Investigation of Interaction between Solitary Wave and Horizontal Plate based on MPS-FEM Coupled Method

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Abstract**—This paper is mainly concerned with the problem of wave-plate interaction. To conduct the simulation of the solitary wave interacting with the horizontal plate, the moving particle semi-implicit and finite element coupled method (MPS-FEM) is employed. In this coupled approach, the MPS method is adopted to calculate the fluid domain while the structural domain is solved through the FEM method. In the simulation, the solitary wave with various amplitude is generated in the numerical wave tank and then be compared with the theoretical wave profile. Thereafter the interaction between the solitary wave and the rigid plate is simulated. The wave amplitude, as well as the elevation of the plate above the surface, varies from case to case in order to study its effects on the wave-induced force. The calculated results are compared with the available experimental data. Finally the interaction between the solitary wave and the flexible plate is simulated. The results are contrasted with the counterparts in the former rigid cases to investigate the contribution of the structural flexibility to the wave-induced force.**

I. INTRODUTION

The wave-structure interaction is a hot issue in the field of naval architecture and ocean engineering. The plate structure, such as the pier, jetty or very large floating structure (VLFS), is among the most common structures suffering from the impact of the wave. While encountering severe wave, these offshore or costal structures would produce considerable deformation which will exert a great influence on the flow field nearby, making the problem even more complex. Thus the research on the wave-plate interaction problem is crucial to the design of the offshore or costal structures.

With the development of the high-performance computer, the numerical method is playing a critical role in the research on wave-plate interaction. The numerical simulation can provide researchers with comprehensive information and consume much less resource than the experiment. Liu and Sakai [1] studied the hydroelastic responses of a 2D flexible plate exposed to waves based on Boundary Element Method (BEM) for fluid and FEM for structure. Liao and Hu [2] combined the Finite Difference method (FDM) with the FEM method to investigate the interaction between surface flow and thin elastic plate. Despite the effectiveness, these mesh-based methods may suffer from the difficulties such as the adjustment or regeneration of mesh while coordinating the interface between fluid and solid domain. Some newly emerged mesh-free methods can exactly overcome the difficulties brought about by the mesh. The Smoothed Particle Hydrodynamics (SPH, Lucy [3]; Monaghan and Gingold [4]) and the MPS (Koshizuka and Oka [5]) are two typical particle-based mesh-free methods. These mesh-free methods display fair adaptation to the problems of large deformation and intense surface because there is no requirement for treatments of mesh or free surface. Although the SPH-FEM model was first proposed by Attaway et al. [6] to investigate the structure-structure interaction, it was subsequently applied into FSI problems by scholars (Antoci et al. [7]; Fourey et al. [8]; Yang et al. [9]). Different from the traditional SPH method, the pressure of the particle is obtained by solving the pressure Poisson equation (PPE) in the MPS method. Thus the obtained pressure field through MPS method is considered to be smoother. Till now, some preliminary researches on FSI have been conducted in the context of the MPS method. Sun et al. [10] proposed MPS-modal superposition method in which the elastic deformation of structure is computed through a mode superposition formulation. In contrast, more scholars chose to combine the MPS with the FEM method in order to address complicated FSI problem. Lee et al. [11] successfully simulated the interaction between dam-break and sloshing flow through the coupled MPS-FEM method. Some other researches performing the MPS-FEM model (Mitsume et al. [12]; Hwang et al. [13]; Zhang et al. [14]) also displayed fair agreement with available experimental results.

In the present paper, the interaction between solitary wave and the horizontal plate is mainly investigated. The performance of the numerical solitary wave generation is first examined to make sure that desired wave can be generated. In the FSI analysis, the interaction between the solitary wave and rigid plate is simulated. The wave amplitude, as well as the vertical position of the plate, varies in different cases in order to investigate their effects on the wave-induced force. Finally the solitary wave interacting with the flexible plate is investigated.

