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Hydrodynamic analysis of marine multibody systems by a nonlinear coupled model

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ABSTRACT

This study investigates the hydrodynamic performance of two freely floating or interconnected barges. A nonlinear decomposition model in the framework of potential flow is employed to simulate the wave-body interactions in the time domain. This piece of work focuses on the accurate calculation of hydrodynamic forces and motions of a multibody floating system. The hydrodynamic forces are indirectly calculated through an auxiliary function approach, which is extended to application of two floating bodies in the present study. The resultant coupled motion equations for two bodies clearly demonstrate the influence of one body on the other. To incorporate an interconnection between two floating bodies, a constraint matrix method is developed where the connection constraints are mathematically represented by a constraint matrix. The constraint forces in the connection are solved in the modified motion equations. The newly formulated coupled auxiliary function and constraint matrix approaches for two bodies with and without interconnections are validated by comparisons of first-order response against linear frequency-domain models. Two types of interconnections, namely, the rigid connection and the middle-hinge connection, are examined in both beam sea and head sea to demonstrate the effectiveness of the proposed method. Coupling effects of different connection scenarios on body motions as well as the influence on constraint forces are discussed. Furthermore, simulations using relatively steeper waves are performed and compared with mild wave cases. The nonlinear effect is highlighted by decomposing the higher harmonic components of nonlinear responses.

1. Introduction

The multibody hydrodynamics has long been studied in the discipline of ocean engineering. The complexity of multibody hydrodynamics lies in not only the structure-induced severe wave field but also the coupled multibody dynamics if the bodies are interconnected. To date, we have seen increasingly more floating multibody systems across the global waters, and they are becoming dramatically crucial in terms of economy and human life. For instance, permanent structures include floating LNG terminal clusters, multiple large floating blocks for the purpose of land claim; and some temporary offshore multibody systems include loading/offloading operations between LNG carrier and FPSO, ship-to-ship cargo transfer, and marine lifting/installation. More reliable tools need to be developed to accurately predict the hydrodynamic behaviors of such complicated coupled systems, and to produce knowledge on multibody hydrodynamics.

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Linear frequency-domain potential flow models for dealing with wave-body interactions were profoundly developed in various research groups a few decades ago and remain dominantly utilized in the industry. Based on the linear frequency-domain models, some works have been done concerning the multibody hydrodynamics. Earlier, Ohkushu (1974), Van Oortmerssen (1979), Loken (1981), Kodan (1984), and Fang and Kim (1986) investigated two adjacent bodies in waves without connection in-between, which highlighted the influence of multibody hydrodynamic interactions. More recently, Kashiwagi et al. (2005) studied two side-by-side ships, with a focus on the wave drift forces and moments. Fairly good agreements were obtained between calculations and measurements for both first order forces and second order drift forces. Nevertheless, these early works did not consider any interconnection between the floating bodies, and the motion equation of each body is individually solved in the frequency domain.

In the cases where the adjacent bodies are interconnected, possibly by hinges or moorings, a key concern is the dynamic behavior of the interconnected bodies and more importantly the motion coupling effect due to the interconnection. Newman (1994) introduced a mode expansion method to compute the motions of simply connected (rigid or hinged) floating bodies as well as the motions of the connection, within the frame work of linear frequency-domain model. In this method, additional motion modes due to the deformation of the simple-link multibody system are solved together with the motion modes of the bodies. It is generally effective in terms of considering the dynamic coupling effect between the bodies, as adopted in Lee and Newman (2000) and Taghipour and Moan (2008). A similar concept of modelling connection is utilized in the analysis of hydroelastic response of flexible floating interconnected structures. For instance, Fu et al. (2007) presented a hydroelastic model by taking into account rigid/hinge modes and studied two flexible interconnected floating plates. Good agreements were found between their numerical results and experiments for a special case with high stiffness connection (equivalent to rigid). Wang et al. (2010) employed the mode expansion method presented by Newman (1994) to model the structure deflection and investigated the hydroelastic response of very large floating structure with a hinge or semi-rigid line connection. Nevertheless, the mode expansion method is mainly suitable to very simply linked bodies where the system can be regarded as a single deformable body. For systems with complex constraints, the connection motions may not be modeled as expanded modes. In addition, frequency-domain calculations in any case present limited information for the hydrodynamic process of wave interaction with an interconnected floating system.

