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A framework for efficient irregular wave simulations using Higher Order Spectral method coupled with viscous two phase model

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Abstract

In this paper a framework for efficient irregular wave simulations using Higher Order Spectral method coupled with fully nonlinear viscous, two-phase Computational Fluid Dynamics (CFD) model is presented. CFD model is based on solution decomposition via Spectral Wave Explicit Navier–Stokes Equation method, allowing efficient coupling with arbitrary potential flow solutions. Higher Order Spectrum is a pseudo-spectral, potential flow method for solving nonlinear free surface boundary conditions up to an arbitrary order of nonlinearity. It is capable of efficient long time nonlinear propagation of arbitrary input wave spectra, which can be used to obtain realistic extreme waves. To facilitate the coupling strategy, Higher Order Spectrum method is implemented in foam-extend alongside the CFD model. Validation of the Higher Order Spectrum method is performed on three test cases including monochromatic and irregular wave fields. Additionally, the coupling between Higher Order Spectrum and CFD is validated on three hour irregular wave propagation. Finally, a simulation of a 3D extreme wave encountering a full scale container ship is shown.
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Keywords: Higher Order Spectral method; Irregular waves; Extreme waves; CFD; Foam-extend.

1. Introduction

With increased availability of CPU resources during past few decades, Computational Fluid Dynamics (CFD) is becoming a standard practice for simulation of transient free-surface waves. CFD methods that model fully-nonlinear, two-phase, viscous flow exhibit high computational costs, which prohibit long time wave evolution in a large domain. This disadvantage is partially overcome using domain decomposition strategies, where the flow in a small, relevant part of the domain is resolved using CFD, while the farfield flow is resolved using potential flow, a computationally cheaper model. Given the potential flow solution, the CFD simulation naturally develops nonlinear, viscous flow with vorticity effects. First decomposition method was developed by Van Dalsem and Steger [1], called Fortified Navier–Stokes (FNS) method. Van Dalsem and Steger used the decomposition to 'fortify' the solution of subset equations in the boundary layer, while solving ordinary Navier–Stokes in the rest of the domain. Jacobsen et al. [2] introduced a domain decomposition method for wave modelling using relaxation zones. Paulsen et al. [3] used one-way coupling between fully nonlinear potential flow solver (developed by Ensig-Karup et al. [4]) and fully nonlinear viscous CFD solver to investigate wave loads on a circular surface piercing cylinder. The same method was used to calculate steep regular wave loads on a bottom mounted cylinder [5]. Pistidda and Ottens [6] used the Euler Overlay Method for domain decomposition to calculate the Response Amplitude Operator (RAO) for a moonpool of a deep water construction vessel.

Vukčević and Jasak [7] developed a modified Spectral Wave Explicit Navier–Stokes Equation (SWENSE) [8–10] solution decomposition method which is used alongside domain decomposition. The solution is decomposed into incident and

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diffracted fields, where the incident field is obtained from the potential flow model, while the diffracted field is solved via two-phase, viscous CFD model. All of the above mentioned CFD methods are computationally expensive because they are modelling highly resolved spatial flow features with nonlinear and coupled equations in time domain. Hence, they cannot be used to perform a large number of long time irregular wave field propagations needed to obtain a naturally emerging extreme wave.

Extreme wave loads are gaining more attention due to increasing number of offshore objects being installed worldwide. Extreme waves emerge due to focusing of wave spectrum components, which is influenced by nonlinear wave modulation and wave-to-wave interaction. It is considered that the influence of wind and atmospheric pressure, bathymetry and current [11] also plays a role in extreme wave generation. Apart from the focusing of unidirectional spectrum, geometric focusing of directional spectrum can also cause extreme wave events.

