Modeling of Complex Coupled Fluid-Structure Interaction Systems in Arbitrary Water Depth

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LONG-TERM GOALS

The long-term goal of this research is to develop a robust multi-physics, multi-scale computational framework for the prediction and analysis of highly nonlinear dynamic behavior of naval systems in the marine environment of arbitrary water depth. The predictive capability will be sufficiently general for a variety of naval systems with a wide range of structural and mechanical complexities operating under deterministic and stochastic environmental conditions from deep water to the surf zone. Physics-specific numerical models included in the framework will take into account nonlinear effects of free surface, turbulence, wave breaking, fluid-structure and structure-structure impacts, large geometry, material, and structural interaction with seabed sediments.

OBJECTIVES

In our previous research, we developed predictive capabilities to analyze highly nonlinear coupled fluid-structure interaction systems for deep water applications using relatively simple fluid and structural models. We analyzed the global deterministic and stochastic behaviors of these systems via perturbation theory, modern geometric analysis, stochastic differential equation approach, and path-integration solution techniques. This combination of analytical and numerical tools enabled us to gain a comprehensive understanding of the global behavior of the sensitive nonlinear coupled fluid-structure interaction systems. The analysis procedures developed are applicable to idealized systems with a few degrees of freedom, and not suitable to study the nonlinear behavior at the local level, which is the source that triggers the high sensitivity of the global system. The objectives of this phase of our research focuses on the development of predictive capabilities to study the detailed physics and scales of coupled fluid-structure interaction at the local level and to expand the region of applicability of the computational framework to shallow water and the surf zone.

APPROACH

The approach to achieve the short term objectives is to: perform an assessment on the existing predictive capabilities of the detailed physics from the perspective of naval applications; identify the

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gaps for needed further development; and to eliminate these gaps by developing advanced multi-physics models and corresponding solution techniques taking into account the details of coupled fluid-structure interaction and the effects of nonlinear free-surface and varying finite water depth. These models will be validated using laboratory experiments. They will then be used to explain the sources of the complex nonlinear sensitive response behavior predicted by the simpler multi-degree-of-freedom (MDOF) models developed earlier. Completed documentations of the findings of the global behavior have focused on pinpointing the linkage between global and local behaviors.

WORK COMPLETED

In FY-2008-09 we completed the proposed tasks scheduled for the year for the intermediate field fluid model: (1) the development of 3-D boundary-element method (BEM) wave generation and absorption models and implementation of the corresponding algorithms; (2) the development of a 3-dimensional (3-D) numerical wave-basin model; and (3) validation of (1) and (2) using experimental bench-mark wave generation and propagation data obtained from the OSU 3-D wave basin. For the particle finite-element method (PFEM) near-field fluid model we completed: (4) the development of a fully-coupled fluid/flexible-structure coupling model and implementation of the corresponding numerical algorithm; (5) the development and implementation of universal wall function technique at fluid-solid boundary; and (6) validation of (4) and (5) using numerical data from existing literature. For the existing LS-DYNA Navier-Stokes fluid model, we completed: (7) evaluation of its coupled fluid-structure interaction capabilities by comparing numerical models with wave-impact on structures experiments conducted at the OSU 3-D wave basin.

Regarding Tasks (1) – (3), it is noted that the LS-DYNA boundary-element method (BEM) solution procedures had been mainly developed and used for solid modeling and internal flow situations. The existing BEM solver in LS-DYNA does not have a fluid free-surface tracking capability, input of wavemaker motion or an efficient computational algorithm needed to handle complex large-scale 3-D simulations. To improve the BEM modeling capabilities for intermediate fluid domain, this past year we completed Task (1) by implementing a collection of state-of-the art fully nonlinear potential flow (FNPF) codes to simulate the intermediate-field fluid domain. The new features implemented include the fast multipole algorithm (FMA), parallelization, generation capabilities of a number of representative 2-D waves, and a 3-D directional flap wavemaker. In addition to improving the Piston wavemaker option for generation of solitary waves, we completed the implementation of the piston wavemaker motion using the external/user-specified input and the multi-directional wavemaker operating on external input. This code is named as NWT3D to represent 3-D numerical wave tank. We also developed a numerical model of the physical 3-D directional wave basin at the OSU Hinsdale Wave Research Laboratory (HWRL), thus completing Task (2). We completed Task (3) by calibrating the resulting BEM model against the results of a wave generation and propagation experiment conducted at HWRL in spring 2009. Particular accomplishments included in Tasks (1) – (3) include:

- Completed the development of a wave generation module. We examined the theory, process and software behind the wavemaker motion of the 3-D wave basin and developed a wave generation code which uses some of the background routines of original wave generation software so as to be as close as possible to the process used in case of the real experiments. The original software had only wave profile generation, whereas the equipment of wavemaker uses its own hardware capabilities to monitor and adjust the motion to match with the wave profile. The enhancements included a complete generation of the input motion of the piston for solitary, Airy and Cnoidal waves. This module is useful to generate the piston/wavemaker motion for the NWT3D code. These capabilities enable us to simulate large-scale experiments of 3-D wave basins.

- Implemented periodic wave generation (with Airy and Cnoidal) in the NWT3D code using input from the wave generation module.

- Developed three alternative formulations for focused wave generation and implemented in NWT3D. The first one uses a time lag algorithm, the second uses the initial geometry condition in the form of a circular arc, and the third uses uniform radial velocity during wave generation.

- The NWT3D code was designed to use memory assigned in Fortran common blocks, so it was found to be far more efficient to implement parallelization using OpenMP rather than DPMTA library to speed up the computations. It takes advantage of multi-core systems, the current big shift in the chip making industry (including Intel). This implementation using OpenMP is completed and the preliminary speedup studies seem impressive.

- Developed the capability to provide output (velocities and pressure) at internal points, free surface and bottom surface of model is fixed and enhanced.

- Post-processing of the mesh, wave generation and animation can now be done using an open source visualization tool xd3d with the help of several utilizes developed for this purpose.

- Validated the NWT3D code by comparison with analytical (LS-DYNA, a general purpose commercial code that uses NS model) and experimental results at the 3-D wave basin at OSU for the solitary wave generation with a very complex bathymetry and the results are in very good agreement.

