MODELLING WAVE INTERACTIONS WITH A SURFACE-PIERCING VERTICAL CYLINDER USING OpenFOAM

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INTRODUCTION

With the intensification of the global energy crisis, the development of marine renewable energy is attracting increasing attention. To achieve the renewable energy targets, a rigorous approach is required leading to the better design of wave energy converters with increased efficiency. Wave loading is a key factor to be considered for structural design. Either over-predicted or under-predicted loading would cause severe consequences. Over-predicting the loading will lead to overdesign and then very expensive structures. The consequence of under-prediction may even more dangerous and expensive - leading to under-design and structural failure.

The use of Computational Fluid Dynamics (CFD) codes is becoming increasing important in engineering design work. The free, open-source library for continuum-mechanics problems known as OpenFOAM is suitable for solving complex free-surface motions (Weller et al., 1998). It has been applied to coastal engineering successfully by Morgan et al. (2010, 2011). The experimental results for the propagation of monochromatic waves over a submerged bar have been reproduced in his numerical simulations, with up to 6th order harmonics correctly modelled.

This research is focussed on the assessment of how OpenFOAM performs when applied to non-linear wave interaction with a vertical surface piercing cylinder, a typical representation of an offshore wind turbine foundation. A few new functions have been developed to advance wave generation and wave absorbing capabilities of the model. A series of experiments performed in the Danish Hydraulic Institute’s shallow water basin in 2009 have been reproduced using OpenFOAM to test the accuracy of the model predicting wave-structure interaction problems. The decomposition of the measured signals into harmonics has also been carried out to examine the effects of wave and loading nonlinearity.

VALIDATION AND RESULT DISCUSSIONS

The experiments were performed at the Danish Hydraulic Institute, details were given in Zang et al (2010). The shallow water basin (35*m* x 25*m*) was used for the tests with a water depth of 0.505*m*. A cylinder of diameter 0.25*m* was suspended from a rigid frame, leaving only a 1*mm* gap beneath to the bed of the basin. The total horizontal hydrodynamic force on the cylinder was measured via a load cell, and 19 wave gauges were placed to monitor the wave-field around the cylinder. The layout for the wave gauges can be seen in Figure 1. The numerical results for the free surface elevations at wave gauges of 1, 5, 9, 13, 17 and 19, and the horizontal force on the cylinder have been compared with experimental measurements for several cases, of which two cases will be discussed in this paper. These two cases correspond to the same slenderness (ka=0.37) and same kD (1.39) for the cylinder, but have different steepness (kA_1=0.1, and kA_2=0.2). Here k is wave number, a is cylinder radius, D is water depth and A is wave crest with A_1=0.035m, A_2=0.07m. For both cases, wave period is 1.22s.

