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An efficient domain decomposition strategy for wave loads on surface piercing circular cylinders

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A B S T R A C T

A fully nonlinear domain decomposed solver is proposed for efficient computations of wave loads on surface piercing structures in the time domain. A fully nonlinear potential flow solver was combined with a fully nonlinear Navier–Stokes/VOF solver via generalized coupling zones of arbitrary shape. Sensitivity tests of the extent of the inner Navier–Stokes/VOF domain were carried out. Numerical computations of wave loads on surface piercing circular cylinders at intermediate water depths are presented. Four different test cases of increasing complexity were considered; 1) weakly nonlinear regular waves on a sloping bed, 2) phase-focused irregular waves on a flat bed, 3) irregular waves on a sloping bed and 4) multidirectional irregular waves on a sloping bed. For all cases, the free surface elevation and the inline force were successfully compared against experimental measurements.

1. Introduction

In recent years a large number of offshore wind turbines have been planned for installation in intermediate and shallow waters particularly in the North Sea and around the British islands. Important for a safe yet economic design of these structures are accurate predictions of the hydrodynamic loading on the foundations. Of particular concern are strong nonlinear forces from steep or breaking wave impacts and "ringing" loads from steep nonlinear waves.

Such ultimate wave loads from extreme waves are normally an important design driver for substructures of offshore wind turbines. However, these are not accurately predicted by the wave models typically applied for design computations as the available nonlinear wave models are usually restricted to regular non-breaking waves. Engineers then have to base their designs on laboratory experiments and empirical correction factors. Laboratory experiments are expensive to carry out and site specific bathymetry and spectral shapes are rarely taken into consideration. Therefore, efficient fully nonlinear CFD computations capable of accurately predicting loads from steep and breaking waves provide a valuable tool for design verification.

In recent years "ringing" forces on monopile foundations have been of increasing concern as they have the potential to decrease the expected lifetime of these structures and/or cause failure. In the present work "ringing" is defined as structural vibrations of large amplitude caused by steep non-breaking waves, which have a non-impulsive nature. The "ringing" phenomenon was first observed in model tests of the two oil-production platforms Heidrun and Troll (see Haver et al., 1998; Natvig and Teigen, 1993). For the prediction of "ringing" loads, analytical solutions for regular waves, accurate to the third order in wave steepness, were derived by Faltinsen et al.(1995) and Malenica and Molin (1995). A semi analytical "ringing" load theory was derived by Krokstad et al. (1998) and verified against experiments in a joint industry project. A substantial amount of experimental work on "ringing" loads has been carried out, e.g. Chaplin et al. (1997); Huseby and Grue (2000); Krokstad and Solaas (2000); and Rainey and Chaplin (2003).

For regular waves Huseby and Grue (2000) presented a comprehensive set of experiments, where harmonic forces up to the seventh harmonic were identified. This work was further extended in Grue and Huseby (2002). Here, special attention was paid to the occurrence of secondary load cycles, which are observed as an additional loading in the direction of wave propagation at the time of minimum loading. Grue and Huseby (2002) observed a strong correlation between the observation of "ringing" responses and secondary load cycles.

Recently numerical computations by Paulsen et al. (2014) has shown that fully nonlinear CFD-computations have the potential to accurately compute secondary load cycles and the hydrodynamic forces related to the "ringing" phenomenon. However, these computations require a substantial CPU effort and were only suited for shorter time series in a limited domain. In order to make this type of computations suitable for long time series and large domains, where site specific bathymetries are taken into account, an efficient domain decomposition strategy is needed.

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In general two types of domain decomposition strategies exist; a two-way coupling where information propagates both from the outer to the inner domain and vice versa. Alternatively, a one-way coupling can be formulated, where information only propagates from the outer to the inner domain. Within these two categories, domain decomposition strategies have previously been formulated by e.g. Biausser et al. (2004); Campana et al. (1995); Christensen et al, (2009); Drevard et al. (2005); Greco et al. (2007); Guignard et al. (1999); Hamilton and Yeung (2011); Iafrati and Campana (2003); Kim et al. (2010; Lachaume et al. (2003), for various flow problems.

Campana et al. (1995) applied a two-way domain decomposed solver to analyse the flow past a ship hull. Here, the linearized potential flow problem was solved in the outer flow domain by a panel method; whereas the steady state incompressible Reynolds averaged Navier–Stokes equations were solved in the vicinity of the ship by a finite volume method. A vertical, two-way viscous–inviscid coupling was developed by Iafrati and Campana (2003), in order to accurately simulate unsteady wavy flows generated by a submerged moving body. Here, a vertical domain decomposition strategy was followed such that the viscous model was applied in the free surface region and the potential flow model for the remaining part of the fluid domain. The air–water interface was captured by a level-set method following the work of Sussman et al. (1994). This enabled computations of the free surface motion even for breaking waves.

