated here: regular waves with a wave height $H = 0.04$ m for three different wave periods $T = 1.00$ s, $T = 1.20$ s, and $T = 1.40$ s.

The cables are discretized using 10 elements of order 5. Figure 7 shows the computed motions of the cylinder as well as the fairlead tensions compared with experimental data. Except for surge, the computed motions and tensions agree well with the experimental data.

The differences in surge can be partially explained by the absence of second order drift forces in the simulations, since WEC-Sim only computes first order wave loads. There was is no viscous drag applied in the simulations either, which also contributes to the difference in the results, especially in the modes with small radiation damping. Further, in the simulation the waves have a constant wave height $H = 0.04$ m, while in the experiments the wave height varied slightly during each test and could not be set to exactly 0.04 m, which explains part of differences too.

The results shown here can be compared with the numerical results obtained using CFD presented in [6]. In general, there is good agreement with the CFD-MooDy simulation results. There are minor differences caused mainly by the absence of second order drift forces in WEC-Sim, which influence the mean surge drift and the tension.

5 Concluding Remarks

A mooring solver based on the *hp*-finite element method (MooDy) was coupled to the BEM based WEC-Sim wave energy converter simulation tool. The coupling was compared with the existing WEC-Sim-MoorDyn coupling for the RM3 tutorial case. The results were seen to be very similar, with the exception of an offset (which decreased with increasing MoorDyn resolution). Disregarding the difference in discretization approach, completely overlapping results are not to be expected as there are some minor differences in the application of

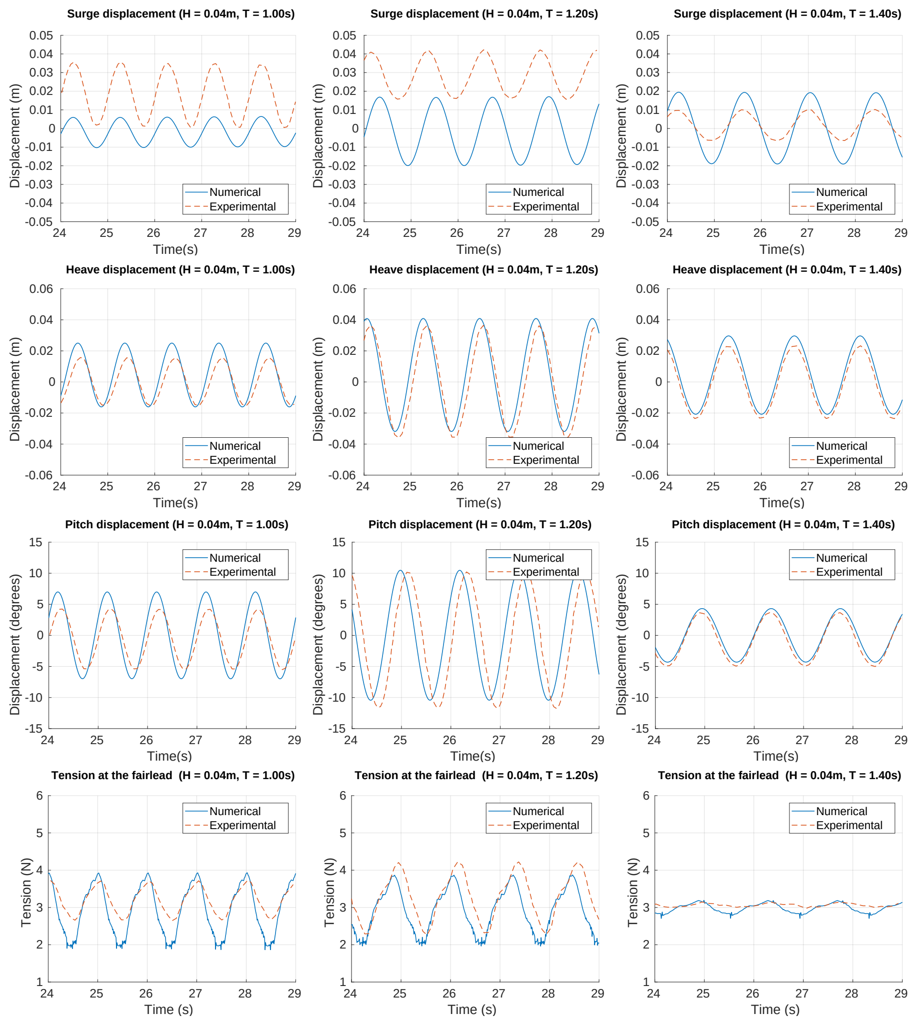


Fig. 7. Motion and tension for the moored cylinder case. Left column: T =1.00 s. Middle column: T =1.20 s. Right column: T =1.40 s. Upper row: surge displacement. Upper middle row: heave displacement. Lower middle row: pitch displacement. Lower row: tension at fairlead of cables. Numerical simulations performed using MooDy.

the ground model (MooDy applies a dynamic tangential friction model) as well as material models (MoorDyn applies an internal damping term). The WEC-Sim-MooDy coupling was then validated against experimental data of a spread moored cylinder. The overall motion and tension showed good agreement with the measured data. However, the tension showed some small amplitude oscillations. These oscillations are due to the ground force being applied on the nodal points in combination with a very stiff cable. The ground force introduces discontinuities inside the higher order elements which in turn cause oscillations in the tension. To address this issue is ongoing work.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 752031 MoWE H2020-MSCA-IF-2016. Johannes Palm acknowledges the support from the Swedish Energy Agency through grant P42246-1.

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