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Accelerated 3D multi-body seakeeping simulations using unstructured finite elements

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ABSTRACT

Being capable of predicting seakeeping capabilities in the time domain is of great interest for the marine and offshore industries. However, most computer programs used work in the frequency domain, with the subsequent limitation in the accuracy of their model predictions. The main objective of this work is the development of a time domain solver based on the finite element method capable of solving multi-body seakeeping problems on unstructured meshes. In order to achieve this objective, several techniques are combined: the use of an efficient algorithm for the free surface boundary conditions, the use of deflated conjugate gradients, and the use of a graphic processing unit for speeding up the linear solver. The results obtained by the developed model showed good agreement with analytical solutions, experimental data for an actual offshore structure model, as well as numerical solutions obtained by other numerical method. Also, a simulation with sixteen floating bodies was carried out in an affordable CPU time, showing the potential of this approach for multi-body simulation.

1. Introduction

Seakeeping is a topic of great interest in marine and offshore engineering. This interest is growing in the last years due to the boost given by the development of marine renewable energies. In this context, the development of time domain seakeeping programs is a main request from the industry. Moreover, the simulation of multi-body systems is a key point in the development of more efficient marine renewable technologies such as wave energy converters, floating wind turbines, etc.

Up to date the numerical simulation of seakeeping has been mostly carried out in the frequency domain. The reason might be that computational cost of time domain simulations were too high and too long when compared to those of frequency domain. Moreover, assumptions like linear waves and the harmonic nature of water waves made the frequency domain to be the right choice. However, nowadays computing capabilities make possible to carry out numerical simulations in the time domain in a reasonable time. Time domain simulation has the advantage of simulating phenomena that cannot be handled in frequency domain such as transient situations due to wave amplitude modulation over time, parametric resonance, and other nonlinear effects. Furthermore, in the frequency domain, the simulation of multi-body systems requires calculating the interaction among the bodies, which increases quickly the computational effort as the number of bodies increase. On the other hand, when simulating in the time domain, the interaction among bodies is solved in a natural way without leading to a big increase of computational effort.

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Regarding the numerical method traditionally adopted for seakeeping simulation, the boundary element method (BEM) has dominated over others like finite element method (FEM). We might find the reason in the fact that most of the computational effort is spent in solving the Laplace equation. Then it might look like BEM offers a lower computational effort. However, Cai et al. [1] carried out a heuristic study regarding the computational effort required for solving the Laplace equation by BEM and FEM. This study concluded that for a similar three-dimensional problem and a discretization size, the number of unknowns of BEM and FEM are $O(N^2)$ and $O(N^3)$, respectively, being N the number of unknowns needed in one dimension to achieve the desired discretization. But the computational costs are $O(N^4)$ and $O(N^3)$ respectively. Therefore, while BEM might be more efficient for problems with low number of unknowns, FEM becomes more efficient respect to BEM as the number of unknowns N increases. Considering that computational capabilities continuously increases, so does the complexity of problems to be undertaken, and the number of unknowns required. Hence FEM might become more efficient than BEM.

Another advantage of FEM is the fact that it has been conceived for naturally solving the Laplace equation on unstructured meshes. This makes easier the discretization of complex computational domains.

In the last decade, there have been extensive applications of the finite element method (FEM) to free surface problems. For example, Oñate and García [2] presented a stabilized FEM for fluid structure interaction in the presence of free surface where the latter was modeled by solving a fictitious elastic problem on the moving mesh. In [3,4] Löhner et al. developed a FEM capable of tracking violent free surface flows interacting with objects. Also García et al. [5] developed a new technique to track complex free surface shapes. However, many works like the previous ones are based on solving the Navier–Stokes equations, too expensive computationally speaking when it comes to simulating real problems regarding ocean waves interacting with floating structures. These sorts of problems can be more cheaply simulated using potential flow theory along with Stokes' perturbation approximation. For details on Stokes' wave theory, the reader is referred to [6].

With regards to wave–body interaction problems, there has been extensive work as well in the last decade. In [7], Wu and Eatock Taylor used both the FEM and the mixed FEM to analyze the two-dimensional (2D) nonlinear transient water wave problems. Later Wu and Eatock Taylor [8] made a detailed comparison between FEM and the boundary element method (BEM) for the nonlinear free surface flow problem and found that the former was more efficient in terms of both CPU and memory requirement. Greaves et al. [9] employed quad-tree-based unstructured meshes to model fully nonlinear waves in 2D, using an ALE formulation in structured meshes. In [10] an hp-element technique was adopted to simulate the 2D free surface flow problem. In [11] and [12], an implementation of FEM schemes to simulate 3D wave–body interaction was introduced using moving meshes along with an explicit time marching scheme for the free surface boundary condition. However, in those cases, re-meshing and interpolation were needed, which leads to a high CPU cost. Westhuis [13] in his PhD dissertation developed a FEM code for nonlinear waves and focused in the development of groups of waves. The code relied in some specific structured mesh configurations and without body interaction. Hu et al. [14] applied FEM to study the case of a vertical cylinder under forced motions based on the works [7] and [8]. Turnbull et al. [15] coupled structured and unstructured meshes to simulate 2D wave–body interactions. The vertical velocity at nodes belonging to the free surface required a prescribed number of nodes to be aligned vertically. Wu et al. [16] solved a 3D problem using a semistructured mesh in the vertical direction. This way the nodes will be aligned vertically and the vertical component of the velocity at the free surface can be easily estimated by finite difference. Wang et al. [17] used FEM to study the effect of second-order wave sloshing within a tank in 2D. The fourth-order Runge–Kutta method was used as a time marching scheme for the free-surface boundary condition. A FEM solver for a second-order wave diffraction by an array of vertical cylinder using semistructured mesh has been presented in [18]. Again, in order to estimate vertical velocity at the free surface nodes it is required a prescribed number of nodes to be aligned vertically. An explicit fourth-order Adams–Bashforth scheme was used as a time marching scheme for the free surface boundary condition. Later on, the same authors in [19] used a structured mesh based on rectangular elements to study second-order resonance effects. Yan et al. [20] applied the fully nonlinear potential for modeling overturning waves. To achieve that, a moving mesh technique was adopted to track down the free surface. Consequently, computational times are large. Recently, Song et al. developed a new scaled boundary finite element method (SBFEM) for linear waves and structure interaction [21]. The SBFEM works in the frequency domain, and base functions for boundary elements based on Hankel functions were used for unbounded sub-domains where waves asymptotically disappear. This leads to a decrease in the number of elements needed for the simulation which improves the numerical efficiency of the method.

Despite of the great effort invested in the last years to the development of FEM algorithms, to the authors' knowledge, yet there has not been developed a fast FEM (by fast we mean in the order of minutes for practical problems) for solving first-order wave structure interaction in the time domain using unstructured meshes. The use of structure or semi-structure meshes is a big limitation since it limits the complexity of the geometry to be used. In this study we present a FEM for wave–structure interaction that can be used with unstructured meshes. Besides, since it is based on Stokes' wave theory, no re-meshing or moving mesh technique are needed, which keeps computational costs and computational times low. The algorithm has been adapted to include nonlinear external forces, like those used to define mooring systems.

Solver deflation is gaining popularity as a way to improve convergence in linear solvers, and therefore to reduce solver iteration and CPU time. Deflation works by solving in a fast and coarse manner eigenmodes associated with the lower eigenvalues [22,23] (slow convergence modes). Therefore, it will better improve convergence in those problems with a larger range of eigenmodes, such as flows in pipes.