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A model test for the wave interaction with a four-cylinder structure

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1. INTRODUCTION

The prediction of the runup and free surface elevation is of great interest for the offshore industry, e.g. to determine the air gap. Air gap is the vertical distance from the underside of the platform deck to the wave crest. This clearance must be sufficient that the wave does not strike the lower deck. At the same time, it must also be minimized in order to avoid raising the centre of gravity and exposed vertical surface area of the platform, which may affect the wind loading and will increase the wind overturning moments.

An important influence on the determination of air gap is the phenomenon known as near-trapping. For a multi-column structure this has been shown theoretically to occur at critical frequencies dependent upon the geometry of the structure. These phenomena can cause the local wave elevations to be significantly greater than that of the undisturbed incident wave. Considering arrays of vertical bottom mounted circular columns, the scattering of water waves by arrays of columns was solved exactly by Linton and Evans (1990). Subsequently Evans & Porter (1997) made a detailed investigation of near-trapping by circular arrays of vertical cylinders. Malenica et al. (1999) extended the studies of near-trapping in an array to the second-order and suggest that second-order near-trapping occurs when the frequency of the second-order components is equal to the frequency of first-order near-trapping. However predicted by theoretical study, the near-trapping phenomenon has rarely been experimentally verified.

In the present study the diffraction of regular waves by an array of four vertical cylinders is investigated by a model test. The test was undertaken in a wave basin at Dalian University of Technology and designed to measure the free surface elevation η at multiple locations close to the body surface subjected to regular waves of the steepness kA varies from 0.06 to 0.10, where k is the wave number, A is the incident wave amplitude. Ohl *et al.* (2001) has carried out a similar experiment and outstanding results are obtained from the experiment. Due to model and facility constraints the experiment was conducted for 6 frequencies in the range $0.449<ka<0.555$, where a is the cylinder radius. In the present test, a wider range of frequencies $0.408<ka<1.966$ were employed and over this frequency range the near-trapping phenomenon both at the first- and the second-order can be investigated. As the near-trapping phenomenon is sensitive to the change in ka, tests were conducted for totally 30 frequencies and the frequencies are distributed densely in the range where near-trapping phenomena are theoretically predicted to occur.

First- and second-order terms of wave elevations are computed from the measured time series. It can be found that high localized wave elevations were observed at both the first- and second-order. The large increases in free surface elevations are found to occur over a range of frequencies, close to the near-trapping frequency. The results are then compared with those obtained by QTFDUT, a hydrodynamic analysis program developed in the frame of potential flow theory. It's found that the potential flow theory can be effective at predicting the first- and second-order qualities. At most frequencies satisfying results can be obtained by using the linear diffraction theory alone. However, at some crucial frequencies, the magnitude of local free surface is affected by significant nonlinear interactions, and the second-order qualities make a considerable contribution.

2. SET-UP OF THE EXPERIMENT

Test was undertaken in a wave basin at Dalian University of Technology. The basin has a plan area of 55m×34m. The water depth for testing is 0.5m. A wave generator with 70 computer controlled individual paddles is arranged at the basin's upstream end. In the procedure of the experiment these paddles generated unidirectional regular waves, with the wave crests parallel to the wave paddles. At the downstream end of the basin, a wave absorbing beach is arranged, which can prevent significant reflection of wave energy. Along the side walls wave absorbers are placed. To obtain a sufficient long period for data acquisition without spurious harmonics all these precautions are necessary.

Fig.1 is a plan view of the model placement in the basin. The four cylinders are arranged at the corners of a square. The diameter of each cylinder is 400mm and the gap between cylinders is one diameter. The origin of the coordinate system is at the center of the cylinders and on the undisturbed free surface. The *z*-axis points vertically upwards, the *x*-axis is in the direction of incident wave propagation and the *y*-axis is parallel to the wave paddles. Four wave gauges are placed in the vicinity of the four cylinders as described in Fig.1. All gauges are 18mm away from the cylinder surface and the wave gauge positions are shown in Table 1.