For Tasks (4) – (6), we introduced and developed a numerical solver for the RANS equations with a *k*- turbulence closure model in an ALE formulation (ALE-RANS). We implemented the model in a particle finite-element method (PFEM) based framework for the ALE-RANS solver [1]. We presented the theory of ALE-RANS with a *k*- turbulence closure model and several numerical examples including: a pure CFD model with a backward facing step, a prescribed moving cylinder in a bounded domain, and a fluid-object interaction simulation of a bridge deck. This year, we completed the fluid-flexible structure interaction model using ALE-RANS and *k*- turbulence closure model implemented by PFEM (Task (4)). In this work a universal wall function (UWF) is introduced and implemented to more accurately predict the boundary layer flow on both fixed and moving walls including interfaces between the fluid and flexible structures (Task (5)) [2]. To complete Task (6), the resulting development of Tasks (4) and (5) are validated using a benchmark numerical study of flow past a rigid block with a trailing plate.

We completed Task (7), the evaluation of the existing LS-DYNA Navier-Stokes fluid dynamic capability of LS-DYNA in modeling complex coupled fluid-structure interaction, by calibrating the model prediction results against a series of wave impact on cylinder experiments conducted at HWRL in spring 2006 [3]. We developed a number of 3-D “numerical wave basin” models and conducted a series of numerical simulations using the compressible flow fluid. We employed a local parallel cluster at Oregon State University and a couple of high-performance computer (HPC) clusters at Army

Research Office and performed a large number of large-scale numerical simulations and comparisons with wave-basin experimental results. In particular, we calibrated the numerical simulations with plane and focused waves on a single cylinder and a multiple cylinder array and compared the predicted and measured wave forces and overturning moments on the cylinders.

RESULTS

A summary of selected results for the BEM and PFEM/FEM models of the intermediate wave field and the near field, respectively, are presented as follow:

- For the simple case of simulation of periodic waves in the OSU 3-D wave basin, e.g. a Cnoidal wave, a typical model has 2976 nodes and 2450 elements. The run of 800 time steps and termination time of 14.7 seconds took 7.75 hrs (on a single CPU). This simulation time represents a significant improvement over previous cases without the FMA algorithm. When running in parallel using four nodes, the run time can be further reduced.

- For the more interesting case of simulation of a solitary wave with a complex bathymetry (a spring 2009 experiment conducted in the 3-D wave basin at OSU), a typical result is shown in Figure 1. The dark blue color indicates deeper part of the wave basin and closer to the wavemaker, whereas white color indicates the higher part. The rest of colors depict slopes in between higher and deeper parts. The BEM mesh has 40,228 nodes and 38,758 elements. Two snapshots illustrating the propagation of the solitary over the complex bathymetry are shown in Figure 2. The simulation took 76 hrs using 4 CPUs and terminated at a solution time of 5.37 sec with a total of 375 time steps. A comparison of the free surface elevations between results of NWT3D and experiment is shown in Figure 3. The solid lines are from computation and dashed lines are from experiment. The results in general match quite well. They demonstrate both the capabilities and limitations of the fully nonlinear potential flow model.

- Figures 4 and 5 show typical cases of a focused wave generation using alternatives-1 and 2, respectively. Both of these models have 22032 nodes and 20690 elements representing the 3-D wave basin at OSU. The termination time for alternative-1 of 8.7 sec and 300 time steps took about 57 hours on 1 CPU. The snapshots illustrate the propagation of the focused wave. For the focused wave in alternative-3, the BEM model has 38550 nodes and 37460 elements, the termination time of 8.5 sec and 300 iterations. The model represents half the length of the 3-D wave basin. This run took about 42 hours on 8 CPUs. The snapshots pertaining to this alternative are shown in Figure 6. These results show that while the newly implemented FMA and parallel algorithms represent a significant improvement, further improvements are still needed for practical applications.

- For the ALE-RANS and *k*- turbulence closure model based on PFEM, numerical predictions are found to match well with experimental and numerical data in the literature [1-2]. We calibrated the predictive capability of the model against a number of experimental and numerical results including flow pass a backward facing step, an oscillating cylinder with a prescribed motion, and coupled fluid-object interaction a bridge section and found the numerical PFEM ALE-RANS model significantly more efficient and the predictions match noticeably better than those obtained by using the Navier-Stokes equations model. We also completed the model development and numerical implementation of the coupled fluid/flexible structure model. An application of the newest feature for flow pass a rigid block with an attached flexible plate was studied in detail. Figure 7 shows the typical result of the distributions of the velocity, turbulence intensity and energy dissipation rate. We note that the code is developed for the 3-D case, although the example is 2-D for simplicity and availability of benchmark data. While a preliminary comparison of the numerical results with available data appears promising, we are developing more complex models for comparison with large-scale experimental data.

- For the study of coupled fluid-structure interaction simulation capabilities using the existing LS-DYNA Navier-Stokes equations model, the wave load on cylinder experiment conducted in the OSU 3-D wave basin for a plain solitary wave was examined. Figure 8 (a) shows a representative experimental test; (b) a typical numerical simulation (the wave comes from right to left); (c) a wave reflection snapshot taken from numerical model. The water depth and wave-amplitude to water-depth ratio used were h = 0.60m and H/h = 0.60, respectively. Figure 9 shows the numerical and measured water surface elevation at selected locations for plain solitary wave on single cylinder: (i) further around cylinder; (ii) close around cylinder. Figure 10 shows the numerical and measured horizontal force and overturning moment for plain solitary wave on single cylinder. These figures together demonstrate that the predictive capability of the existing LS-DYNA numerical model provides good matches with experimental results. However, the computational time required, which is often on the order of several days, needs significant improvement for practical applications.

IMPACT/APPLICATIONS

The advanced, state-of-the-art fluid-structure-interaction models including breaking waves adopted in this project, when fully developed, will enhance the modeling, prediction, operation and control capabilities of naval marine systems over a wide range of environmental conditions including the littoral zone, where rapid deployment of floating platforms and mine counter measures is essential. The 3-D numerical code being developed will provide additional tools to validate the accuracy of estimation of extreme value and cumulative fatigue predictions of complex responses of highly nonlinear marine structural systems and will advance the development of a systematic analysis procedure.

