COMPARISON OF WAVE GENERATION METHODS FOR TWO-PHASE VOF SOLVERS

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Introduction

CFD solvers rely on specific methods to generate waves for realistic marine and offshore applications. In this paper, three wave generation methods for two-phase VOF solvers are presented and compared, including the relaxation zone method, the internal wave generation method and the Spectral Wave Explicit Navier Stokes Equations (SWENSE) method. The methods, implemented either in *OpenFOAM* or in *ISIS-CFD* are tested by simulating a Catenary Anchor Leg Mooring (CALM) buoy in regular waves on a series of mesh with different spatial discretizations. The experimental data obtained by our laboratory is used to validate the results. The mesh requirements of the three methods are discussed in the end.

Wave Generation Methods

The target incident waves used by CFD are often defined in prior and introduced into the computational domain with wave generation methods. The simplest wave generation method is to impose wave velocity and free-surface elevation at the wave generation boundary. Such approach suffers from wave reflection problems and is unsuitable for wave diffraction simulation as the case investigated in this paper. Two common alternatives to overcome this difficulty are the relaxation zone approach[1] and internal wave generation approach[2]. They generate target incident waves in a upstream zone to the area of interest and let the waves propagate freely in the computational domain. On the contrary, the SWENSE method[3, 4] does not define specific zones for wave generating. It imposes explicitly the incident wave solution in the entire computational domain, and solves the disturbance of the incident waves as a complementary correction. The principles of the three methods are briefly explained as follows.

Relaxation Zone

The relaxation zone technique defines regions at the boundaries of the computational domain, where the computed value is gradually blended to the target value using a space-dependent weight function ω as shown in Figure 1(a). The value in these regions is relaxed as the linear combination of the CFD solution and the target value, as follows:

$$\chi = \omega \chi_{target} + (1-\omega)\chi_{CFD}$$

This technique is able to generate incident waves at the inlet of the CFD domain, and can also be used to prevent wave reflections at the outlet if the target value is set accordingly[5]. A fine mesh is needed from the inlet boundary to the area of interest to ensure the accuracy of the incident waves.

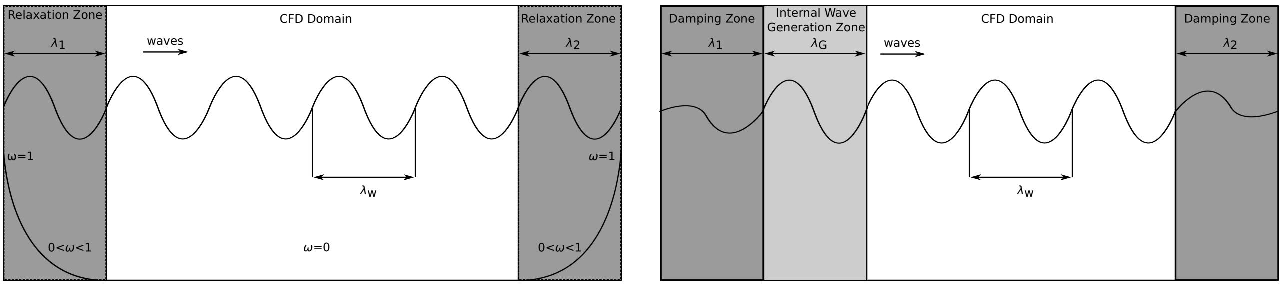
Internal Wave Generator

The internal wave generation method defines either mass or momentum source function in a specific region inside the computational domain, where the wave is generated according to the target value. This method is always used together with damping zones on the boundaries to prevent wave reflections. An illustration of this technique can be found in Figure 1(b). Coarse meshes can be used in the damping zone with little influence on the incident wave accuracy since the wave generation zone locates inside the pure CFD domain. However, a fine mesh is needed in the rest of the computational domain for an accurate description of the wave field.