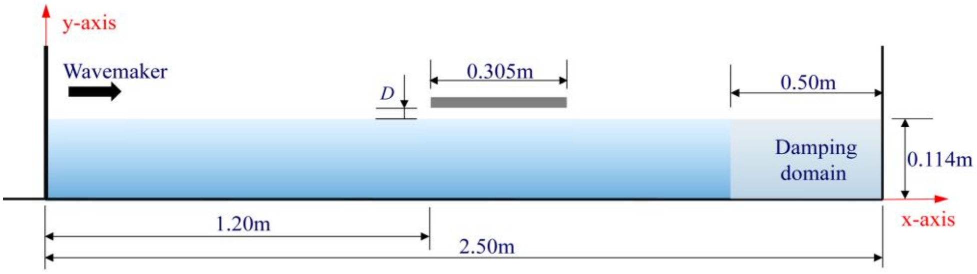


Figure 1. Geometric model of the numerical wave tank

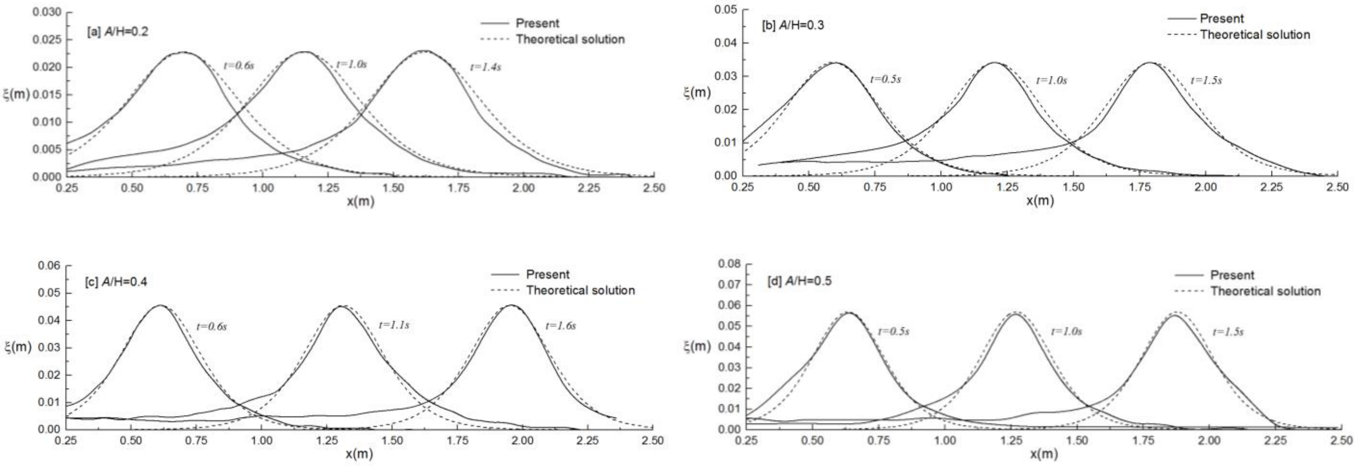


Figure 2. Comparison of the wave profiles between the calculated and theoretical solutions

II. NUMERICAL SIMULATIONS

The interaction between the solitary wave and a horizontal plate is simulated using the in-house solver in this section. The solver was developed based on the proposed MPS-FEM coupled method. The theory about the MPS, FEM method and the partitioned coupling strategy was introduced in our previous papers (Zhang et al. [15, 16]; Rao et al. [17]). The geometric model of the wave tank, as well as the horizontal plate, is depicted in Fig. 1. The length and water depth of the tank are 2.5 m and 0.114 m, respectively.

A. *Numerical Wave Generation*

The accuracy of the wave generation is crucial in the study of wave-structure interaction. In this sub-section, the wave generation is conducted in the numerical wave tank without the plate to validate the accuracy of the generated solitary wave. The piston-type wavemaker is employed to generate the solitary wave. Different wave amplitudes (*A*), including *A*/H=0.2, 0.3, 0.4 and 0.5, are adopted in the simulations. The computational parameters are listed in Table I.

TABLE I. COMPUTATIONAL PARAMETERS FOR MPS

Parameter	Value
Water density	1000(kg/m^3)
Water depth	0.114(m)
Kinematic viscosity	1×10^{-6}(m^2/s)
Gravitational acceleration	9.81(m/s^2)
Particle spacing	0.002(m)
Fluid number	71193
Total number	75762

Figure 2 shows the comparison of the wave profiles between the numerical simulation and the theoretical solution. It can be seen that the wave crests of the simulation agree well with the theoretical solution presented by Goring [18]. However, there are still some slight distinctions, such as in the ascending portion of the curve, owing to the finite length and depth of the wave tank. It can be concluded that desired solitary wave can be generated based on the MPS method.