TRANSITIONS

Several analytical and numerical techniques developed in this research project have been used in other naval structural system analyses. Specifically, NFESC has employed the probability- and time-domain stochastic techniques to analyze nonlinear stability and capsizing probability of barges. We are currently developing 3-D fully-coupled analysis and simulation capabilities for mine scour problem using the LS-DYNA numerical code.

RELATED PROJECTS

This research project complements those supported by other ONR programs on the study of physical systems including nonlinear ocean waves and manned and unmanned structures. There are significant cross fertilization of ideas and development/implementation of numerical techniques on nonlinear stochastic analyses between this project and those under hydrodynamics, mathematical sciences, physics and other programs. This research will eventually benefit higher category programs when the resulting systematic analysis methodology can be employed in the analysis of rogue waves; the design of Naval ships, barges, platforms and other special “structures” including remotely operated vehicles for mine detection and sweeping; mine scour; and wave energy conversion.

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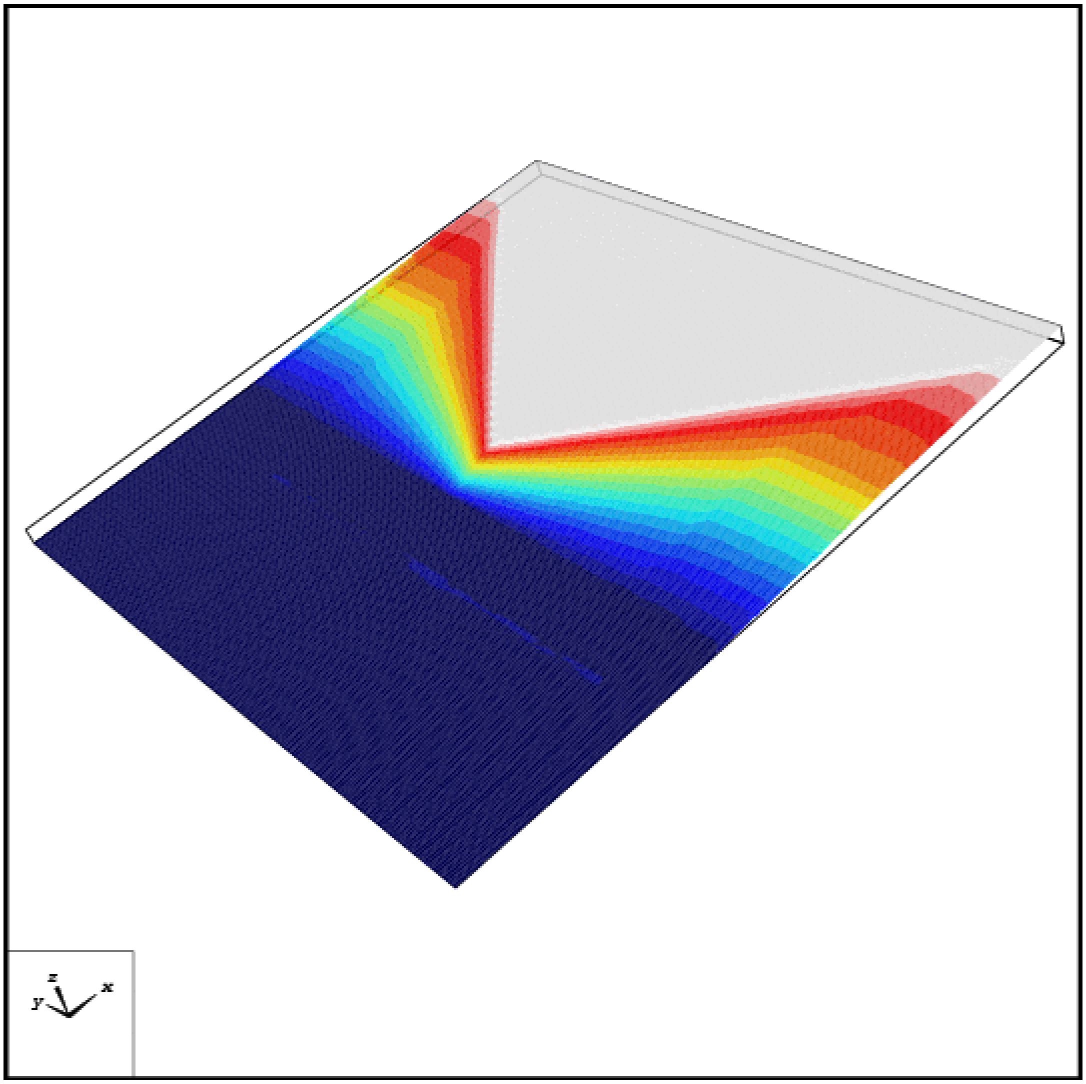


Figure 1. Complex bathymetry used in the solitary wave experiment at OSU.

