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Direct time domain analysis of floating structures with linear and nonlinear mooring stiffness in a 3D numerical wave tank

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ABSTRACT

In this paper, motion response of a moored floating structure interacting with a large amplitude and steep incident wave field is studied using a coupled time domain solution scheme. Solution of the hydrodynamic boundary value problem is achieved using a three-dimensional numerical wave tank (3D NWT) approach based upon a form of Mixed-Eulerian–Lagrangian (MEL) scheme. In the developed method, nonlinearity arising due to incident wave as well as nonlinear hydrostatics is completely captured while the hydrodynamic interactions of radiation and diffraction are determined at every time step based on certain simplifying approximations. Mooring lines are modelled as linear as well as nonlinear springs. The horizontal tension for each individual mooring line is obtained from the nonlinear load-excursion plot of the lines computed using catenary theory, from which the linear and nonlinear line stiffness are determined. Motions of three realistic floating structures with different mooring systems are analyzed considering various combinations of linear and approximate nonlinear hydrodynamic load computations and linear/nonlinear mooring line stiffness. Results are discussed to bring out the influence and need for consideration of nonlinearities in the hydrodynamics and hydrostatics as well as the nonlinear modelling of the line stiffness.

1. Introduction

For evaluating the global performance of a floating body with station keeping system, an integrated coupled dynamic analysis in the time domain is preferred over frequency domain approaches. Wichers [1] carried out a coupled time domain simulation of a tanker moored to a single point mooring system using impulse response functions and a constant frequency domain hydrodynamics coefficient model. Coupled analysis for a turret moored FPSO with mooring and risers operating in different water depths were studied by Ormberg and Larsen [2]. In their study frequency dependent added mass and damping coefficients were computed in the frequency domain based on linear hydrodynamics and mooring line dynamics was modelled by Finite Element Method (FEM). A comparative study of quasi-static and dynamic approaches for a spar platform with mooring lines was carried out by Chen et al. [3] where the wave force on the spar platform are calculated by Morison equation and the nonlinear FEM code CABLE3D was used to calculate the dynamics of mooring lines. Kim and Sclavounos [4] studied large amplitude coupled motions of spar and TLP structures where the mooring line dynamics was solved by finite difference scheme and hydrodynamic interaction forces were computed based on linear radiation/diffraction theory. Coupled and uncoupled time domain analysis of a turret moored FPSO in a harsh environment was studied by Heurtier et al. [5] where hydrodynamics loads acting on the FPSO are calculated from linearized potential theory and mooring lines and production risers were represented as cable, bar and slender beam elements, and solved in the framework of FEM. Garrett [6] compared fully coupled analysis in both time and frequency domain for a semisubmersible floating production platform in which the rigid body motions were computed using the radiation–diffraction programme WAMIT and the mooring lines were represented by elastic rods in FEM. Tahar et al. [7] made a comparative study of time and frequency domain coupled analysis using a computer programme WINPOST with full-scale data of a Horn Mountain spar during *Hurricane Isidore*. Low and Langley [8] proposed a hybrid method (time/frequency domain) for efficient computation of coupled analysis of vessels/mooring/risers. Tahar and Kim [9] studied dynamic analysis of polyester mooring lines in deepwater in the time domain and assessed the effect of large elongation of polyester line and nonlinear stress–strain relations. Zhang et al. [10] compared the results of frequency domain, semi-coupled and fully coupled time domain analyses with experimental data for a cell–truss spar and concluded that the frequency domain and semi coupled time

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Nomenclature

d	water depth [m]
H	incident wave height [m]
K_{xx}	roll radius of gyration
K_{yy}	pitch radius of gyration
K_{zz}	yaw radius of gyration
$\bar{n}$	unit normal vector
r	distance between field and source point
T	wave period [s]
β	wave angle [°]
η	free surface elevation
ρ	fluid density [kg/m^3]
g	gravitational constant [m/s^2]
σ	solid angle
X_F	fairlead x-coordinate in earth axis
Y_F	fairlead y-coordinate in earth axis
X_{AC}	anchor x-coordinate in earth axis
Y_{AC}	anchor y-coordinate in earth axis
$\rightarrow \dot{r}_G$	time derivative of vector $\rightarrow r_G$
$\rightarrow \dot{\Theta}$	time derivative of vector $\rightarrow \Theta$

domain analysis were computationally more efficient for initial conceptual design. Kim et al. [11] carried out experimental studies of a spread moored twin pontoon four column semisubmersible and compared with numerical simulation computed by higher order panel method for hydrodynamic forces and FEM method for mooring system dynamics in the time domain. Yang et al. [12,13] carried out time domain coupled analysis of floating bodies based on Stokes perturbation procedure using suitable time integration scheme. Hydrodynamic wave loads were computed in the time domain rather than transforming from frequency domain and the rigid body dynamics was coupled with mooring line dynamics computed based on rod theory of Garrett [14]. Kim et al. [15] made a comparative study in the time domain for linear and nonlinear mooring systems for a turret moored FPSO and spread moored semi-submersible and concluded that the effect of mooring dynamics were significant only for deep water whereas in shallow water the influence of mooring dynamics on the overall restoring forces and thus to the overall motions was negligible.