B. *Interaction between Wave and Rigid Plate*

The interaction between the solitary wave and a rigid plate is simulated in this sub-section. The plate is placed at the position of 1.2 meters from the wavemaker. And the distance between the bottom of the plate and the still water line (SWL) is defined as plate elevation (*D*), which can be altered by moving the plate vertically. In the simulations, the plate elevation (*D*) and wave amplitude (*A*) vary in different cases in order to investigate their effects on the wave-induced force on the plate. The dimensionless parameters of all the cases are shown in Table II.

TABLE II. CONFIGURATIONS OF THE CASES

Case No.	**Amplitude (*A*/H)**	**Elevation (*D*/H)**
1	0.2	0.03
2	0.2	0.06
3	0.2	0.1
4	0.3	0.03
5	0.3	0.06
6	0.3	0.1
7	0.4	0.03
8	0.4	0.06
9	0.4	0.1
10	0.5	0.03
11	0.5	0.06
12	0.5	0.1

The calculated vertical force on the plate of Case 6 (*A*/H=0.3, *D*/H=0.1) is shown in Fig. 3. Some snapshots of the simulation are presented in Fig. 4. It can be seen that the wave contacts the plate around *t*=1.76s. Then the force starts to rise as the water suffuses the bottom of the plate. When the wave crest hits the leading edge of the plate, the vertical force reaches its peak at *t*=1.96s. With the descending of the force, the phenomenon of slight oscillation can be easily observed. Finally the plate suffered a negative vertical force after *t*=2.28s owing to the green water on the plate. In addition, the experimental result from Seiffert et al. [19] is also given in Fig. 3. The comparison shows that the peak value, oscillation and the negative force in the experimental result are well reproduced in our simulation.

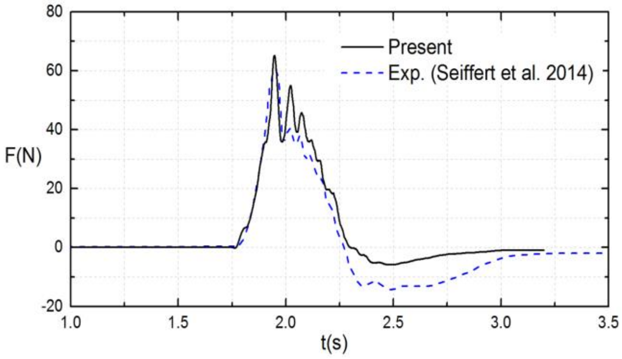
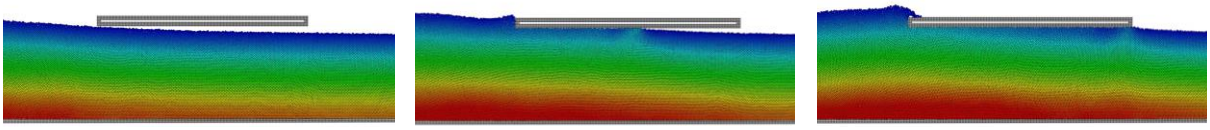
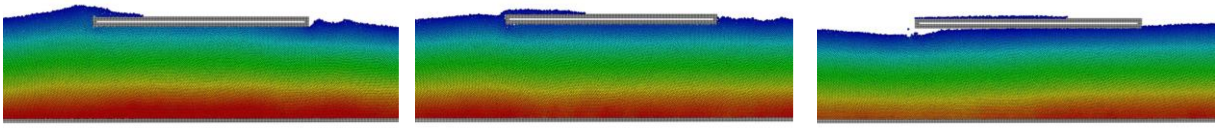


Figure 3. Comparison of the vertical force on plate (*A*/H=0.3, *D*/H=0.1).