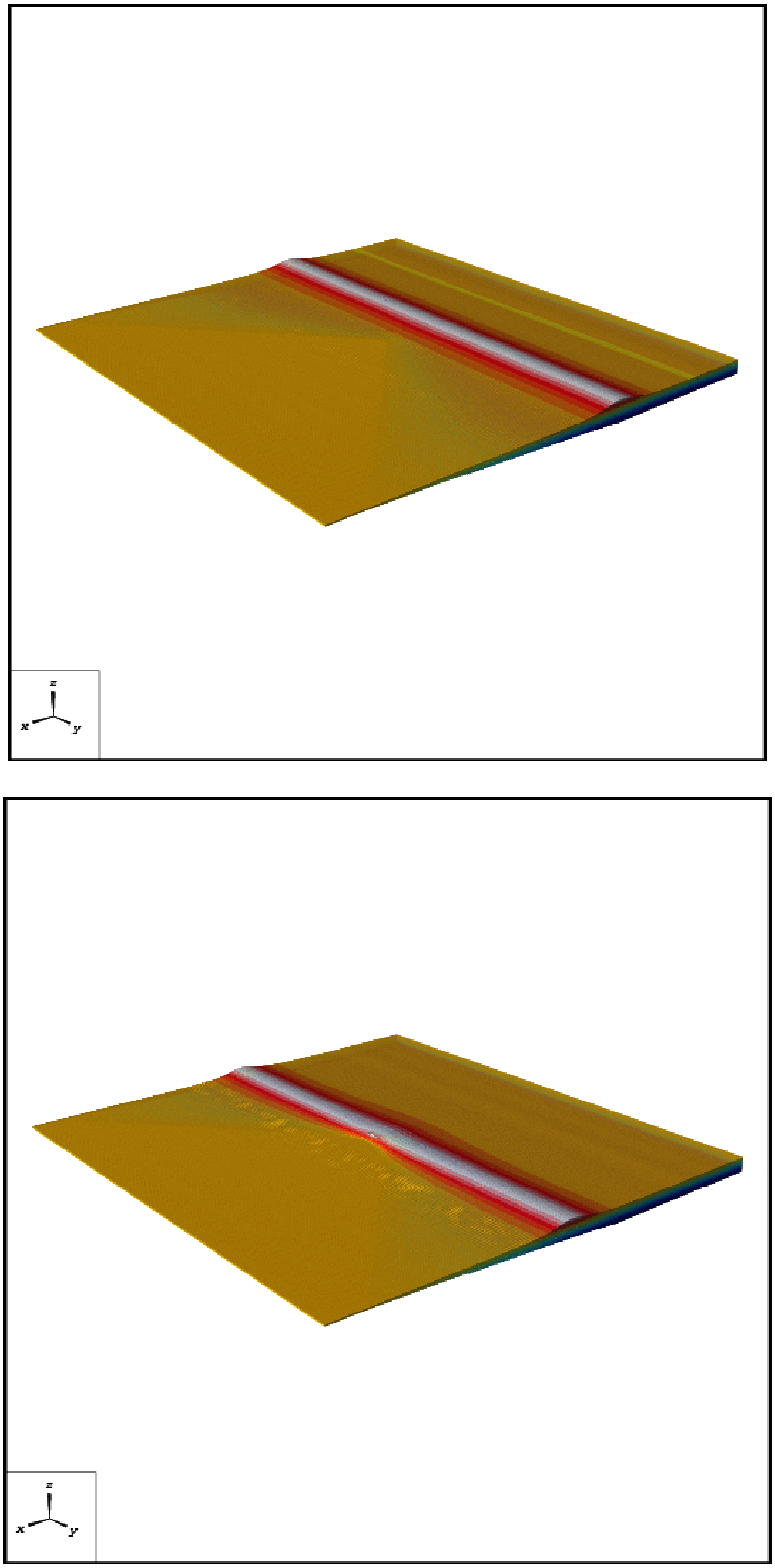


Figure 2.Two snapshots illustrating the simulation of a solitary wave propagating over a complex bathymetry.

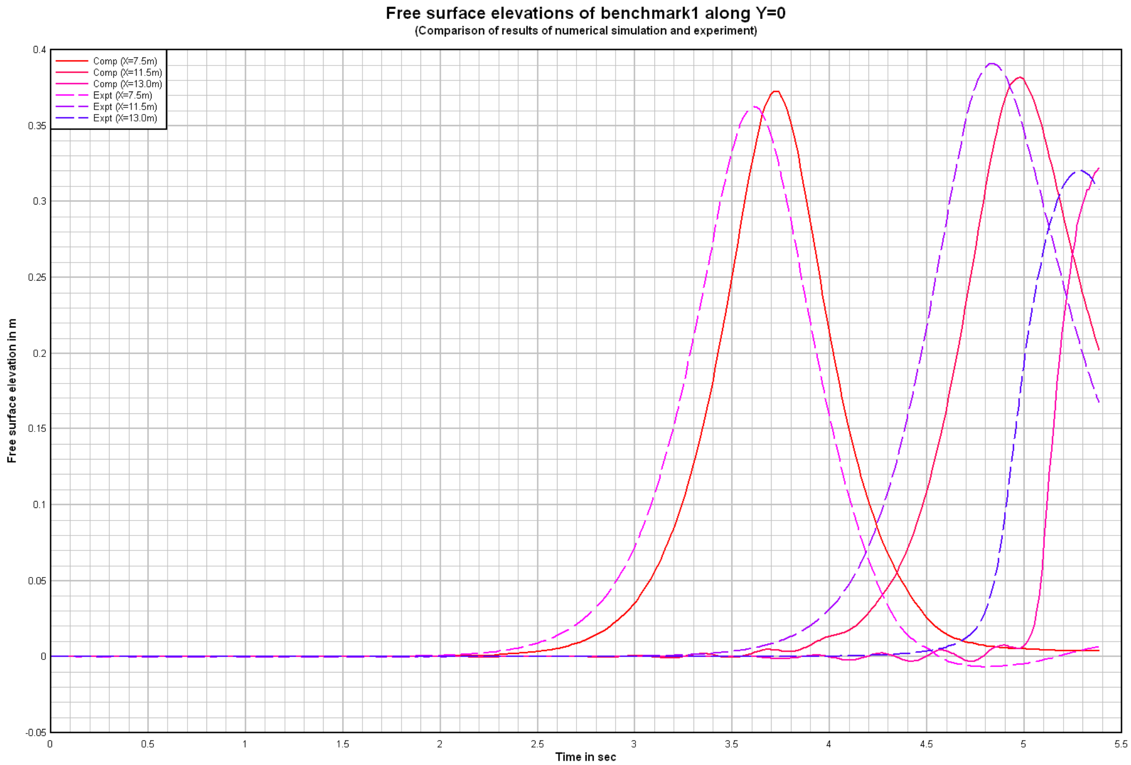


Figure 3. Comparison of surface elevation of the solitary wave propagating over a complex bathymetry.

