Experimental investigation on interactions between two monochromatic wave trains with different approaching directions

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Abstract

Interactions between two identical monochromatic wave trains with a relative approaching angle of 24° were experimentally investigated in a well-designed 'X' configuration. Wave trains with different amplitudes and frequencies were generated. The results showed that the interactions were strongly dependent on both wave amplitudes and frequencies. The wave trains can approximately maintain its initial status after the interactions for waves with small initial steepness. However, for larger waves, the interactions were enhanced and the surfaces were significantly distorted, no longer two-dimensional after the encounter. During the interaction process, there was an obvious increase in wave height, reaching the maximum amplification about 1.55 times of the initial height at the middle of the interaction region. Furthermore, the images captured by high-speed cameras illustrated that two wave trains enter the interaction region at the same time and then merged together during the interaction process, resulting in increase of the wave amplitude. The combined wave crest was initially composed of two straight segments and gradually morphed into a straight segment from the plan view. Then, wave broke in the downstream part of the interaction region with a crescent pattern of the crest.

Introduction

Wave-wave interaction is a remarkable property of ocean gravity waves. Now it is well accepted that wave-wave interaction is one of the most important mechanics for causing wave breaking [1] and plays a key role in the process of the formation of extreme large waves [2]. During the past decades, the characteristics of wave-wave interactions for unidirectional propagating waves were studied extensively by means of theoretical [3], experimental [4,5] and numerical [6,7] manners. However, ocean waves are multidirectional spreading and are usually characterized by the coexistence of two wave systems with different directions of propagation, i.e. crossing sea state [8]. Compared with the amount of researches on wave-wave interactions within unidirectional propagating wave trains, studies on wave interactions of bidirectional propagating waves are rare, especially for experimental researches. Petrova and Soares [9] conducted an experiment to investigate the maximum wave crest and height statistics of two different long-crest irregular wave systems propagating at different angles. Toffoli et al. [10] also presented an experiment of two identical long-crest irregular waves with different approaching angles, and found that the number of extreme events depends on the angle between the two interacting systems. As the waves used in the above mentioned researches were generated by well-prescribed spectra and mainly focused on the statistical properties of cross-sea states, the interactions between the two wave systems were therefore very complicated.

Recently, Liu et al. [11] designed an ingenious experiment to study interactions between two identical regular wave trains which were propagating along two different directions. In the experiment, an 'X' configuration was constructed to assure that the two wave trains could propagate isolatedly with a specified approaching angle of 8° which was symmetrically with respect to the normal direction of the wave maker and then encountered each other in an interaction region. The results indicated that the increase of wave height at the central of the interaction was about 1.37 times of the initial wave heights and not influenced by wave heights and frequencies. Later, Liu et al. [12] studied wave breaking induced by two identical focusing wave groups in this experimental configuration. However, only a relative approaching angle between two wave trains is far from enough.

In this study, an 'X' configuration considering a relative approaching angle of 24° for two wave trains was constructed in a wave basin. Monochromatic wave trains with different amplitudes and frequencies were generated to study the influence of initial steepness. By comparing with the previous results, the influence of approaching angles can also be examined.

Experimental Setup

The experiments were conducted in a wave basin located at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. This basin was 32 m long, 24 m wide and was used with a water depth of 0.6 m. The detailed description of the equipment can be found in the paper of Liu et al. [11,12]. An 'X' configuration was installed in the basin to permit two long-crest wave trains propagating separately along two directions, which were symmetrical and 12° with respect to the normal direction of the wave maker. And make sure the two wave trains encountered in an interaction region and then transmitted in the downstream sections. The experimental setup can be seen in Figure 1. Hereafter, we denote the right hand side of the normal direction of the wave maker right flume and another one is left flume. Two coordinate systems were adopted herein. One was a global coordinate system (x_G, y_G), the other was a local coordinate system (x, y). For the local coordinate system, the x direction follows the left/ right flume and the y direction was perpendicular to the left/right flume. The origin was defined at the mean position of the wave-maker. The beginning of the two flumes were located $x = 1.5$ m.

