NUMERICAL INVESTIGATION OF UNSTEADY HYDRODYNAMIC LOADS ON A VERTICAL CYLINDER IN WAVES AND SHEARED CURRENTS

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INTRODUCTION

The co-existence of waves and currents is practically important because of the interaction between these flow components. In existing design methods the current profile is usually assumed to be uniform with depth. The case of regular waves propagating over a uniform current was investigated by Fenton (1985) using a fifth-order Stokes theory, and the combined water kinematics can be treated simply as a Doppler shifted solution. The uniform current approximation may apply in large-scale ocean currents and deep tidal flows, but it fails to model wind-driven currents that exhibit some degree of shear in the vertical direction. Alternatively, the current profile may be represented by either a linear shear flow with constant vorticity (Tsao, 1959; Dalrymple, 1973) or an arbitrarily depth-varying current with depth-varying vorticity distribution (Swan and James, 2001; Nwogu, 2009). Comparisons between the results with a uniform current approximation and a depth-varying current indicate that the vorticity distribution is of importance and would reduce the effect of the Doppler shift (Swan and James, 2001).

The extended OpenFOAM model presented by Chen et al. (2014), developed to investigate extreme wave loading on a vertical surface-piercing cylinder on otherwise still water, has been extended in this research. This model solves the RANS equations for the combined flow of air and water, and uses the VOF method to capture the free surface. A new input boundary condition has been added to input a vertically sheared current so as to allow an investigation of the interaction between focused wave groups and co-linear, depth-varying, currents. The current profile is defined by a second-order polynomial, and an iterative correction method proposed by Stagonas et al. (2014) is applied in order to achieve symmetric wave focusing more accurately and efficiently. The numerical results are compared with experimental measurements collected at University College London (UCL), UK, and a good agreement is achieved. Considerable effort is made to predict the modification in the wave spectrum due to the interaction with a depth-varying current in this study.

VALIDATION, RESULTS AND DISCUSSION

The physical model tests used to validate the numerical model were carried at University College London (UCL), UK, details are given in Stagonas et al. (2014). The flume with a length of 20 m and a width of 1.2 m was used with a uniform water depth of 0.5 m for all test conditions in which a series of focused wave groups propagated on non-uniform currents. A Gaussian wave spectrum was used with various incident spectral peak frequencies so as to cover long waves down to short waves. The peak wave amplitude of incident focused wave group and thus corresponding wave steepness was varied from small close to linear waves up to much larger nearly breaking waves. The current was introduced via a re-circulation system below the flume and a wire structure of variable density was carefully designed and inserted in the flume to generate a strongly sheared mean velocity profile. For the results presented in this paper, the spectral peak frequency f_p = 0.6 Hz, the peak amplitude of incident focused wave group measured in the absence of a current A_{linear} = 0.05 m, and the surface flow velocity U_0 = 0.2 m/s traveling in the same direction as the wave celerity. This therefore corresponds to a relatively linear sea states. The current profile was very close to linear, varying from close to zero at the bed and the maximum at the surface; in the numerical simulation the inlet profile is defined by a second-order polynomial.

A full-depth vertical surface-piercing cylinder with the diameter of 0.165 m and 0.25 m was located 8.7 m away from the wave-maker. This location is also the predefined focus point of the input wave group, so that all wave components are in phase at the upstream stagnation point of the cylinder giving a violent wave-structure interaction. The focused time of the incident focused wave group was 64 s. The total horizontal force on the cylinder was measured via load cells installed at the top of the cylinder, and the free surface elevation, η (t), was recorded at 7 fixed spatial locations via an array of wave gauges shown in Figure 1.

In the numerical simulations, the focused wave groups are fluxed into the computational domain through a vertical wall and the current is introduced by specifying the current velocities of the predefined profile at the input boundary faces, different from the mechanically generated waves and currents in the experiments. Thus, the iterative correction method proposed by Stagonas et al. (2014) is applied to ensure that the incoming flow field in the numerical tank is very close to that in the experiments. As the linearized spectrum is used as the target spectrum in the iterative correction method, harmonic decomposition of the energy spectrum is required. The linear harmonic part is separated using a four-phase manipulation method proposed by Fitzgerald et al. (2014). Four wave groups, which have the same amplitude spectrum, are generated with four constant phase shifts of 0, $\pi/2$, π, $3\pi/2$, both in the experiments and the numerical simulations. The input amplitude spectrum and the phases of individual wave components in the numerical simulation are corrected iteratively until the numerical solution of the linear wave components at the focus point coincides with its measured counterpart in the experiments.