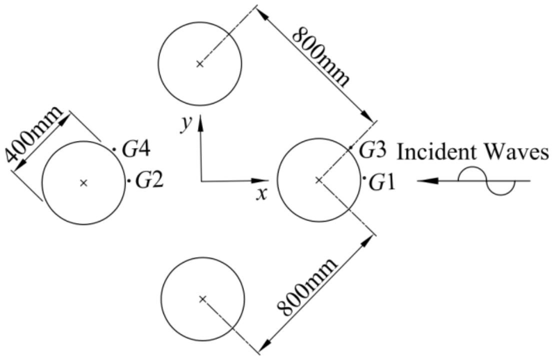


Fig.1 plan view of the model placement in the basin

Table.1 The wave gauge positions

Gauge	*x*(mm)	*y*(mm)
*G*1	618.00	0.00
*G*2	-182.00	0.00
*G*3	554.15	154.15
*G*4	-245.85	154.15

Tests were conducted for 30 regular wave periods. For each wave period, three waves with steepness *kA* of 0.06, 0.08 and 0.10 were chosen. Minor difference was found during the experiment between the measured incident amplitude *A* and the target value.

3. NUMERICAL PROGRAM

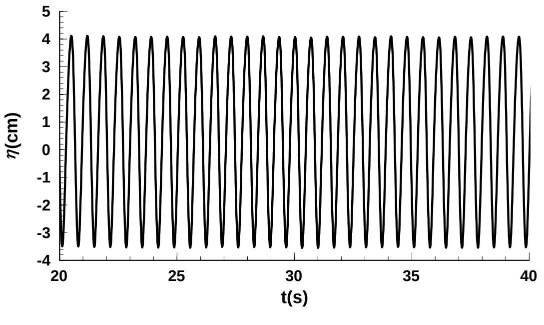
The hydrodynamic analysis program QTFDUT is used to compare with the experimental results. This program is developed in the frame of potential flow theory and utilizes the higher order boundary element method to solve the diffraction and radiation problem. First- and second-order velocity potentials can be computed for wave incident upon fixed and floating bodies of arbitrary shape.

Prior to the present study, the program has been used to investigate wave diffraction for various geometries. Through comparisons with analytical solutions, semi-analytical solutions and published data, the validation of the program has been rigorously verified. Teng *et al*. (2012) has verified the program in a study, which considered the wave interaction with fixed arrays of bottom mounted cylinders. The second-order wave elevations generated by QTFDUT agree remarkably well with the Malenica *et al.*'s (1999) semi-analytical solutions.

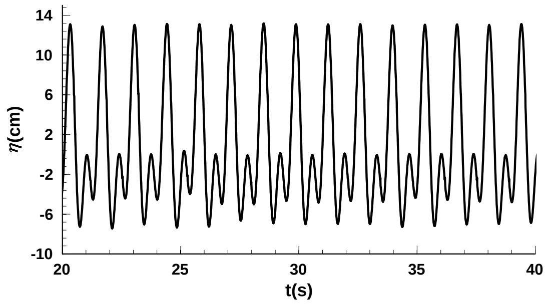
4. SOME RESULTS OF THE EXPERIMENT

The results from the regular wave tests are presented in this section. Firstly, the time history of measured data is shown for two typical conditions. From Fig.2 it can be observed that the measured data is stable and reaches their intended height. It also can be seen that the data used to be analyzed contains more than 15 steady-state waves, is of sufficient length to fully capture subtle features in the test. At *T*=0.68, the contribution from the nonlinear quantities is insignificant which implies that the results can be well predicted by linear wave theory. At *T*=1.36, nonlinear interactions have a strong effect on the local free surface ($\eta^{(1)}$=5.742cm and $\eta^{(2)}$=6.627cm) and can't be accurately predicted by using linear wave theory alone. Band pass filtering method is used to analyze the measured data series and the measured data are decomposed into the first- and the second-order quantities.

The results are then discussed with reference to linear and second-order wave theory. The results for the 4 gauge positions are presented in Figs. 3~4. For each gauge position, amplitude versus test wave period *T* is plotted. The validation of higher-order diffraction theories has primarily conducted on forces or moments which are integrated quantities. In present study, more rigorous comparison is carried out based on the free surface elevation.