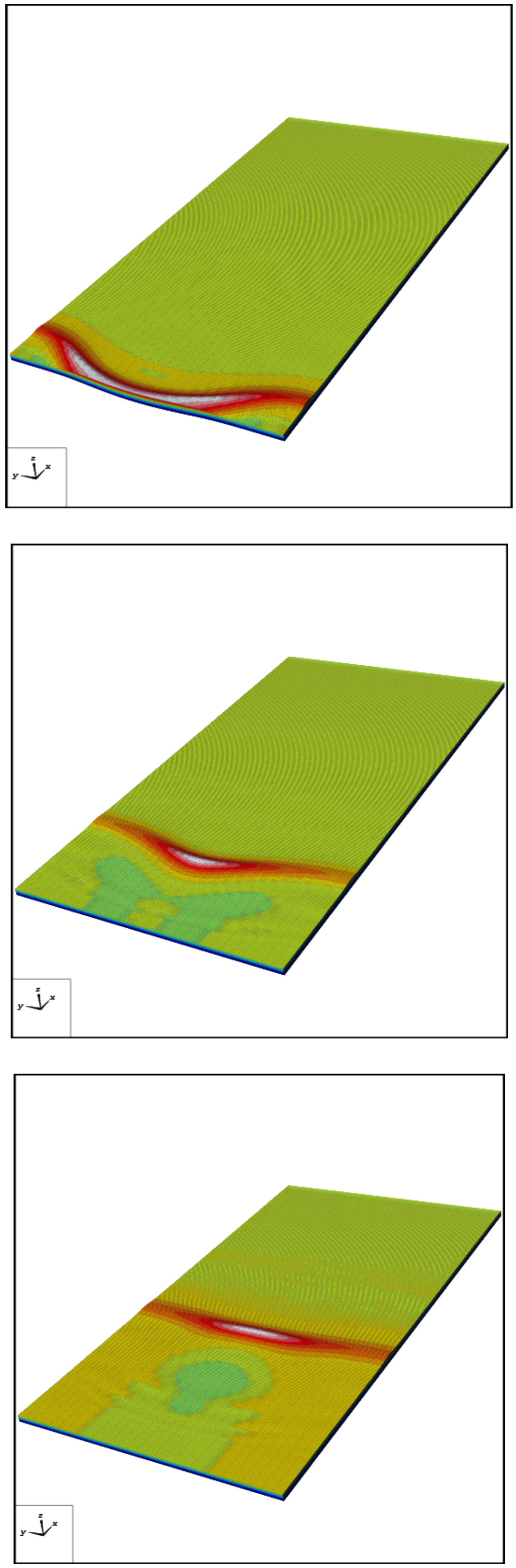


Figure 4. Snapshots of focused wave generation and propagation using alternative-1.

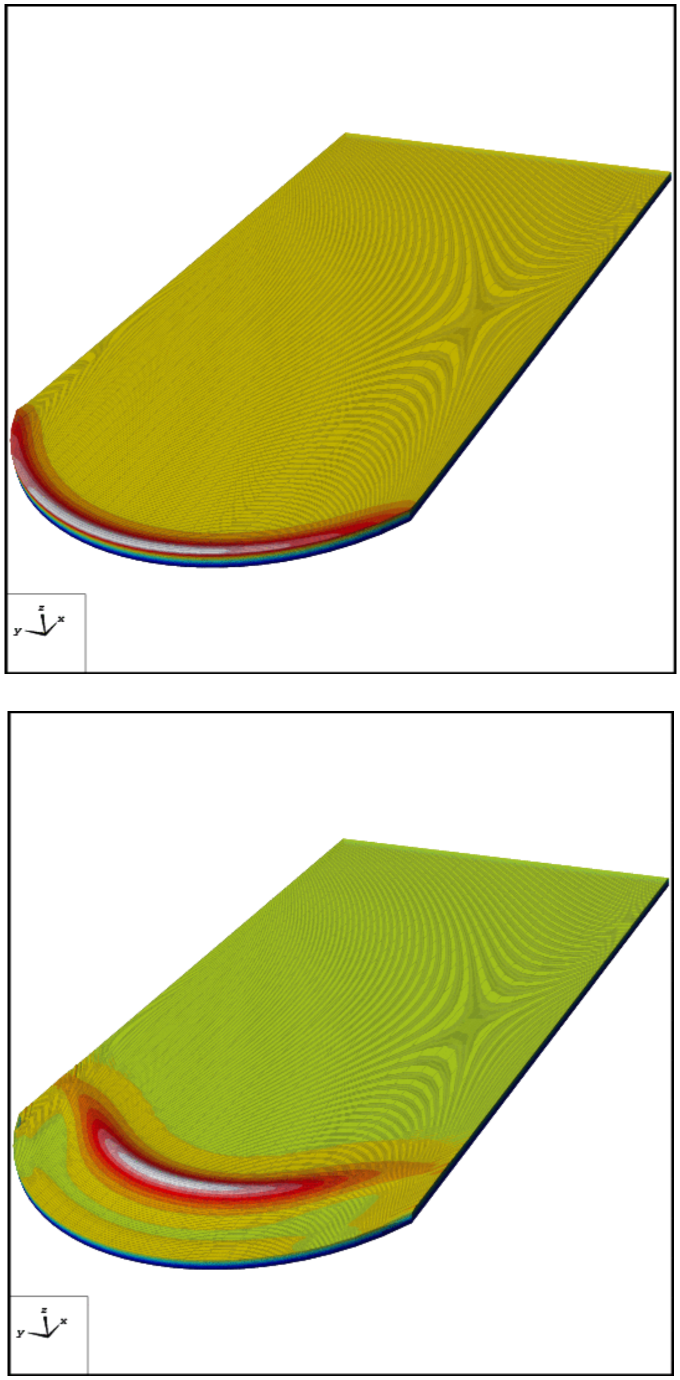


Figure 5. Snapshots of focused wave generation and propagation using alternative-2.