In modelling the dynamic response, a prevailing strategy is to firstly calculate wave forces and hydrodynamic coefficients (added mass and radiation damping coefficient) from a linear frequency-domain diffraction-radiation model, then the motion equations of multibody systems are solved in the time domain. This two-step strategy is favored nowadays in the industry, because it is quite convenient to add whatever extra external loading (mooring, fender, hawser and riser) into the motion equations to perform dynamic analysis. Applying this strategy, Koo and Kim (2005) simulated two moored vessels in side-by-side offloading operation in irregular waves by using a combined matrix method. They considered both vessel and mooring dynamics, as well as the coupled hydrodynamic coefficients. The sway and roll motions were found significantly influenced by the mechanical coupling effects of the two vessels. Hong et al. (2005) numerically and experimentally investigated three side-by-side moored vessels. They adopted a generalized mode concept to obtain their time-domain motion equations by expanding the transient motion equation of a single body which was described in Cummins (1962). This generalized mode approach was previously presented in Choi and Hong (2002). O'Cathain et al. (2008) modeled and analyzed a hinged-barge wave-energy system in the time domain by solving the Newton-Euler equations of motion and eliminating degrees of freedom associated with the hinge constraints. Again, by employing the hydrodynamic coefficients computed from a linear frequency-domain model DIFFRACT, Sun et al. (2011) implemented the motion equations with constraints by using Lagrange multipliers and studied a tank connected with an FLNG barge by rigid, hinge and spring-type connections. It was shown that the free surface elevation in the gap between the two vessels is obviously influenced by the behavior of the floating vessels and the constraint forces in the connections. A similar work concerning a multibody pier was also presented by Tajali and Shafieefar (2011). Nevertheless, at any rate simulations via the two-step approach do not reproduce the real hydrodynamic process of wave interaction with a multibody floating system. The reason is that the two-step approach requires the linear frequency-domain results which are essentially obtained at the equilibrium positions of the system.

The aim of this study is to develop an effective dynamic model capable of calculating responses of a multibody system with or without interconnections in the framework of three-dimensional fully nonlinear potential flow theory. Unlike the two-stage approach, we solve both the wave field and the body motions simultaneously in the time domain, which reproduces the real dynamic responses of the multibody floating system. Two main contributions of the newly developed model are: (a) extension of the formulation of the auxiliary function approach, which is used for indirect calculation of wave forces, in application of multiple floating bodies; and (b) development of a constraint matrix method for modelling interconnections between bodies. The newly derived motion equation system clearly demonstrates the hydrodynamic coupling effect of two floating bodies and the constraint effect on the floating system due to the interconnection. Furthermore, through simulations by employing this model, a better understanding of coupled hydrodynamic behavior of marine multibody systems with/without interconnections is created. The nonlinearity associated with free surface conditions is also identified by comparisons between mild and relatively steep wave conditions.

The organization of this paper is as follows. Section 2 briefly presents the governing equations of the fully nonlinear potential flow model as well as a wave decomposition strategy. Based on this model, we, for the first time, derive the formulation of the coupled auxiliary functions approach to indirectly calculate wave forces for the case of two floating bodies. In cases where the bodies are interconnected, we present a constraint matrix method for modelling the connections of various types, and the constraint forces in the connection are solved simultaneously with the coupled body motions. Section 5 simulates a case of two freely floating barges. The first order results, extracted from the present fully nonlinear time-domain simulations, are compared with the linear calculations, where satisfactory agreements are achieved. Section 6 simulates two side-by-side interconnected barges of a simple configuration. Validation is also performed by comparisons against a linear model in Newman (1994). Two types of connections are