Assessment of extreme wave loads demands accurate wave modelling. Since extreme waves occur randomly in an irregular sea state, in order to obtain a statistically and physically accurate extreme wave, irregular sea state needs to be evolved for a long time on a large domain. Moreover, the evolution of the irregular sea state has to take into account nonlinear effects of wave interaction and modulation. CFD takes into account all nonlinearities of the flow, and inherently the nonlinearities of wave-to-wave interaction and wave modulation. However, even with domain decomposition methods, it is challenging to propagate arbitrary wave field for a sufficient amount of time to observe a natural emergence of extreme waves. Apart from that, long time CFD simulation might accumulate discretization errors which will inevitably influence the wave field. To obtain a realistic extreme wave in an irregular sea state, as much as a thousand peak periods need to be simulated. Paulsen et al. [3] reported that one irregular wave peak period took 8 hours to compute on 10 CPU's, extrapolating to almost a year for 1000 peak periods, which might be necessary to obtain a realistic extreme wave.

Nonlinear wave field can be efficiently propagated using spectral potential flow approach. In this work, potential flow pseudo-spectral Higher Order Spectral (HOS) method is used. Nonlinearities of wave-to-wave interaction and wave modulation are taken into account, while viscous effects, vorticity, wave breaking, diffraction and radiation are neglected. Since the latter effects have minor influence on extreme wave emergence, HOS method can be used to perform a long time evolution of an irregular wave field on a large-scale domain to obtain a statistically and physically consistent extreme wave. HOS can then be coupled with CFD in a small spatial domain containing the extreme wave, and for a short period of time to capture viscous effects, wave breaking and fluid–structure interaction. In this work one-way coupling between HOS and CFD is achieved using the decomposition model [7].

HOS method was first developed by Dommermuth and Yue [12] and West et al. [13] independently. West et al. used order consistent Taylor and perturbation series expansion, which is adopted by most HOS algorithms today [14,15]. Since the publication of the original method in 1987, numerous authors continued its development. Ducrozet et al. [15] enhanced numerical efficiency and aliasing treatment, while Tanaka [14] combined HOS with complex amplitude function. Dommermuth [16] developed a time relaxation scheme which enables HOS calculation to be initialized with a linear solution. This is of crucial importance since wave energy spectra are defined for linear wave components.

In this paper a mathematical overview of the HOS method is given, followed by a detailed description of numerical procedure. The CFD model and coupling with potential flow by Vukčević and Jasak [7] is used. Three test cases are considered for HOS validation purposes. The first case considers monochromatic wave train propagation, where modal amplitudes are compared with analytical Stokes solution. Second test case considers propagation of four uniformly steep spectra, where the HOS solution is compared to viscous, two-phase CFD solution. Third test case shows naturally occurring Benjamin–Feir instabilities [17]. In addition to the validation of the implemented HOS model, the coupling between HOS and CFD using SWENSE is also validated on a three hour irregular wave propagation case. Finally, an example simulation of a 3D extreme wave encountering a full scale container ship is shown. According to ITTC guidelines, the present method applied on this case presents a fully-nonlinear seakeeping calculation.

2. Mathematical model

In this section mathematical model for the HOS method is outlined; the reader is referred to [12–15] for more details.

Pseudo-spectral HOS method is used to reformulate nonlinear partial differential equation set via perturbation, Taylor and Fourier series into a set of ordinary differential equations.

2.1. Governing equations

In this model, free-surface flow is assumed irrotational, inviscid and incompressible. Surface gravity wave propagation is described with the following governing equations:

- Laplace equation for incompressible, irrotational, inviscid flow:

$$\nabla^2 \phi(x, y, z, t) = 0, \tag{1}$$

where ϕ is the velocity potential, while x, y, z are spatial coordinates and t is time.

- Dynamic free surface boundary condition:

$$\frac{\partial \phi}{\partial t} + gz + \frac{1}{2}(\nabla \phi)^2 = 0, \tag{2}$$

where g is the gravitational acceleration in the direction of negative z axis.

- Kinematic free surface boundary condition:

$$\frac{\partial \eta}{\partial t} + \left(\frac{\partial \phi}{\partial x}, \frac{\partial \phi}{\partial y}\right) \cdot \left(\frac{\partial \eta}{\partial x}, \frac{\partial \eta}{\partial y}\right) = \frac{\partial \phi}{\partial z}, \tag{3}$$

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