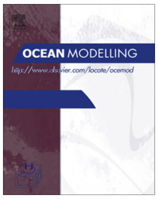
Ocean Modelling xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod



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Stochastic simulations of ocean waves: An uncertainty quantification study

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ARTICLE INFO

Article history:
Received 20 June 2014
Received in revised form 29 November 2014
Accepted 3 December 2014
Available online xxxx

Keywords:
Phase-averaged model
Ocean wave modeling
Uncertainty quantification
Generalized polynomial chaos
Sparse grid collocation
Sensitivity analysis
Karhunen–Loeve decomposition

ABSTRACT

The primary objective of this study is to introduce a stochastic framework based on generalized polynomial chaos (gPC) for uncertainty quantification in numerical ocean wave simulations. The techniques we present can be easily extended to other numerical ocean simulation applications. We perform stochastic simulations using a relatively new numerical method to simulate the HISWA (Hindcasting Shallow Water Waves) laboratory experiment for directional near-shore wave propagation and induced currents in a shallow-water wave basin. We solve the phased-averaged equation with hybrid discretization based on discontinuous Galerkin projections, spectral elements, and Fourier expansions. We first validate the deterministic solver by comparing our simulation results against the HISWA experimental data as well as against the numerical model SWAN (Simulating Waves Nearshore). We then perform sensitivity analysis to assess the effects of the parametrized source terms, current field, and boundary conditions. We employ an efficient sparse-grid stochastic collocation method that can treat many uncertain parameters simultaneously. We find that the depth-induced wave-breaking coefficient is the most important parameter compared to other tunable parameters in the source terms. The current field is modeled as random process with large variation but it does not seem to have a significant effect. Uncertainty in the source terms does not influence significantly the region before the submerged breaker whereas uncertainty in the incoming boundary conditions does. Considering simultaneously the uncertainties from the source terms and boundary conditions, we obtain numerical error bars that contain almost all experimental data, hence identifying the proper range of parameters in the action balance equation.

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1. Introduction

We first present an overview of the action balance equation along with the numerical model, a description of the HISWA experiment, and a review of the stochastic modeling approach we employ. We then present the objectives of this work and the organization of the rest of the paper.

1.1. Phase-averaged equation and source terms

We model ocean waves through the spectral ocean wave equation (Holthuijsen, 2007; Young, 1999) also referred to it as phased-averaged model. We solve for the energy density (or action density) to obtain important statistical wave parameters, such as the significant wave height, mean wave period, etc. The phase-averaged model is well suited for slowly varying wave fields, such as ocean waves in deep water, and it is more appropriate for large spatial domains (Battjes, 1994). In contrast, the model simulating the surface elevation in space and time is called phase-resolving, and is more efficient for waves in a small region of the sea such as a harbor (Battjes, 1994). The spectral ocean representation is essentially a superimposition of many different linear harmonic waves to represent complex ocean surface waves.

Today, most operational ocean codes employ the phase-averaged model. Some of the most well-known codes are SWAN (Simulating Waves Near-Shore) available from http://www.swan.tudelft.nl/, ECWAM (European Center Wave Model) available from http://www.ecmwf.int/, and NOAA's WAVEWATCH available from http://polar.ncep.noaa.gov/waves/. These established operational wave codes employ up to third-order of finite difference discretization in Tolman (1995) for spatial derivatives. To be able to construct arbitrary order of discretization with this new scheme is its biggest advantage over the traditional discretization methods. Although finite difference on structured mesh is an established and efficient method and relatively easy to implement, it is not

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http://dx.doi.org/10.1016/j.ocemod.2014.12.001
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Please cite this article in press as: Yildirim, B., Karniadakis, G.E. Stochastic simulations of ocean waves: An uncertainty quantification study. Ocean Modell. (2014), http://dx.doi.org/10.1016/j.ocemod.2014.12.001

well suited for complex geometries, e.g. in coastal applications. Recent effort to use finite difference on unstructured mesh for spectral wave model can be found in the work of Zijlema (2010). On the other hand, the finite element (FE) and finite volume (FV) methods that work on a general grid offer an accurate and efficient algorithm. Recent works have incorporated these methods into the wave models to handle complex coastal boundaries (Hsu et al., 2005; Qi et al., 2009).

1.2. High-order numerical model

Recently we introduced a new numerical method for the spectral ocean wave equations (Yildirim and Karniadakis, 2012), which is distinctively different from previous approaches (Booij et al., 1999; Hsu et al., 2005; Qi et al., 2009; Zijlema, 2010) and employs high-order discretization. Specifically, we compute the spectral space derivatives by Fourier-collocation while we discretize the physical space using a discontinuous Galerkin (DG) method (Yildirim and Karniadakis, 2012; Karniadakis and Sherwin, 1999; Hesthaven and Warburton, 2007; Cockburn et al., 2000). The DG discretization in geophysical space is performed on an unstructured grid to handle the complex boundaries. The overall scheme has exponential convergence rather than algebraic convergence typical of low-order schemes. We have verified the exponential convergence in both the geophysical and spectral spaces in previous work (Yildirim and Karniadakis, 2012). The low-order methods associated with strong numerical dissipation and phase errors smear out the amplitude of solution and shift the position of it. In long time integrations, the accumulated numerical dissipation and phase errors become so large that accurate simulation is not possible. Numerical diffusion test case for first order scheme presented in Booij et al. (1999) shows that first-order scheme is not suitable for the long distance wave propagation. High-order discretization is particularly effective for long-time integration, which is typically required to eliminate the associated dissipation and phase errors in the deep ocean wave simulations.