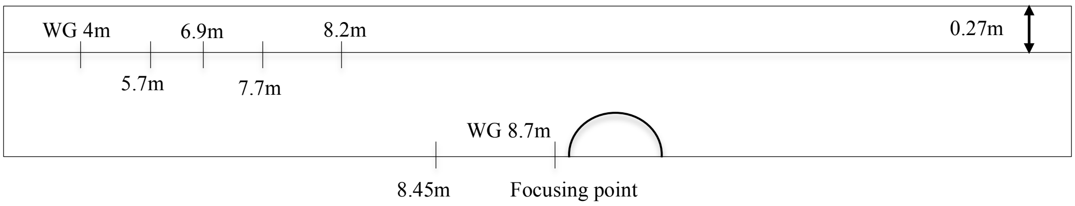

Figure 1: The arrangement of the wave gauges in the wave tank.

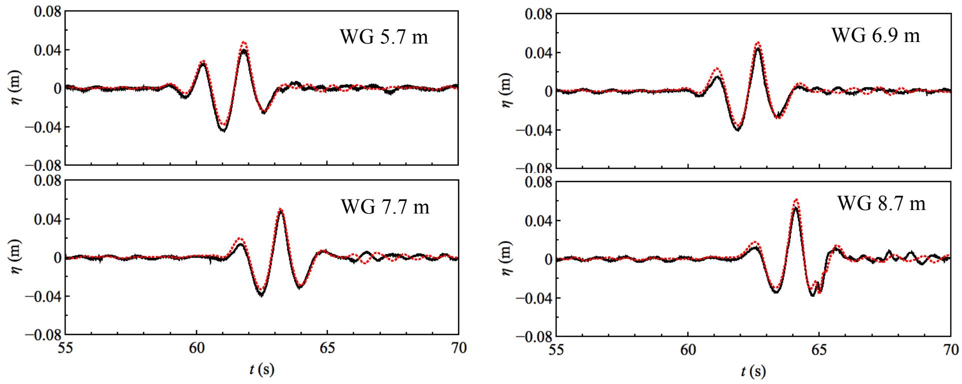

Figure 2: Time histories of the free surface elevation at fixed spatial locations with the cylinder in place for a focused wave group on a sheared current. Exptal data - black solid line; numerics as red dash line.

The 3-D numerical wave tank domain consists of a rectangular domain with a vertical cylinder located at the centre of the tank. Time series of experimental and numerical free surface elevations at a few fixed spatial locations with the cylinder in place for the case of a focused wave group co-existing with a sheared current of surface velocity 0.2 m/s that is traveling in the same direction as the focused wave group are given in Figure 2. The diameter of the cylinder is 0.165 m here. It can be seen that a largest wave event is produced at the upstream stagnation point of the cylinder as desired, which indicates that the applied iterative correction method performs very well for focused wave groups propagating over a sheared current. All the components of the linear part of the Gaussian spectrum come into phase at the focused point giving a localized tall crest and leading to a rather violent wave-structure interaction. The measured and numerically predicted horizontal hydrodynamic loads on the cylinder are shown in Figure 3. Both the physical and numerical experiments can effectively model the extreme event within a short time. Good agreement between the experimental and numerical results demonstrates that the numerical wave tank can provide accurate simulations - both for the interaction of the unsteady wave group with the sheared current and then the interaction of both with the surface-piercing cylinder.

Additionally, it can be seen that there is a phase lag of about $\pi/2$ between the free surface elevation at the upstream stagnation point of the cylinder and the wave loading on the cylinder; as would be expected for a relatively small diameter cylinder where the Morison inertia term would dominate the loading.

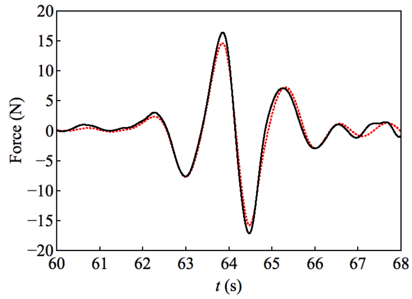

Figure 3: Time histories of the wave loading on the cylinder with the diameter of 0.165 m for the case of focused wave groups on a sheared current. Exptal data - black solid line; numerics as red dash line.

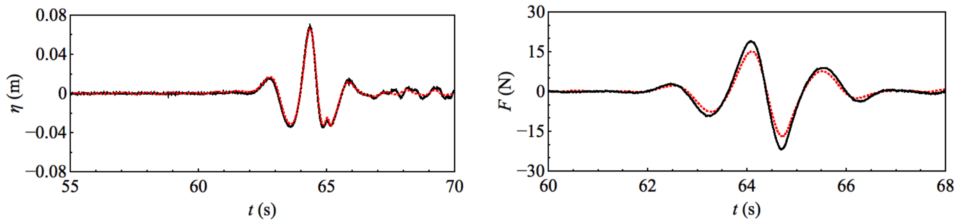

Figure 4: Time histories of the surface elevation at the upstream stagnation point and the wave loading on the cylinder with the diameter of 0.165 m for the wave-only case. Exptal data - black solid line; numerics as red dash line.