Nearly all of the time-domain simulation studies in the above except [12] appears to follow a similar approach in which the frequency-dependent hydrodynamic coefficients (added mass, and damping) are usually computed by linear radiation–diffraction code, and the frequency-domain equations of motion written in the time domain through impulse response and convolution integral originally suggested by Cummins [16] and further developed by Ogilvie [17]. In a fully coupled solution method, mooring system dynamics is formulated using either FEM or lumped mass method given by [18], and the combined dynamic equation of motion of the floating body and the mooring line are solved in the time-domain. Almost all studies conclude that FEM modelling or lumped mass method to capture the dynamics of mooring lines are effective for deep water but their influence on floating body motions in water depth below 500 m are less important. For the relatively shallow water cases, therefore, a simpler spring-model for the mooring line may be adequate for studying the body-motions in place of using a far more time-consuming modelling of the mooring line dynamics through FEM or lumped mass model.

The main objective of the present study is to carry out a coupled analysis of moored floating structures in a direct time domain solution method following a form of the three dimensional numerical wave tank (3D NWT) approach. For full nonlinear wave-structure interactions in potential flow, one of the available methods is the Mixed Eulerian–Lagrangian (MEL) based NWT approach. After the pioneering work of Longuet-Higgins and Cokelet [19] on development of the MEL method for simulating extreme and breaking waves, many works have been reported describing developments of a MEL based NWT simulation for wave-structure interactions in 2D as well as 3D. A detail review of the available NWT based nonlinear methods may be seen in Ma and Yan [20] containing a large number of references therein. Although many of the difficulties associated with this method for a full nonlinear simulation of extreme waves with 2D floating bodies have been resolved, a full nonlinear simulation of extreme waves with 3D floating bodies still remains difficult particularly for generating long duration simulation results for practical geometric configurations like offshore platforms and ships. One of the constraints in this context is the prohibitively large computational time the method demands, see e.g. the recent work of You and Faltinsen [21].

In the present method, a simplified form of the NWT based method has been developed, following the approach outlined in [22,23] but with modifications in the numerical implementation that enable generation of long duration converged steady-state results for practical 3D structures. In this scheme, a circular tank is considered in which there exists an incident wave. The moored structure is then introduced at the centre of the tank, and the subsequent interaction of the incident wave with the structure is simulated. The interaction hydrodynamics of radiation and diffraction are determined at each time step as the solution progresses through a discretized integral equation solution based on Rankine panel method. Certain simplifying approximations are however introduced in the solution method which allows the formation of the integral equation over a time-invariant surface, which in turn enables the computation count to be brought to a level suitable for routine use and comparable to the available schemes based on convolution integral formulations. The incident wave forces and the hydrostatic forces which consist of significant nonlinearities are determined on the exact wetted surface under the incident wave profile. This is often referred to as body-exact formulation for Froude-Krylov (FK) and hydrostatic forces. The incident wave can be steep and defined by a nonlinear numerical model. As the radiation and diffraction are computed at every time step along with the solution of the equations of motion, it is in this spirit that the term direct time-domain solution has been used above. The mooring lines are treated as springs but nonlinear stiffness is considered, determined from pre-computed load excursion characteristics of individual lines. Thus the formulation enables consideration of certain important nonlinearities of the hydrodynamic forces, and also nonlinear stiffness of the mooring lines. A consistent linear solution can be recovered from this by simply taking a linear incident wave, determining all parameters on the mean surface and taking a linear spring model for the mooring lines. Numerical computations are performed for three realistic moored floating structures and comparative studies made for various combinations of linear and nonlinear hydrostatics and incident-wave hydrodynamics with linear and nonlinear mooring line stiffness, to bring out the relative importance of nonlinearities.

2. Floating body equation of motion

The problem considered is the motion of a moored floating body in an incident wave field, a schematic diagram of which is shown in Fig. 1. At the outset, two right-handed Cartesian coordinate systems are introduced: an earth fixed coordinated system ***OXYZ*** with origin O at the undisturbed water surface $z = 0$ with z directed vertically upwards, and a body-fixed system $Gx'y'z'$ with origin $\boldsymbol{G}$ coincident with the body centre of gravity.