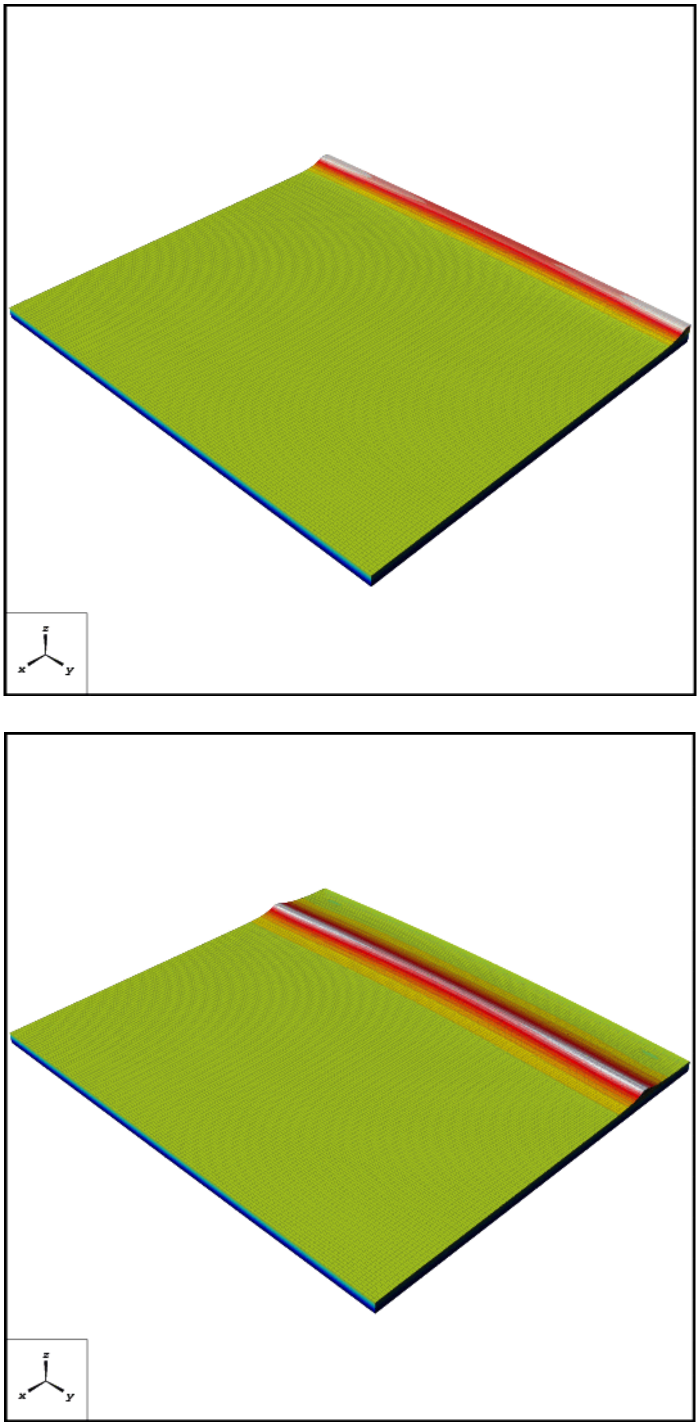


Figure 6(a). Snapshots of focused wave generation and propagation using alternative-3.

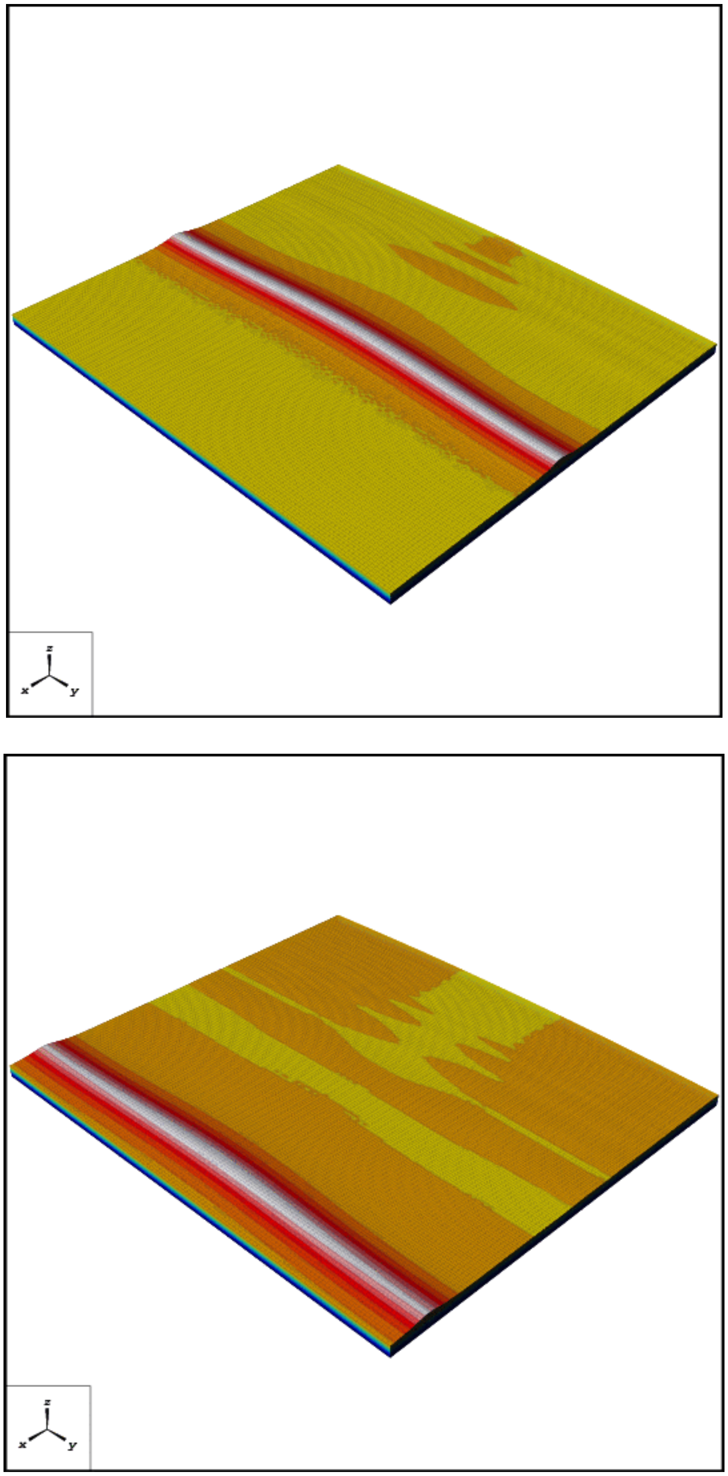
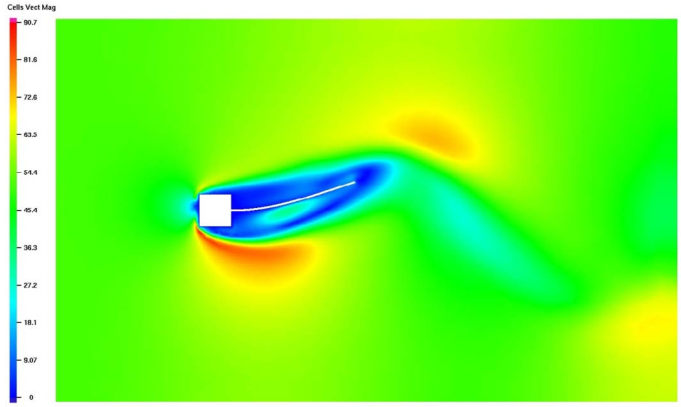
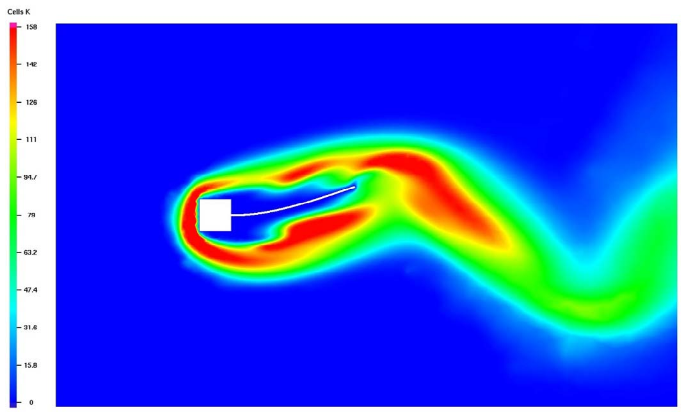