Greco et al. (2007) applied a two-way fully nonlinear domain decomposed solver to study the problem of green-water on decks. The computations were carried out in two dimensions and were successfully compared against experimental measurements. Here a boundary element model was combined with a Navier–Stokes solver in two dimensions. Recently Kim et al. (2010) presented a nonlinear two-way coupling between a nonlinear boundary element model and a Navier–Stokes solver, where the free surface was captured by a volume of fluid (VOF) surface capturing scheme, see Hirt and Nichols (1981). The model was formulated in 2D with the purpose of calculating long time series of irregular waves. For detailed computations of viscous flow effects around three-dimensional bodies an important contribution was made by Hamilton and Yeung (2011), who presented a generalized, three-dimensional two-way coupling between a linearized inviscid outer region and a linear viscous inner region.

A different approach to domain-decomposition is the one-way coupling first presented by Guignard et al. (1999), and later by Lachaume et al. (2003). Here, information only propagates in one direction — from the outer to the inner domain. The method was applied by Biausser et al. (2004) for computations of two- and three-dimensional breaking waves. Using the same method Drevard et al. (2005) studied shoaling and breaking of solitary waves. Christensen et al. (2009) coupled the weakly nonlinear Boussinesq model of Madsen et al. (1991) to a Navier–Stokes/VOF solver for the computations of wave loads from unidirectional waves on monopiles at intermediate and shallow depth. The advantage of the one-way coupling is its simplicity and that an efficient coupling between fully nonlinear models can be achieved without subiterations. On the other hand, the one-way coupling requires that the inner domain is sufficiently large such that the solution is converged with respect to the size of the inner domain.

In the present work, a three dimensional one-way coupling between a fully nonlinear potential flow wave model and a Navier–Stokes solver combined with a VOF surface capturing scheme is presented. The domains are coupled via generalized coupling zones of arbitrary shapes, which ensure a smooth transition between the outer and inner solution. By this method, fully nonlinear boundary conditions for realistic irregular three-dimensional waves can be provided to the Navier–Stokes solver with a minor increase in the computational cost. Hereby, site specific computations of fully nonlinear wave loads on monopiles, or any other offshore structure, can be carried out for realistic sea states with a reasonable computational cost.

The paper is organized as follows. First in Section 2, the governing equations for the two numerical models are presented, along with a detailed description of the coupling scheme. Further, the coupling scheme is verified by two generic test cases. In Section 3, the numerical method is applied to four different test cases, all compared to experiments. The test cases consist of regular waves moving past a bottom mounted circular cylinder (Section 3.1); phase-focused irregular waves on a flat bed impacting on a bottom mounted circular cylinder (Section 3.2); unidirectional irregular waves impacting on a circular cylinder placed on a sloping bed (Section 3.3) and multi-directional irregular waves impacting on a circular cylinder on a sloping bed (Section 3.4). Finally conclusions are drawn in Section 5.

2. The numerical model

The domain decomposed solver consists of an outer flow domain governed by a three-dimensional, fully nonlinear potential flow solver, and an inner domain, which is described by a fully nonlinear Navier–Stokes/VOF solver. A sketch of the numerical domains is shown in Fig. 1. The outer domain is denoted: Ω. Here the fully nonlinear three-dimensional potential flow problem is solved for the wave motion only. To account for local diffraction effects, wave breaking at the structure and viscous effects, a local inner domain, Γ, is defined, covering a confined volume around the structure. Here, the Navier–Stokes equations are solved in combination with a VOF surface capturing scheme. In designated coupling zones, information from the global numerical domain, Ω, is interpolated onto the local domain, Γ, to provide the driving boundary condition for the inner flow around the structure. In this manner, fully nonlinear boundary conditions are applied for the inner domain, which includes the effect of nonlinear wave transformation and wave–wave interaction. It may be noted that the potential flow solver is orders of magnitudes faster than the Navier–Stokes/VOF solver. Hereby, large numerical domains and/or long time series can be considered, which would otherwise not be computationally feasible. Further, due to the higher-order numerical discretization applied in the potential flow solver, water waves can be propagated over long distances with a minimum of numerical diffusion and phase error. This is opposite

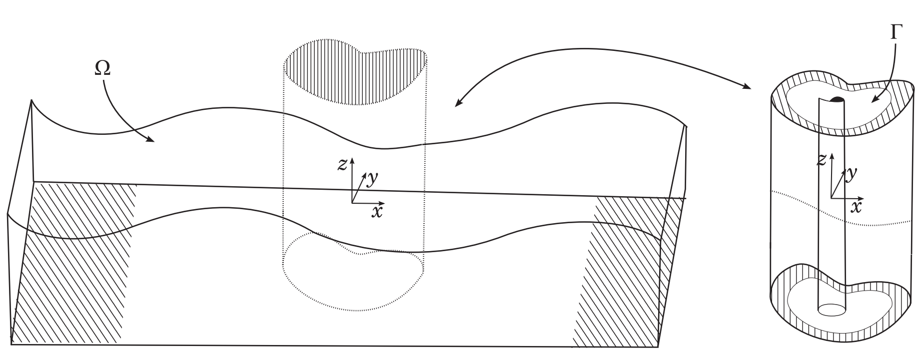

Fig. 1. Sketch of the numerical domain.