SWENSE

Spectral Wave Explicit Navier-Stokes Equations(SWENSE) method treats the wave-structure interaction problem by decomposing the total fields into the incident waves and a complementary correction, as illustrated in Figure 2. A primitive variable χ(velocity, pressure, or free surface elevation) in the Navier-Stokes equations is considered as the sum of an incident variable χ_I and a complementary variable χ_C. The governing equations of χ_C are mathematically derived by subtracting the Navier-Stokes equations by Euler equations as follows.

$$\nabla.\mathbf{u}_C = 0 \quad ; \qquad \frac{\partial \mathbf{u}_C}{\partial t} + \mathbf{u}_C.\nabla\mathbf{u}_C + \mathbf{u}_C.\nabla\mathbf{u}_I + \mathbf{u}_I.\nabla\mathbf{u}_C = -\frac{\nabla p_C}{\rho} + \nu\nabla^2\mathbf{u}_C$$



(a) Relaxation Zone (b) Internal Wave Generator

Figure 1: Wave Generation Techniques

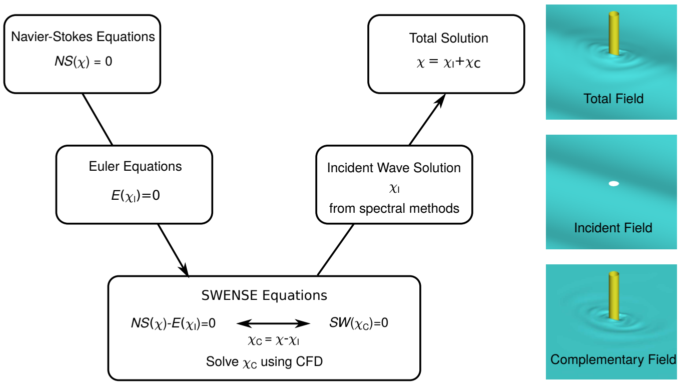
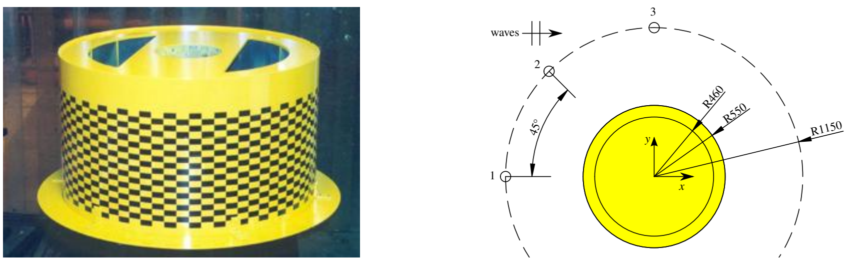


Figure 2: The SWENSE method decomposes the total field into an incident and a complementary field

With such decomposition, the mesh requirement regarding the incident wave propagation can be loosened since the incident wave information is explicitly known in the entire computational domain. A good mesh quality is only necessary near the structure to solve the wave-structure interaction with a high level of accuracy.

Test Case: CALM Buoy in regular waves

The test case reproduces an experiment carried out in the ocean wave basin of Ecole Centrale de Nantes (50m long, 30m wide and 5m deep). It deals with the interaction between regular waves and a fixed CALM buoy[6]. The buoy has a truncated cylinder form with a thin skirt near the bottom to provide additional damping forces through vortex shedding, as shown in Figure 3(a). Measurement data for the horizontal and vertical forces on the buoy and the free surface elevation at three points around it are used to validate the CFD simulation. (See Figure 3(b).)