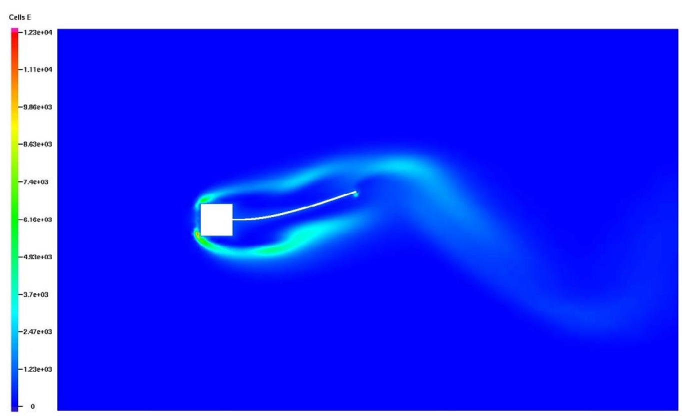
Figure 6(b). Snapshots of focused wave generation and propagation using alternative-3.



(a): Typical velocity distribution



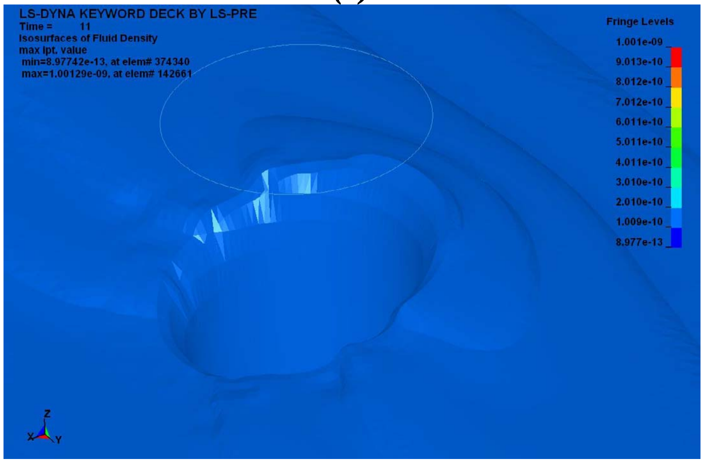
(b): Typical k distribution



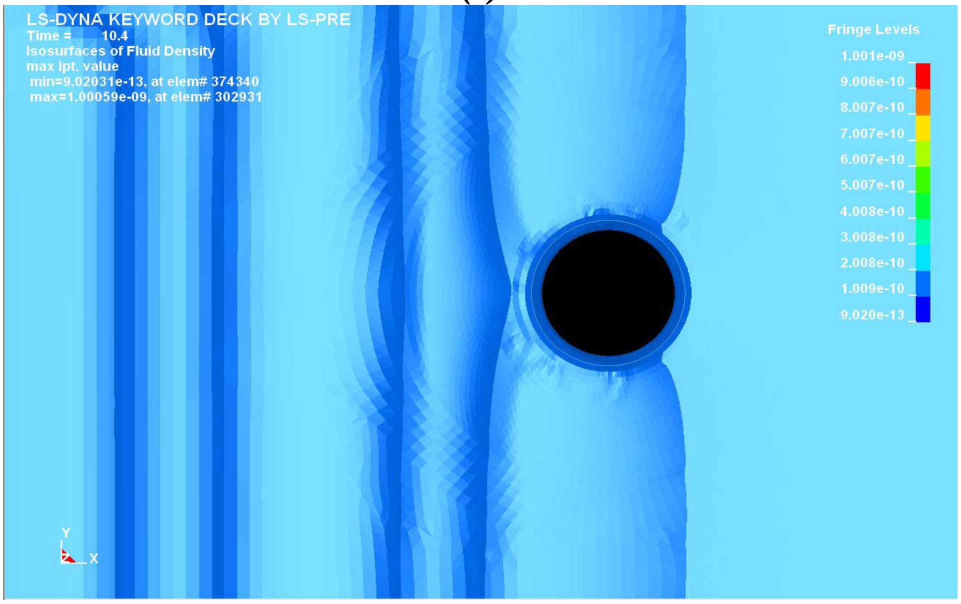
(c): Typical ε distribution

Fig. 7. A representative case of flow passing a rigid block with an attached flexible plate.

(a)



(b)



(c)

Figure 8. Wave load on cylinder experiment for plain solitary wave: (a) from experimental test; (b) from numerical model (the wave comes from right to left); and (c) a wave reflection snapshot taken from numerical model.