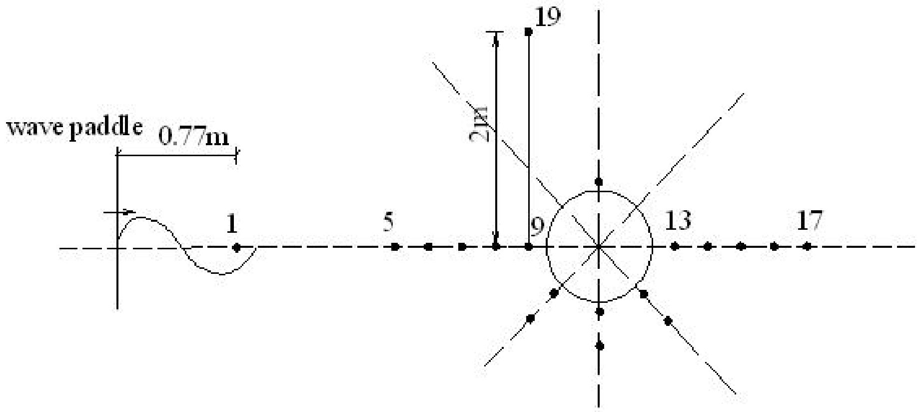

Figure 1: The arrangement of wave gauges in the wave tank

In the numerical simulations, a few key factors have been examined to ensure accurate reproduction of the experiments. As the wave generation in the numerical model is via the flux into the computational domain through a fixed vertical wall, different from wave generation by piston paddles in the experiments, a careful match between experiments and numerical models for the first wave gauge (0.77m from the paddle) was made to ensure the incoming waves in the numerical tank are very close to the waves generated in the experiments. Wave focus time, focus distance and phase angle are all carefully chosen to match the experiments. A damping zone is also added in the computational domain to avoid reflection at the downstream end of the numerical tank.

Time series of experimental and numerical free surface elevations at a few locations along the central line for the cases with cylinder in place are given in Figure 2. Note that the wave gauge 19 is placed close to the side wall of the numerical tank for a second check of the incoming waves. At location of wave gauge 9, which is 2mm in front of the upstream stagnation point of the cylinder, all wave components are in phase and the wave group produces a large energetic events. Wave breaking at wave gauge 13, which was observed in experiments, may lead to a relatively larger discrepancy between the predicted and measured values of the free surface elevations. A finer mesh would be required to obtain a better match. Apart from gauge 13, the numerical model appears to have captured all the main physical features of the nonlinear focused wave interaction with the vertical cylinder, with close matching of both crest values of the free surface and horizontal forces, and the wave shapes.

In order to extract the harmonic structure of the free surface and wave loading on the cylinder, both crest focused waves and trough focused waves were performed, both in the experiments and the numerical simulations. Following Zang et al. (2006), Zang et al. (2010) and Fitzgerald et al. (2012), our simple phase-based separation method has been applied to decompose higher order harmonics cleanly without cross-contamination between adjacent harmonics. Table 1 shows the comparisons of the crest values of each harmonic of free surface elevations and horizontal forces for wave amplitudes with the cylinder in place. This is clear that the 2^{nd} order components for case 2 are much larger than case 1, about 4-5 times larger than the values in case 1, which is consistent with the expected Stokes-type behavior.