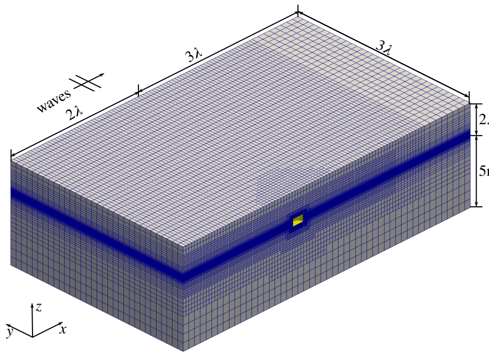


(a) CALM Buoy Model (b) Wave Gauge Positions

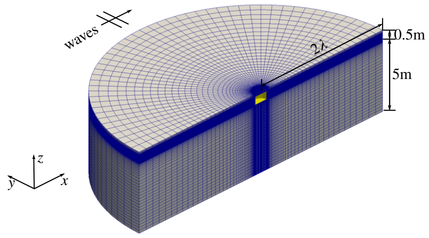
Figure 3: Experiment setup for CALM buoy in waves

Three CFD solvers, *foamStar*, *foamStarSwense* and *ISIS-CFD*, are selected for the comparison. They generate waves with the relaxation zone, the SWENSE method, and the internal wave generator respectively. *FoamStar*[7] and *foamStarSwense*[8] are solvers derived from *interDyMFOAM*, the native *OpenFOAM* solver for incompressible two-phase flow. *ISIS-CFD* is an incompressible two-phase flow solver developed at Ecole Centrale de Nantes and distributed commercially as a part of *Fine^{TM}/Marine* by NUMECA International; it uses the finite-volume method with unstructured mesh and captures the interface with the VOF technique[9].
A rectangular computational domain with a series of spatial discretization is used to test the mesh quality required by different wave generation methods. As Figure 4(a) shows, the background mesh is Cartesian; the mesh is locally refined and fitted to the body. Three configurations: 20L, 40L, and 80L are used with 20, 40, and 80 cells per wave length in the x direction. The differences between

the configurations are only in the far-field. The mesh density near the buoy is kept invariant. A cylindrical configuration, which is typically used by the SWENSE method, is added only to test *foamStarSwense* (see Figure 4(b)). The details of the different meshes are summarized in Table 1.



(a) Rectangular Computational Domain



(b) Cylindric Computational Domain

Figure 4: Mesh configuration for the test case

Table 1: Mesh configurations for CALM buoy in regular waves

Mesh	$\lambda/\Delta x$	$\lambda/\Delta y$	$H/\Delta z$	Number of cells
20L	20	10	16	1.3 M
40L	40	10	16	1.5 M
80L	80	20	16	2.5 M
Cylindrical	-	-	16	0.7 M

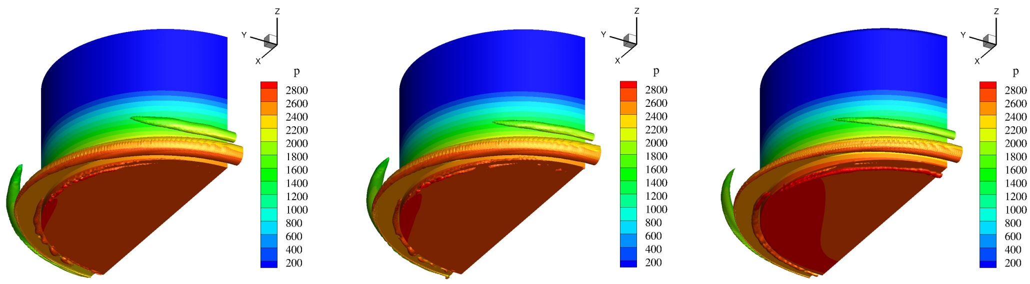
The CFD results and the experiment data are shown in Table 2 and summarized as follows.