Capacitance wave probes were used to measure the time series of water surface elevations. The locations of these probes are denoted in Figure 1 (a) by dots. Additionally, two high-speed cameras (Flare, 12M125MCL-F) with 28 mm focal length Nikon lens, were located 5 m above the interaction region to capture the interaction processes. The two cameras were used as a resolution of 3000×1248 pixels and 200 frames per second (f.p.s.).
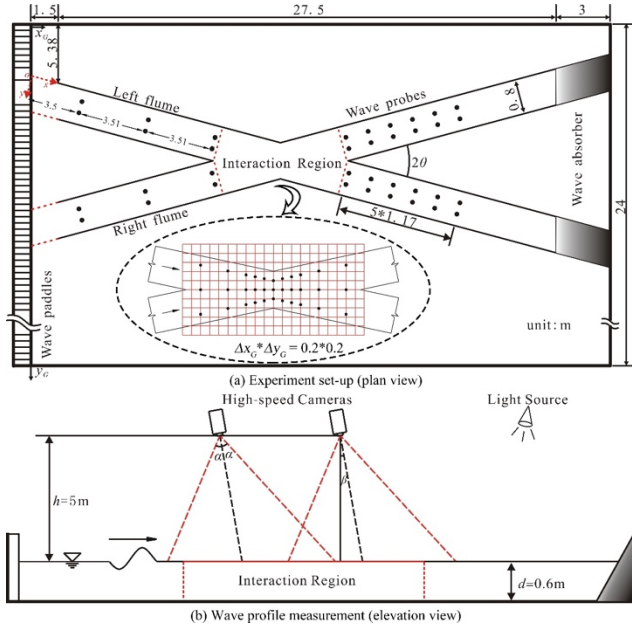
Figure 1. Sketch drawing of the experimental setup.

The present investigation considered monochromatic waves with different initial wave steepness (see Table 1). For each experimental case, three repeated measurements were collected with a record of 60 s and a sample interval of 0.01 s. The parameters presented in Table 1 are estimated from the surface elevations measured at the locations $x = 3.5$ m.

Case	f(Hz)	k(m^{-1})	H_0(cm)	IMS	Comments
A1			14.84	0.21	non-breaking
A2	0.8	2.77	17.11	0.24	breaking
A3			18.77	0.26	breaking
B1			7.07	0.21	non-breaking
B2	1.2	5.81	8.43	0.24	non-breaking
B3			12.50	0.36	breaking

Table 1. Wave Parameters.

Experimental Results

As can be seen in Figure 2(a), the measured surface elevations laterally agree well along the left flume as the wave trains propagating to the interaction region, indicating that the two-dimensional structure of the waves was retained before the superposition. In addition, the surface elevations measured at same propagating distances but different flumes are also almost identical (Figure 2(b)). Hence, two nearly identical wave trains can be generated by our present facility, and the interaction between the two wave trains could be investigated further. To mitigate the influence of reflection and refraction in the interaction region, only the front few measured waves were used in the following-up analysis. Comparisons of the other cases show similar results and therefore it is not illustrated herein.

Figure 4 illustrates the variations of the non-dimensional wave height in the interaction region for two experimental cases without breaking. It can be found that the wave heights increased after the two wave trains encountered. They reached to the maximum at the middle part of the interaction region $x_G = 12.28$m and then decreased gradually in the downstream part. The maximum wave heights can be reached during the interaction process are about 1.55 times of the initial wave heights and the influence of wave frequency is negligible. There are clearly divergences of wave heights between the left and the right part of the interaction region, suggesting that the distribution of wave height was not symmetric with respect to the central line of the interaction region. This divergence is partly due to the diffractions and reflections from the side-wall during the active interactions. However, the divergence for the case with frequency $f = 0.8$Hz was much smaller than the case of $f = 1.2$Hz, especially in the downstream part, indicating that interactions between two wave systems strongly depend on wave frequencies.
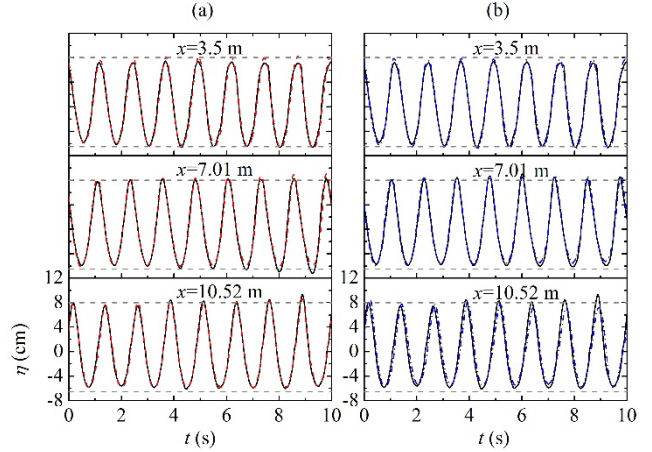

