Ocean Engineering 72 (2013) 77–86

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

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

Simulation of two-dimensional internal waves generated by a translating and pitching foil

Sangmook Shin *

Department of Naval Architecture and Marine Systems Engineering, Pukyong National University, Busan 608-737, Republic of Korea

ARTICLE INFO

Article history:
Received 1 August 2011
Accepted 8 June 2013
Available online 15 July 2013

Keywords:
Discontinuity
Approximate Riemann solver
Immersed boundary
Collapse mechanism
Internal solitary wave
Waveform inversion
Traveling vortices

ABSTRACT

A code developed on the basis of the flux-difference splitting scheme and the hybrid Cartesian/immersed boundary method is applied for two-dimensional simulation of internal waves generated by a foil that is translating and pitching simultaneously near a material interface. The interface is captured as a moving contact discontinuity without any additional treatment along the interface. An approximate Riemann solver is used to estimate numerical fluxes across the discontinuity. Immersed boundary nodes are distributed within an instantaneous fluid domain on the basis of edges crossing a boundary. Dependent variables are reconstructed at the immersed boundary nodes along local normal lines to the boundary. The present results on the propagation of internal solitary waves generated by the collapse mechanism are compared with other computational results and good agreement is found. The code is validated through comparisons with recent experimental results on the waveform inversion from depression type to elevation type during the interaction between an internal solitary wave and a trapezoidal obstacle. Internal waves generated by a translating and pitching foil are simulated. Grid independence tests of the computed results are carried out. Pairs of traveling vortices are correlated to local sinking or rising at the interface.

1. Introduction

Internal waves are related to a wide range of engineering problems such as oil and water flows or ocean acoustics. In the ocean, a thin pycnocline separates two well-mixed layers so that internal waves are modeled as incompressible flows of two layers. Because of the small density difference, internal waves of great amplitude and wavelength have frequently been observed. Song et al. (2011) compared the effects of internal waves and surface waves on marine structures and reported that the low frequency of the internal waves causes large horizontal displacement of a spar platform. The periodic variations of horizontal velocity modulate the distribution of surface roughness, and they can be detected by synthetic aperture radar (SAR). This implies that the internal waves can be used to detect a submarine. Chang et al. (2006) carried out a numerical simulation for internal waves generated by a submarine.

Many numerical methods have been developed to analyze flows of incompressible fluids of different densities. Most of the methods introduce the δ-function formulation, in which the density variation is smoothed over a few grid cells to avoid difficulties with the discontinuity of the density field. The robustness of a scheme can be attained by the smoothing. However, numerical smearing across the material interface cannot be avoided and the additional treatment required along the interface may cause difficulties as the interface undergoes complicated deformation. Shin (2004) used the ghost fluid method on unstructured grids to handle the discontinuity across an interface without any smoothing. However, the method requires tracking the material interface and assigning dependent variables for the ghost cells.

For problems that contain the discontinuities within a domain, many methods based on the Riemann solver have been successfully developed. For incompressible free surface flows, Kelecy and Pletcher (1997) suggested a free surface capturing method that is based on the approximate Riemann solver. Because the scheme uses the solution of a hyperbolic problem with a discontinuous initial condition, the propagation of the discontinuities can be captured without any additional treatment along the interface. Pan and Chang (2000) applied Roe's flux-difference splitting scheme, which is a kind of approximate Riemann solver, to simulate water waves generated by a surface ship. Qian et al. (2006) combined Roe's flux-difference splitting scheme and the Cartesian cut-cell method to simulate free surface flows with moving bodies.

Due to its inherent flexibility in handling a boundary, the non-boundary conforming methods have been developed by many researchers. Peskin (1972) suggested the immersed boundary method to simulate flows inside a heart. Gilmanov and Sotiropoulos (2005) suggested the hybrid Cartesian/immersed

* Tel.: +82 51 629 6617; fax: +82 51 629 6608.
E-mail address: smshin@pknu.ac.kr

0029-8018/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.06.011

boundary method, in which the modified domain is a subset of the original instantaneous fluid domain. This feature enables the method to handle a very thin body and inviscid flows. Shin et al. (2007) suggested a new criterion for immersed boundary nodes on the basis of edges crossing a boundary so that the discretized flow problem is guaranteed to be well-posed and the scheme can handle an infinitesimally thick body. Shin et al. (2009) applied the hybrid Cartesian/immersed boundary method to simulate a fluid-structure interaction of a flexible heaving foil.

Shin et al. (2012) suggested a new method, in which the flux-difference splitting scheme and the hybrid Cartesian/immersed boundary method are combined to simulate free surface flows with moving or deforming boundaries. This method was validated through comparisons of its results with those of experiments and other numerical methods for various free surface flows, and then the code was applied to simulate a three-dimensional violent sloshing in a moving spherical tank. In this study, the code is expanded to simulate internal waves, where the density ratio is very close to unity. To validate the code for internal waves, the internal solitary waves generated by the collapse mechanism are simulated and the results are compared with other numerical results reported by Nakayama (2006). Moreover, to validate the code for an interaction between internal waves and a body boundary, the waveform inversion from depression type to elevation type is simulated for an internal solitary wave that propagates over a trapezoidal obstacle. The results are compared with recent experimental results on waveform inversion reported by Cheng and Hsu (2010). The validated code is applied to simulate internal waves generated by a pitching foil with a constant speed as a simplified model for effects of maneuvering of an underwater vehicle near a density-cline on generated internal wave patterns.