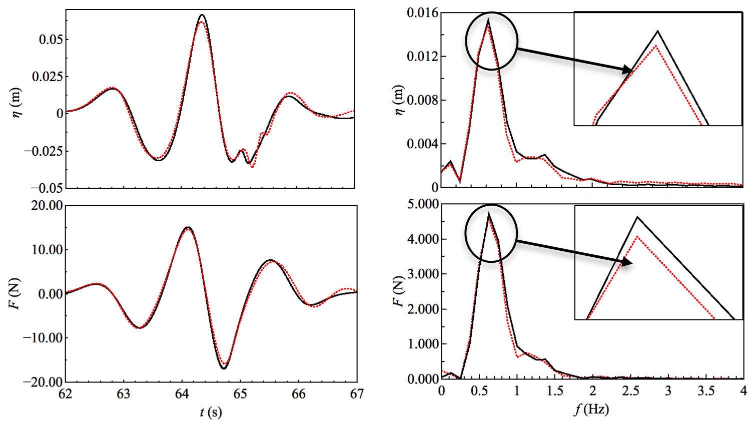

Figure 5: Time histories and corresponding wave spectra of the free surface elevation at the focused point and the wave loading on the cylinder with the diameter of 0.165 m for both the wave-current case and the wave-only case. Wave-only solution - black solid line; Wave-current interaction - red dash line.

This analysis concentrates on the interaction of a wave group with an identical linear shape both on a sheared current and on still water at the position of the cylinder, both wave groups interacting with the same cylinder. Hence, the same spectral adjustment scheme was used, allowing the modeling of the same focused wave group propagating on still water. The resulting free surface elevation and wave loading on the cylinder are again recorded and compared with the experimental measurements collected at UCL for verification, see Figure 4. Figure 5 compares the wave shape and the wave spectra recorded on still water with the results on a sheared current. The upper two plots show the time series of numerical free surface elevations at the upstream stagnation point of the cylinder and the corresponding spectra, and the lower two plots correspond to the numerical results of the wave loading on the cylinder. It can be seen from Figure 5 that the magnitude of the amplitude spectrum for both the free surface elevation and the wave loading both marginally decrease due to the interaction with a sheared current propagating in the same direction as the wave celerity. This slight discrepancy may result from the difference in the 2nd order harmonics as the iterative correction method is applied in the cases both with and without current. For a compact array of smaller cylinders, Santo et al. (2015) found that the 2nd frequency term contributes to skew the total inertial force for regular waves with no current.

Fig. 6 shows the amplitude spectra for the first three harmonics of the measured horizontal force on the cylinder with the diameter of 0.25 m. The same linear wave shape and the current profile as for the case with smaller cylinder in place were used. It can be seen from Fig. 6 that the applied four-phase manipulation method allows a clear separation of harmonics with the ordered harmonics being at the 'right' frequency. And it can also be found that the linear components for wave groups traveling on still water and on sheared currents are quite similar with each other as the result of tuning the free surface elevation of wave group using the iterative correction method so that it has same frequency content at the location of the cylinder. Additionally, the 2nd and 4th order harmonics are observed to be ordered from largest on following sheared currents, on still water and on opposing sheared currents but the 3rd order harmonic is not. This is consistent with the observation that the 3rd order was in some general sense different to all the other components for waves with no current presented by Fitzgerald et al. (2014). Further discussion of the effect of a sheared current on the wave loading and the free surface elevation around a single cylinder will be presented at the workshop.

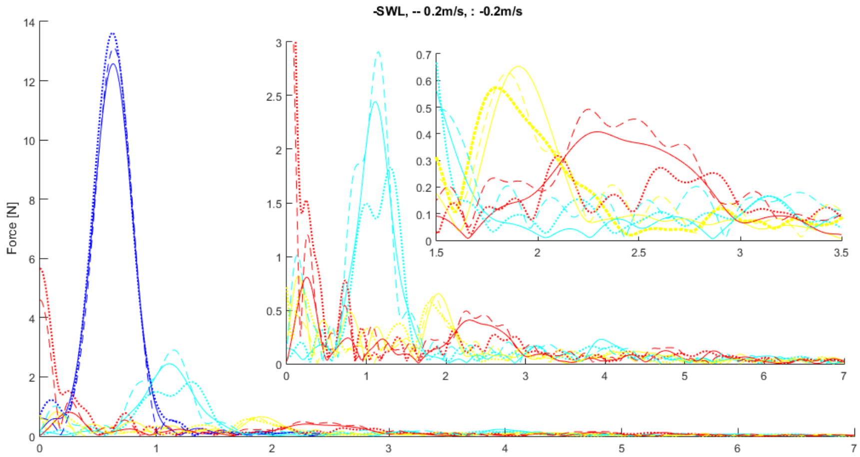

Figure 6: Amplitude spectra for the first three harmonics of the measured force on the cylinder with the diameter of 0.25 m. Wave-only case – solid line; Wave on a sheared current with the surface velocity of 0.2 m/s – dash line; Wave on a sheared current with the surface velocity of -0.2 m/s – dot lines.

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