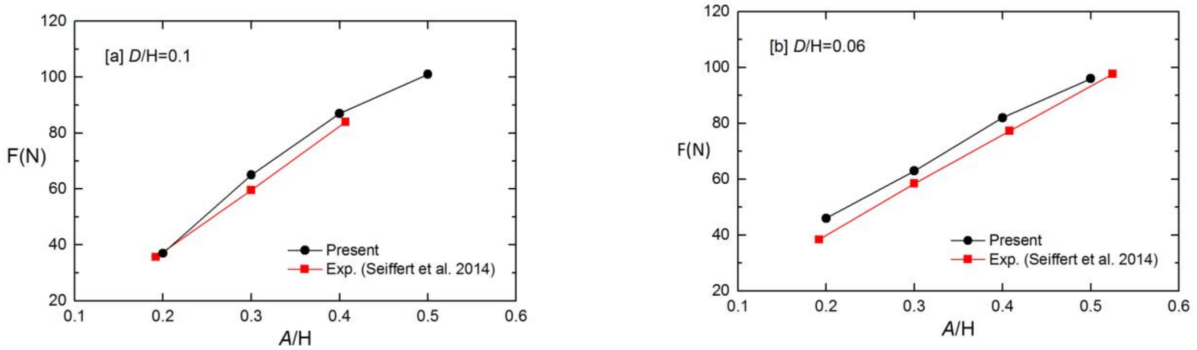


(a) t=1.76s (b) t=1.88s (c) t=1.96s



(d) t=2.08s (e) t=2.16s (f) t=2.32s

Figure 4. Snapshots of the simulation (*A*/H=0.3; *D*/H=0.1; Rigid plate).



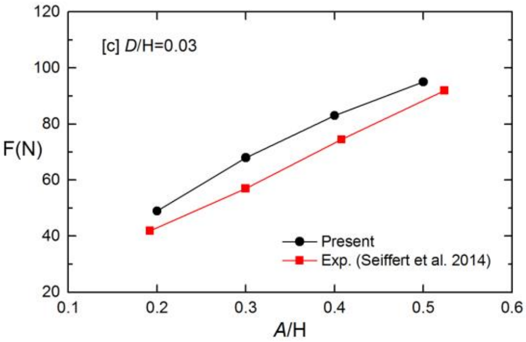


Figure 5. The maximum vertical force on the plate

To investigate the effects of the wave amplitude and plate elevation on the wave-induced force, the maximum value of the vertical force history in each case is collected. The comparison of the computed and experimental result is shown in Fig. 5. It can be seen that the vertical force on the plate is in proportion to the wave amplitude. However the maximum forces in the cases of different elevation are close to each other, which indicate that the maximum vertical force is not as sensitive to the plate elevation as to the wave amplitude. Although the comparison shows good agreement, the computed maximum force in each case is higher than the experimental result. It is partly due to the surface elevation resulting from the movement of the piston-type wavemaker. The length of the wave tank is relatively short compared with the experimental condition and the effects of the surface elevation cannot be neglected.

C. Interaction between Wave and Flexible Plate

To study the effects of structural flexibility on the interaction, the simulation of the solitary wave interacting with flexible plate is conducted in this sub-section. The FSI solver employed in this sub-section has proved to be reliable in our previous researches (Zhang et al. [14-16]; Rao et al. [17]). The setup of the wave amplitude and plate elevation is identical to that in the former sub-section, which is shown in Table II. However, the former rigid plate is replaced by a flexible plate with its ends clamped. The two-dimensional plate is divided into 152 planar beam elements in the structure analysis. The fluid parameter is the same as the one in the former simulations, which is shown in Table I. The structural parameter is shown in Table III.

TABLE III. COMPUTATIONAL PARAMETERS OF STRUCTURE

Parameters	**Values**
Structural density	1040 (kg/m^3)
Elastic modulus	1(MPa)
Cross area	2.5×10^{-5}(m^2)
Inertia moment	1×10^{-3}(m^4)
Damping coefficient α_1	1.6646
Damping coefficient α_2	0.00096
Element type	Planar beam element
Element number	152

Figure 6 shows the vertical wave-induced force on the flexible plate, which is compared with the counterpart in the rigid case in order to investigate the contribution of the structural flexibility to the wave-induced force. The case of *A*/H=0.3 and *D*/H=0.1 is selected specifically to be analyzed.