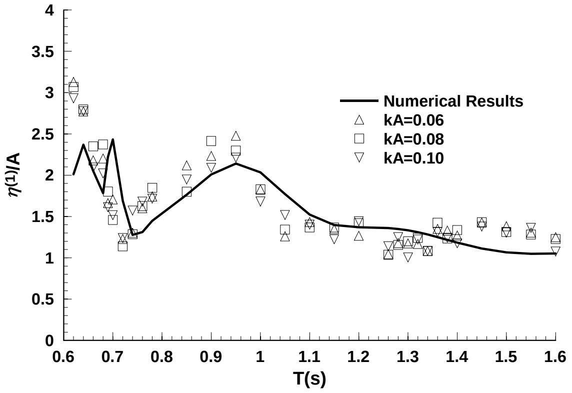


(*a*) *A*=1.184cm, *T*=0.68s, *kA*=0.103

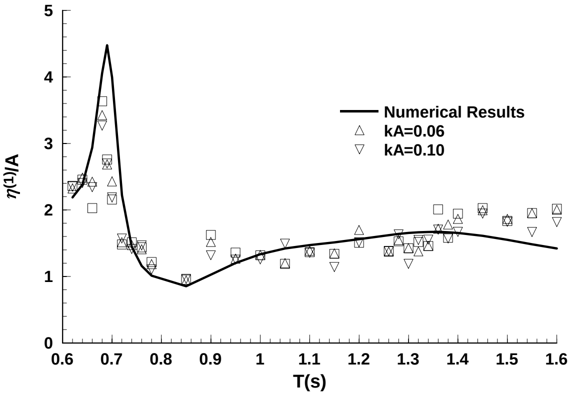


(*b*) A=3.890cm, T=1.36s, kA=0.099

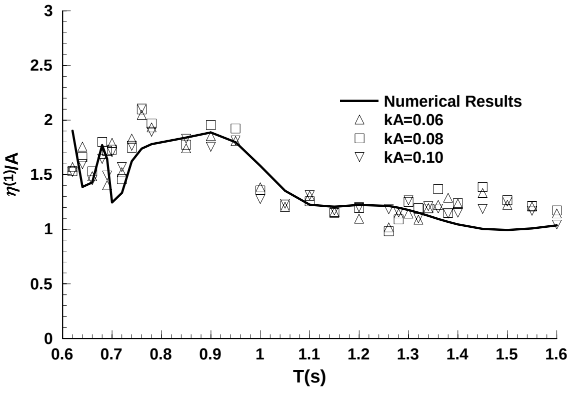
Fig. 2 Measured time history of the free surface elevation at $G1$ for two conditions



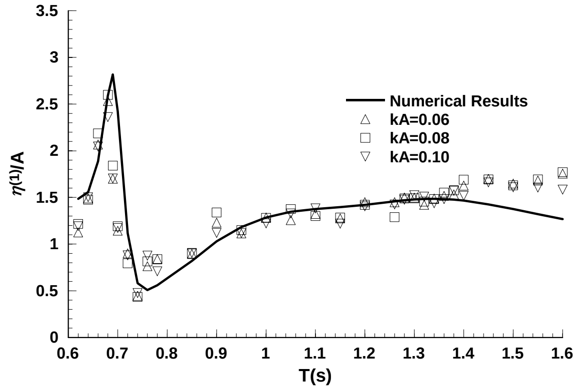
(*a*) at $G1$



(*b*) at $G2$



(*c*) at $G3$

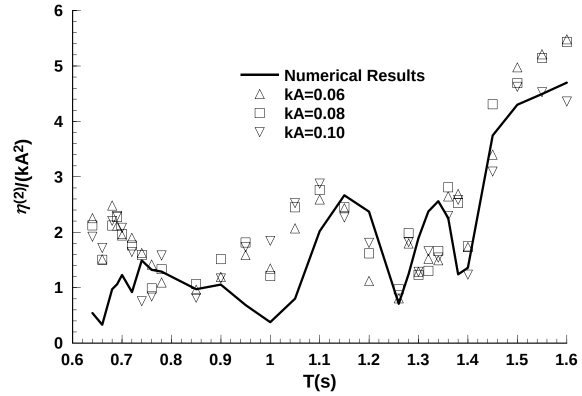


(*d*) at $G4$

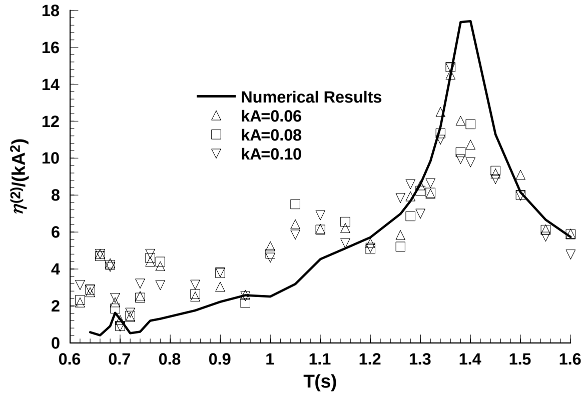
Fig. 3 The first-order wave elevation at gauge positions