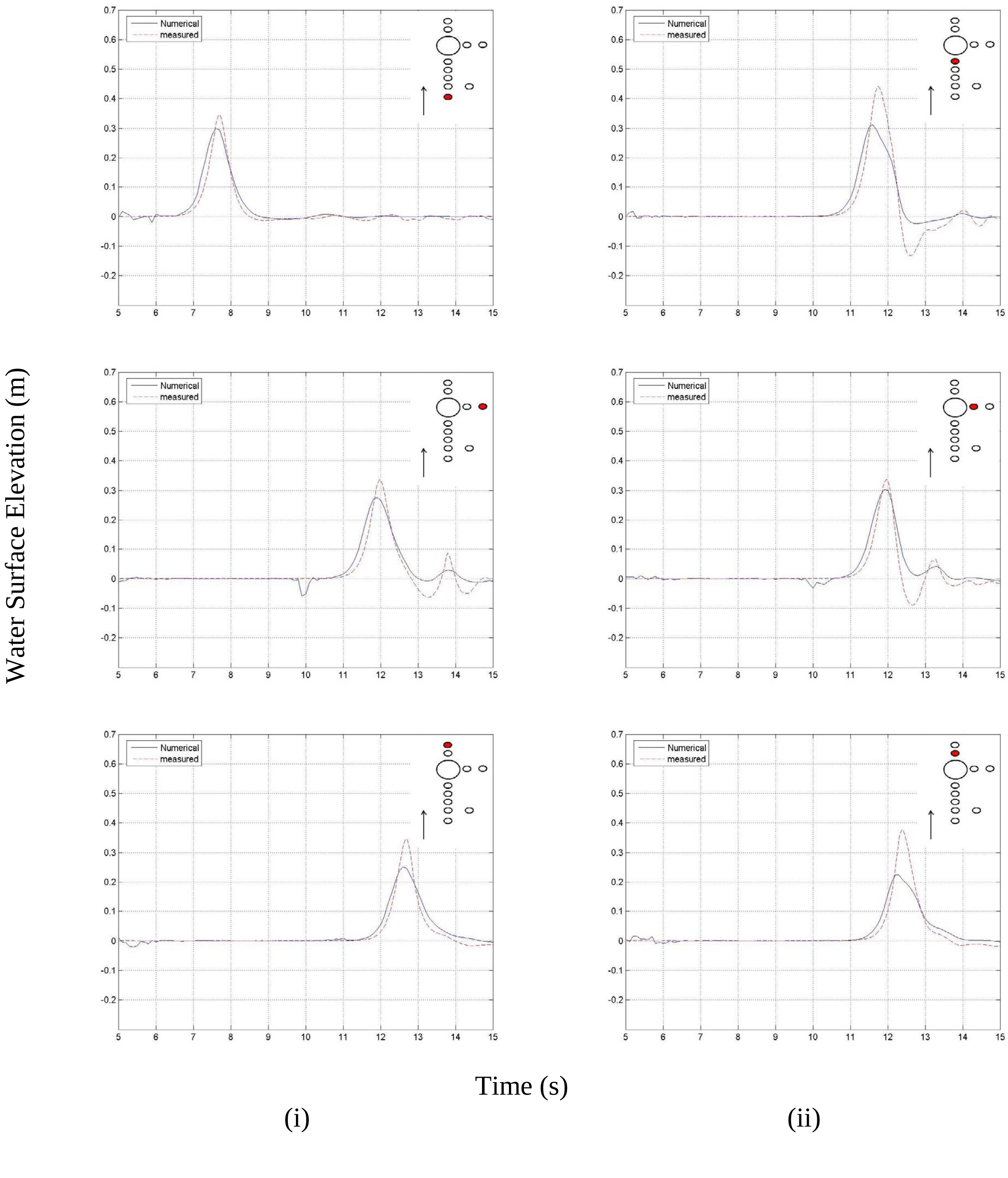


Figure 9. Numerical and measured water surface elevation at selected locations for plain solitary wave on single cylinder: (i) further around cylinder; and (ii) close around cylinder.

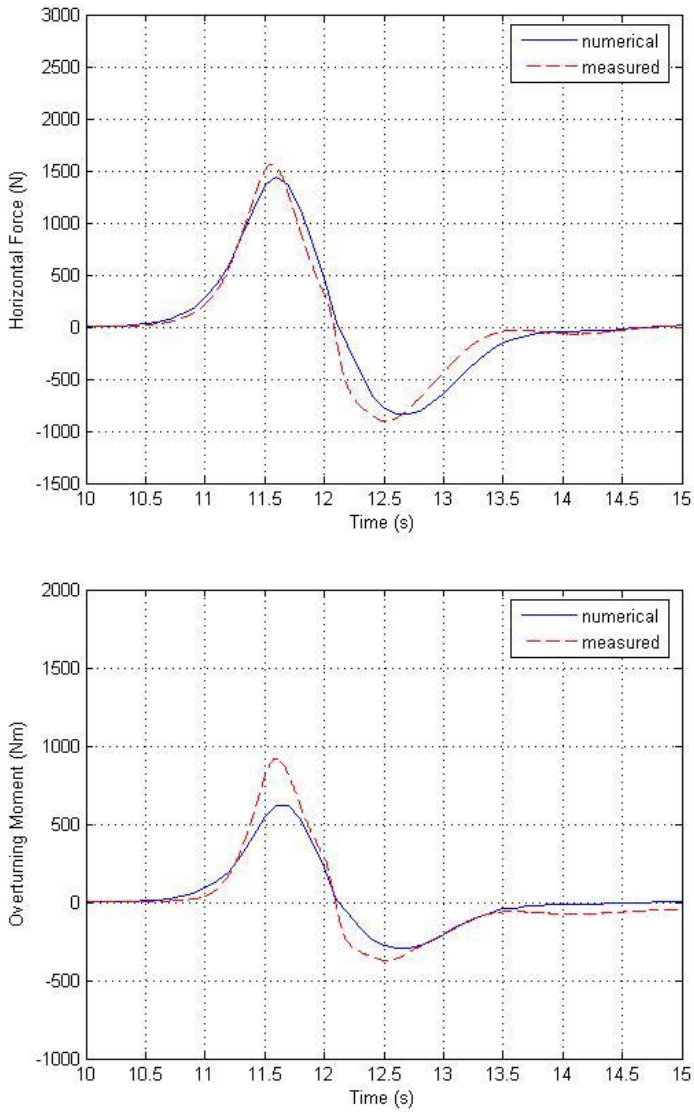


Figure 10. Numerical and measured horizontal force and overturning moment for plain solitary wave on single cylinder.

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