- 80L: The results of the three CFD solvers are in good agreement. The difference between *foamStarSwense* and *ISIS-CFD* are inferior to 1% for the first harmonic amplitudes. *foamStar* gives slightly smaller predictions on the first harmonic amplitudes. The experiment results has a better agreement with the results of *foamStarSwense* and *ISIS-CFD*.
- 40L: According to ITTC's recommendation, 40 cells per wave length is the minimum requirement for wave simulations by CFD[10]. With this discretization, *foamStarSwense* and *ISIS-CFD* are able to predict correctly the wave force and elevation with an accuracy of 1% compared with the 80L configuration. This difference is about 3% for *foamStar* with the relaxation zone technique.
- 20L: This discretization is known to be too coarse to simulate waves in CFD. The coarse mesh causes excessive numerical diffusion and damps the incident waves. Both *foamStar* and *ISIS-CFD* give smaller predictions. However, *foamStarSwense*'s results are still within 3% different to the finest resolution.
- Cylindrical: This configuration has large cells in the far-field, and the mesh is gradually refined towards the domain center. The results of *foamStarSwense* compare well with the references, while the number of points is drastically reduced. The corresponding gain in CPU time compared to *foamStar* with the mesh 80L is a factor of 5.53 on the same hardware.

Table 2: Comparison between CFD results and experimental data

		$F_x^{(1)}$	$F_x^{(2)}$	$F_z^{(1)}$	$F_z^{(2)}$	$\eta_1^{(1)}$	$\eta_1^{(2)}$	$\eta_2^{(1)}$	$\eta_2^{(2)}$	$\eta_3^{(1)}$	$\eta_3^{(2)}$
Experiment		1.390	0.170	1.180	0.015	1.220	0.065	1.210	0.040	1.040	0.035
foamStar (Relaxation Zone)	20L	1.202	0.130	1.018	0.017	1.063	0.057	1.057	0.037	0.924	0.039
	40L	1.328	0.165	1.075	0.011	1.172	0.057	1.164	0.035	0.983	0.041
	80L	1.359	0.168	1.098	0.010	1.195	0.060	1.180	0.036	1.002	0.045
foamStarSwense (SWENSE)	20L	1.360	0.183	1.134	0.011	1.199	0.059	1.185	0.039	1.020	0.051
	40L	1.376	0.181	1.144	0.012	1.208	0.060	1.195	0.032	1.028	0.051
	80L	1.387	0.186	1.149	0.012	1.213	0.063	1.197	0.039	1.037	0.040
	Cylindrical	1.369	0.180	1.159	0.019	1.216	0.070	1.199	0.044	1.027	0.056
ISIS-CFD (Internal Wave Generator)	20L	1.314	0.150	1.094	0.014	1.169	0.065	1.155	0.038	0.997	0.042
	40L	1.369	0.171	1.133	0.013	1.216	0.070	1.199	0.043	1.032	0.049
	80L	1.378	0.173	1.141	0.014	1.224	0.064	1.208	0.040	1.041	0.050

To ensure the accuracy of the simulation, especially to validate the result of *foamStarSwense* on the coarse mesh, the flow details of the simulation are compared. Figure 5 plots the Q-criterions and the pressure fields obtained by *foamStar*, *foamStarSwense*, and *ISIS-CFD*, with 80L, 20L, and 80L respectively. The results show a good agreement and are consistent with previous numerical simulations[4].



(a) foamStar 80L (b) foamStarSwense 20L (c) ISIS-CFD 80L

Figure 5: Comparison of the iso-surfaces of Q-criterion = 50 and pressure field when a wave crest passes the buoy

Conclusion

The present work compared three wave generation models for two-phase CFD solvers: the relaxation zone technique, the internal wave generator, and the SWENSE method. The mesh requirement of each method is studied by simulating a CALM buoy in regular waves. Results show that the relaxation zone method requires a mesh quality of at least 80 cells per wave length. The internal wave generator technique need 40 cells per wave length to keep a good accuracy of the incident waves; 80 cells per wave length should be used when a high level of accuracy is required. The SWENSE method gives good predictions even if the far-field mesh is very coarse (20 cells per wave length). The efficiency of the SWENSE method is confirmed, both in terms of mesh and CPU requirements.

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