Fig.3 shows the numerical and experimental first-order quantities. The plotted quantities are non-dimensionalized with A. It can be seen that the experimental results and theoretical results are in good agreement. There is also little difference between the results with different wave steepness. Above observations indicate that the potential flow theory can be effective at predicting the first-order elevation. Then at $G2$ large increases in free surface elevations occur over a narrow range of frequencies can be observed. The behavior of the experimental results in the range is close to the corresponding behavior described by the numerical results. Which implies that the near-trapping phenomenon indeed exist in the practice. While the match between experiment and theory is close, there are discernible differences in the magnitude and wave period of the maximum amplitude. The highest first-order elevation $\eta^{(1)}/A$ is equal to 3.63 and occurs at T=0.68s at $G2$. At the same time the corresponding highest numerical value occurs at about T=0.69s and is greater than the maximum experimental value. The reason for the shift of the period corresponding to the maximum value needs further investigation. It is also meaningful to note that the magnitude of the diffracted first-order amplitude at $G2$ never drops below that of the incident wave amplitude.

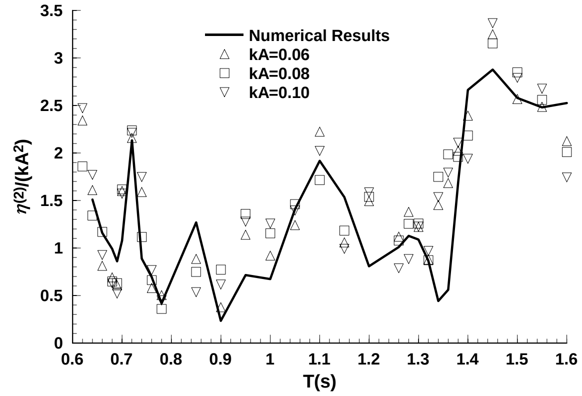
Fig.4 shows the numerical and experimental second-order quantities. The plotted quantities are non-dimensionalized with kA^2. It can be seen that overall trends of the experimental results are similar and all experimental results seem to correspond to the numerical prediction in general. The highest second order elevations $\eta^{(2)}/kA^2$ is equal to 14.90 and occurs at the gauge $G2$ when T=1.36s. As wave period approaching 1.36s, the magnitude increases rapidly and the resonance like phenomenon occurs over a broader range than that of the first-order. Shift of the period corresponding to the maximum value is also observed at the second-order. The geometry used in the present test is identical to the case studied by Evans & Porter (1997) and Malenica *et al.* (1999). Malenica *et al.* (1999) found that near-trapping of the second-order wave occurs when its frequency coincides with the linear near-trapping frequency. In the present study, for the first-order component high localized wave elevations are observed at T=0.68s and for the second-order component the corresponding phenomenon occurs at T=1.36s. This finding coincides with the conclusion of Malenica *et al.* (1999).



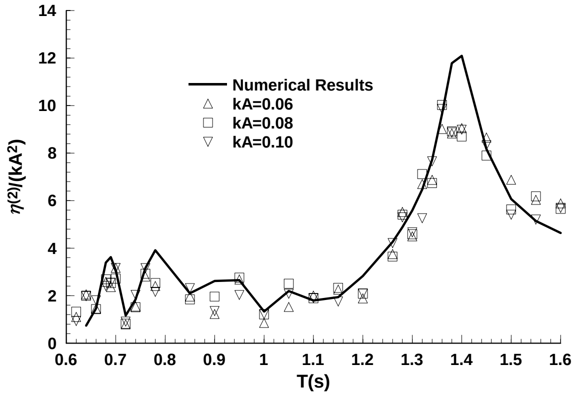
(*a*) at *G*1



(*b*) at *G*2



(*c*) at *G*3



(*d*) at *G*4

Fig. 4 The second-order wave elevation at gauge positions

5. CONCLUSION

Though analyzing the results of a model test it is found that the potential flow theory can be effective at predicting both the first- and the second-order qualities. The resonant like phenomena were observed in the model test. When the important phenomenon occurs at the second-order, significant nonlinear interactions can be observed and it makes a considerable contribution to the free surface elevation.

ACKNOWLEDGEMENTS

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