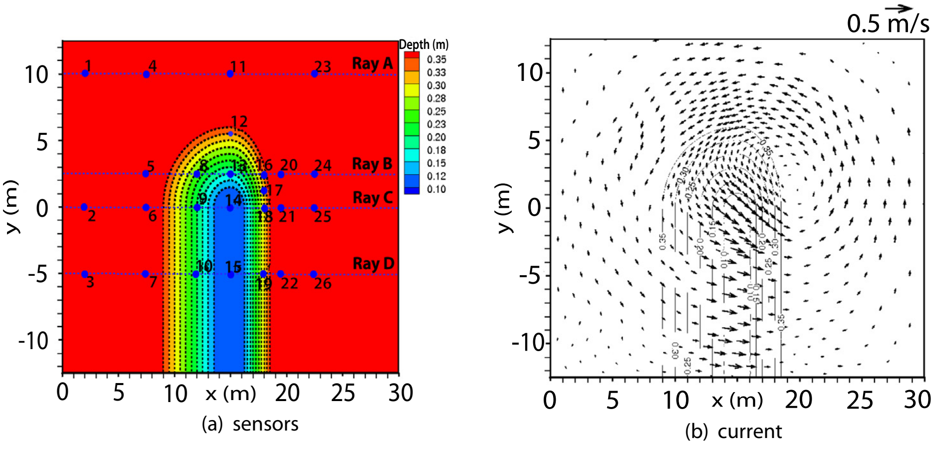
1.3. HISWA tank experiment

The HISWA experiment (Dingemans, 1987; Dingemans et al., 1986) is a laboratory experiment conducted for random, short-crested waves to validate numerical spectral ocean models (Holthuijsen et al., 1989). This is benchmark experiment that provides measurements for comparisons with simulations and it is one of the most comprehensive works for wave propagation in a laboratory. It includes three different bathymetry shapes as (1) a flat basin, (2) a simple one (fully cylindrical bar), and (3) a complicated one (semi-cylindrical bar with a rounded head), as well as many different operating and boundary conditions. The water level is set to 40 cm from the flat bottom. We chose the complex shape bathymetry (semi-cylindrical with rounded head; see its depth contours in Fig. 1(left)) for this study. The shape of the submerged breakwater can be exactly generated by using the transformations given in Dingemans et al. (1986).

In particular, we consider case me35, where '3' and '5' denote, respectively, bathymetry of semi-cylindrical bar with round over and a specific input in (Dingemans et al., 1986). The input case 5 has specified incoming waves with relatively wide JONSWAP spectrum (Hasselmann et al., 1973) and significant wave height of 10 cm, peak period of 1.25 s, and directional spreading of 25°. The peak enhancement factor of JONSWAP spectrum γ is chosen 3.3 with the spreading widths ($\sigma_A = 0.07, \sigma_B = 0.09$). Case 5 is considered here because this case contains most of the processes that also occur in nature. The current field has been measured at 81 points on a grid of 3 by 3 m at half the water depth. The experiment was done on a relatively large rectangular basin 26 m× 34 m. The wave maker generates waves from left (along $x = 0$ line, see Fig. 1) to the right. This experiment has been used to validate the SWAN model (Ris, 1997).

1.4. Stochastic modeling and uncertainty quantification (UQ)

The spectral wave models contain source terms to represent important wave physics (wave generation, white-capping, depth-induced breaking, and bottom friction) and wave interactions (triads, quadruplets). Among them, we know the exact mathematical expression only for nonlinear wave interactions (quadruplets) (Hasselmann, 1962) but for computational efficiency we have to adopt suitable approximations (Lin and Perrie, 1998; van Vledder et al., 2000; Lavrenov, 2003; van Vledder, 2006; Cavaleri et al., 2007); for the rest of the source terms we employ other empirical models, see Appendix A. In our work, we have adopted a bottom friction parametrization of the source terms from WAMDI Group (1988) using the so-called *third-generation* ocean wave prediction model, source term parametrization of triad interactions from Eldeberky (1996) and of depth-induced breaking from Battjes and Janssen (1978) and Battjes and Stive (1985). Although waves in the HISWA experiment are not generated by wind, we point out that wind input dominates (as a single source of energy into the system) in the modeling of wind-generated waves (Komen et al.,



(a) sensors

(b) current

Fig. 1. *HISWA experiment*: sensor locations and bathymetry contours (left) and current vector field (right).

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