2. Governing equations

The governing equations are those of mass and momentum conservation for unsteady flows of immiscible and incompressible fluids. The material interface is regarded as a moving contact discontinuity in a density field, whereas the pressure and the normal velocity should be continuous across the material interface. To allow for the discontinuity within the domain, the governing equations are written in the integral conservation law form as follows:

$$\frac{\partial}{\partial t}\int_{\Omega}\mathbf{Q}\,d\Omega+\oint_S\mathbf{F}_{inv}dS-\oint_S\mathbf{F}_{vis}dS=\int_{\Omega}\mathbf{B}\,d\Omega \qquad (1)$$

where Ω is the control volume, S is the control surface, $\mathbf{Q}$ is the vector of conserved variables, $\mathbf{F}_{inv}$ and $\mathbf{F}_{vis}$ are the inviscid and viscous flux vectors, and $\mathbf{B}$ is the body force due to gravity. The vectors $\mathbf{Q}$, $\mathbf{F}_{inv}$, and $\mathbf{F}_{vis}$ are given as follows:

$$\mathbf{Q}=\begin{bmatrix}\rho\\ \rho u_i\\ 0\end{bmatrix},\ \mathbf{F}_{inv}=\begin{bmatrix}\rho\theta\\ \rho u_i\theta+pn_i\\ \theta\end{bmatrix},\ \mathbf{F}_{vis}=\begin{bmatrix}0\\ \tau_{ij}n_j\\ 0\end{bmatrix} \qquad (2)$$

where ρ is the density, u_i is the ith velocity component, p is the pressure, n_i is the ith unit normal vector component, θ is the normal velocity at the control surface, and τ_{ij} is the shear-stress tensor.

The first equation in the set of conservation laws determines the time derivative of the density field on the basis of mass conservation, and the last equation enforces the incompressibility constraint on both fluids. Although the instantaneous material interface can be identified on the basis of the calculated density field, the method does not require any additional treatment along the interface. The requirement for continuity of the normal velocity across the interface is fulfilled, because of the incompressibility constraint on both fluids. Once the normal velocity is continuous across the interface, the pressure should also be continuous across the interface to ensure momentum conservation, regardless of the discontinuity in the density field.

3. Numerical flux computation using the flux-difference splitting scheme

Because discontinuity is allowed in the domain and there is no additional treatment across the interface, the fluxes should be calculated using a scheme that can handle discontinuities. In this study, the flux-difference splitting scheme, which is a kind of approximate Riemann solver, is used to estimate the numerical

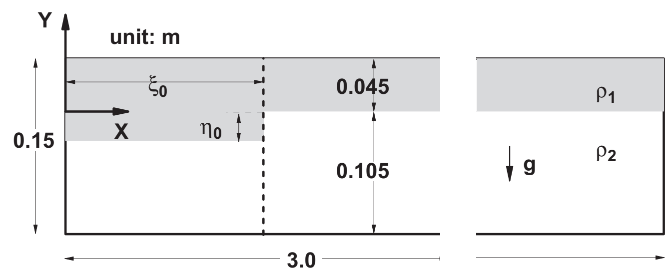

Fig. 1. Sketch of the generation of internal solitary waves by the collapse mechanism.

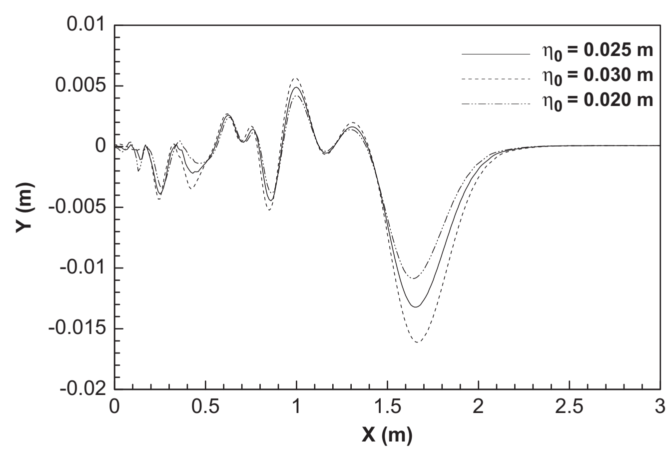

Fig. 2. Wave elevations computed for $t=15$ s according to the depth of the initial disturbance with $\xi_0=0.2$ m.

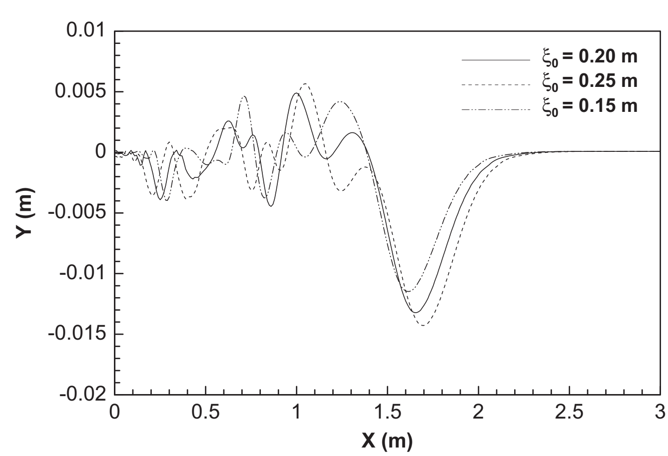

Fig. 3. Wave elevations computed for $t=15$ s according to the width of the initial disturbance with $\eta_0=0.025$ m.