Figure 2. Comparisons among the surface profiles measured before the interaction for Case A1 along the two flumes: (a) Comparisons of the lateral surface profiles measured in the left flume; (b) Comparisons of the surface profiles at the same positions but in the different flumes. The solid lines represent the surface profiles measured on the right side of the left flume; the dash lines represent the surface profile measured on the left side of the left flume; the dash dot lines represent the surface profile measured on the left side of the right flume.

Recalling that the maximum wave height in the previous experiment of a smaller relative approaching angle (16º) between two wave trains was about 1.37 times of the initial wave heights, the value is smaller than the present experiment. Additionally, the divergences of wave heights in the interaction region of the experiment with relative approaching angle 16º was not apparent [11]. Therefore, by comparing with the two experiments, interactions between two wave systems are strongly dependent on approaching angles, consisting with the previous studies [10].

It is well known that wave reflection increases with the decreasing of the incident angle with respect to front structures. Therefore, the increasing of approach angle can increase the influence of wave reflection from the walls of the opposite directions. Furthermore, the width of the interaction region in the present 'X' configuration with the larger angle is wider than that of the experiment with the smaller approaching angle. Consequently, the diffraction is also more evident in the present experimental setup. Both reflection and diffraction may play no ignorable influence on the spatial distribution of wave heights in the interaction region. For this reason, special consideration should be regarded to mitigate reflection and diffraction in further studies.
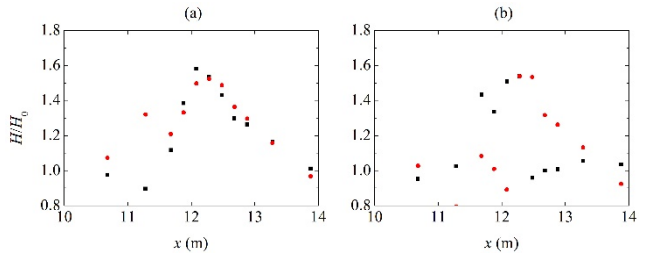

Figure 3. Variations of the non-dimensional wave heights for Case A1 (a) and Case B1 (b) along the interaction region. (●) the wave height measured on the extension line of the left flume; (■) the wave height measured on the extension line of the right flume.

To observe the process of interaction, two high-speed cameras, which were located above the interaction region, were used to capture the variations of the wave surface. Moreover, four iodine tungsten lamps were placed around the interaction region to facilitate the surface profile measurement during the process of wave interaction. Meanwhile, polyethylene particles with diameter about 1mm were seeded on the water surface to prevent the transmission of light and therefore the wave crests can be identified clearly.

As an illustration, Figure 8 shows the pictured images during the interaction process of the Case A3. As can be seen in these images, the two wave trains enter the interaction region at the same time. Then the two wave crest merged into a longer straight crest as the interaction continued, contributing to the increasing of wave height. Finally, the wave broke in the downstream part of the interaction region with a crescent pattern of the crest. During the wave interaction, it is clear that diffraction, especially near the side walls of the middle of the interaction region, may have significant influence on the rapid changes in elevation form shape of the crest.
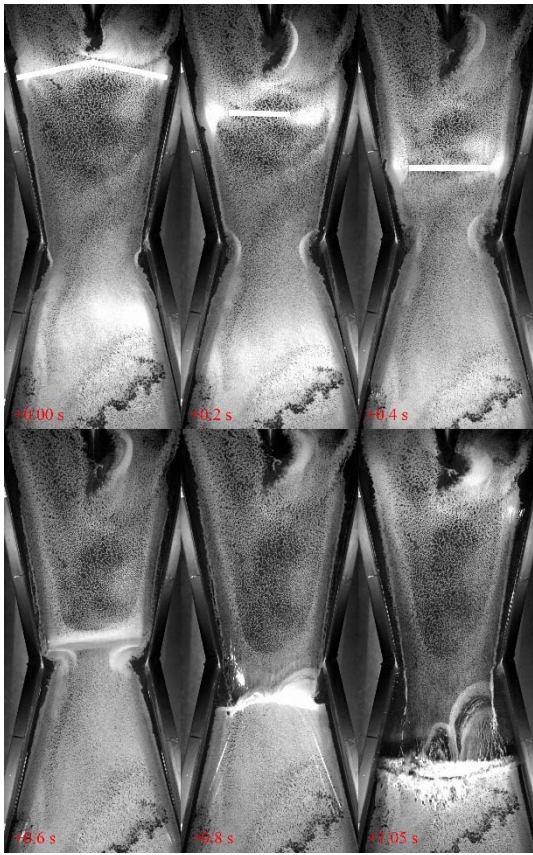