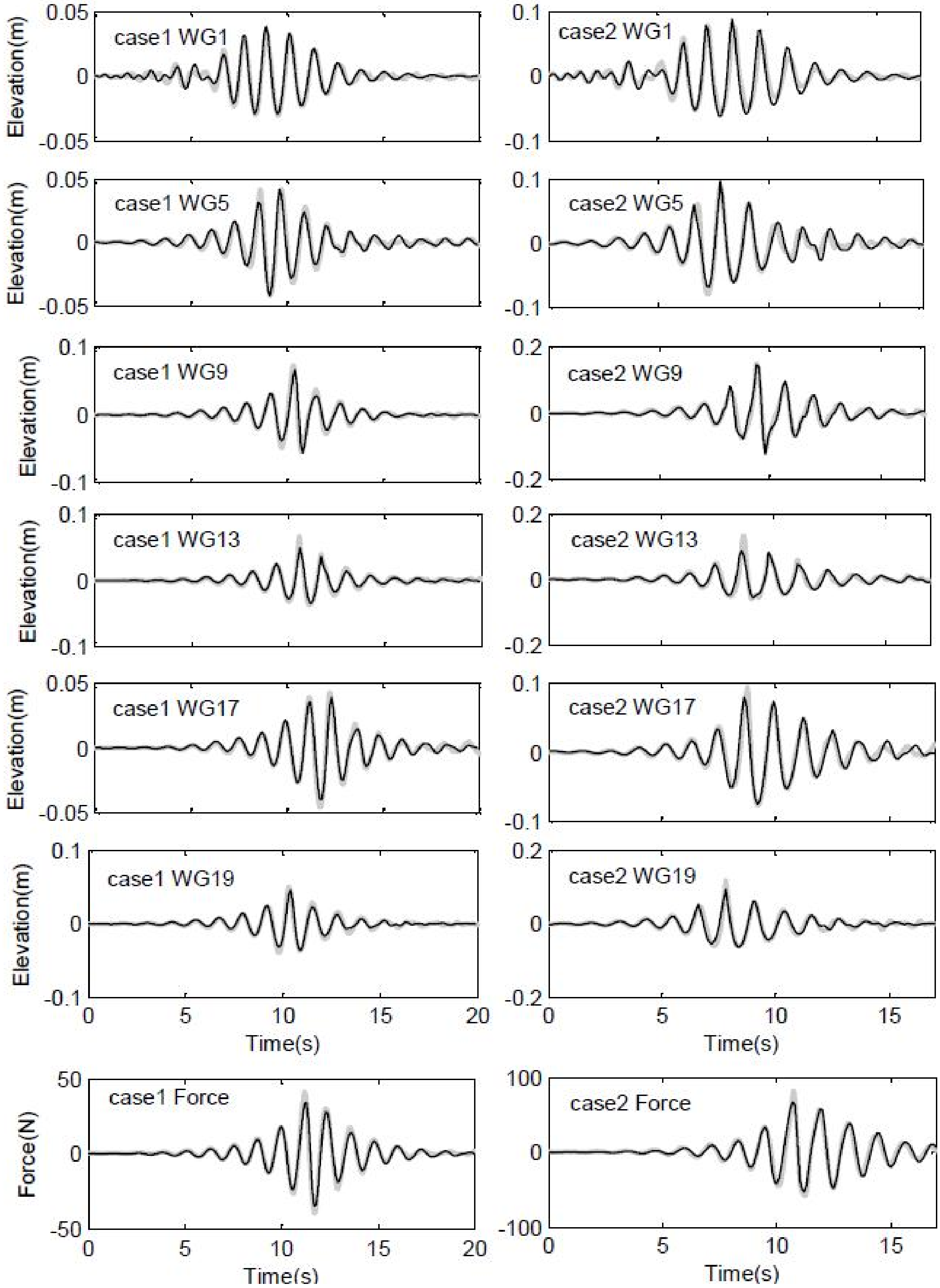

Figure 2: Time series of free surface elevations and horizontal forces for both cases with cylinder in place. The experimental data is in thick grey line and the numerical results are in thin black line.

Given the good match for all the components, we are confident that accurate predictions of the free surface elevations in the wave-field and the horizontal force on the cylinder can be made by using the present model based on OpenFOAM.

harmonics	Peak free surface elevations (m)				Peak horizontal forces (N)			
	case 1		case 2		case 1		case 2	
	kA_1=0.1		kA_2=0.2		kA_1=0.1		kA_2=0.2	
	Exp	Num	Exp	Num	Exp	Num	Exp	Num
long wave	0.0016	0.0017	0.0050	0.0130	1.91	1.80	7.50	7.50
linear	0.0530	0.0560	0.0930	0.1050	40.0	32.0	67.0	57.0
2nd	0.0105	0.0104	0.0370	0.0430	2.20	3.20	9.50	12
3rd	0.0020	0.0020	0.0080	0.0130	1.30	0.70	9.50	4.50
4th	0.0055	0.0075	0.0057	0.0034	1.00	0.20	1.70	2.70

Table 1: Each harmonic of free surface elevations at the location of WG9 and horizontal forces for both cases with cylinder in place. Exp means Experimental data and Num means Numerical results.

From the preliminary results, we conclude that the present model based on OpenFOAM can accurately predict the non-linear wave interaction with a vertical cylinder up to at least the 4^{th} frequency harmonic. By using the crest-trough phase-based separation method, we can reproduce harmonic structure in both the free surface and the wave loading on the structure. Further examples of the validation and the harmonic structure of the free surface and hydrodynamic loading on a surface-piercing column will be presented at the workshop.

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