Figure 4. Camera recording of the process of the interaction for Case A3.

Figures. 5 and 6 show the measured surface elevations at two positions downstream of the interaction region. For the case with low wave frequency (f = 0.8 Hz), the waveform is close to the initial state in both flumes at x = 16.35m, which was close to the interaction region. It is evident that the wave profiles were still approximately two-dimensional except for a small decreasing of wave height mainly caused by the friction of the sidewalls and the bottom, suggesting the interaction of bidirectional wave trains can be reversible without breaking. However, divergences were clearly observed for the surface profiles of the case with a higher frequency (f = 1.2 Hz) measured at downstream of the interaction region. There was evidence of three-dimensional feature on the transverse wave surface after the interaction, indicating that the increasing frequency can affect the interactions of bidirectional wave trains on wave profiles. Considering that, for the same

wave parameters, the divergences between the measurements in both lateral positions in the same flume and corresponding locations in different flumes at the experiment with the relatively approaching angle of 16° was not evident [11], which is further confirming that that both wave frequencies and approach angles play important role on the interactions.
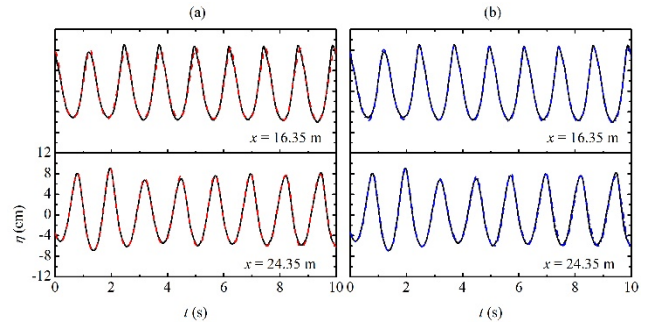

Figure 5. Comparisons of the measured surface profiles downstream of the interaction region for Case A1 (f = 0.8 Hz, MIS = 0.21). The description of the data as in Figure 2.
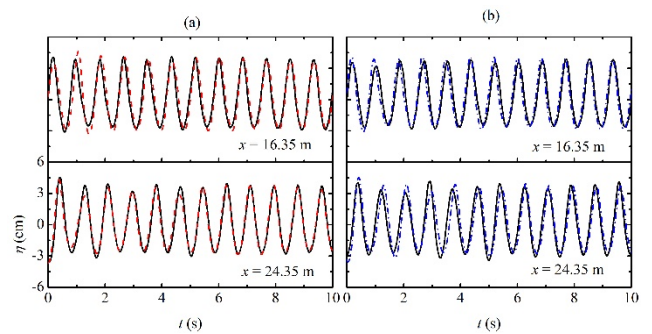

Figure 6. Comparisons of the measured surface profiles downstream of the interaction region for Case B1 (f = 1.2 Hz, MIS = 0.21). The description of the data as in Figure 2.

Conclusions

An experimental study on interactions of two identical monochromatic wave trains with a relative approaching angle of 24° is presented. In the experiments, monochromatic wave trains are generated in an 'X' configuration constructed in a wave basin. The results show that, during the interactions, wave heights are enhanced and reached to about 1.55 times of the initial wave heights. The increasement of wave heights is larger than the interactions of two wave trains with relative approaching angel of 16°. After the interactions, the wave profiles can retain its initial feature in the downstream region for cases with the lower frequency. However, for the cases with a higher frequency, the wave pattern is apparently demonstrated in three-dimensional property. The present experiment indicates that both approaching angles and wave frequencies play important roles in the interactions of cross-sea state.

Acknowledgments

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