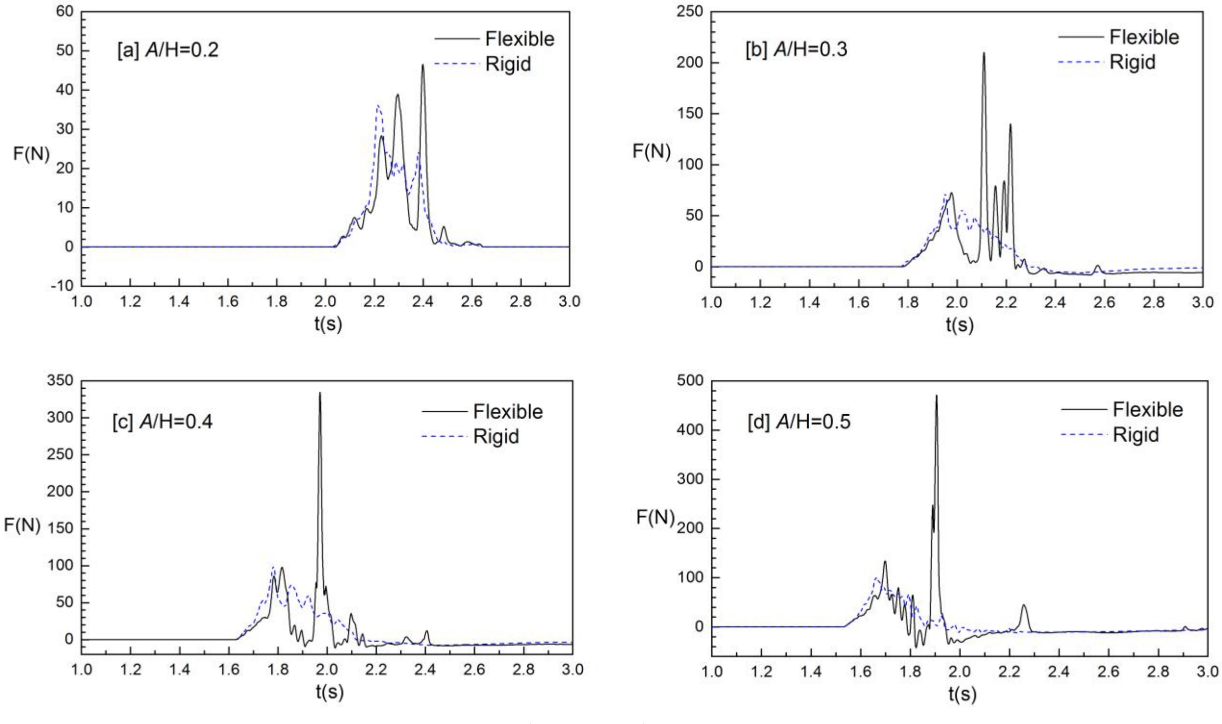
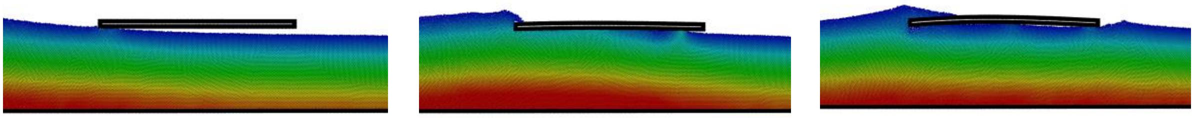
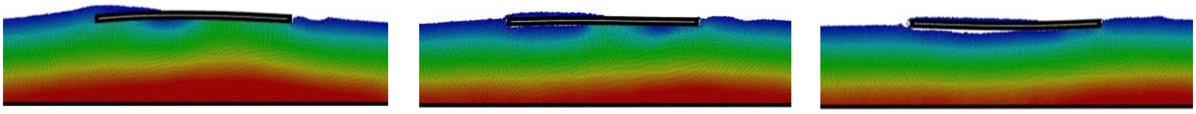


Figure 6. Comparison of the vertical forces on the plate (*D*/H=0.1)



(a) t=1.80s (b) t=1.96s (c) t=2.02s

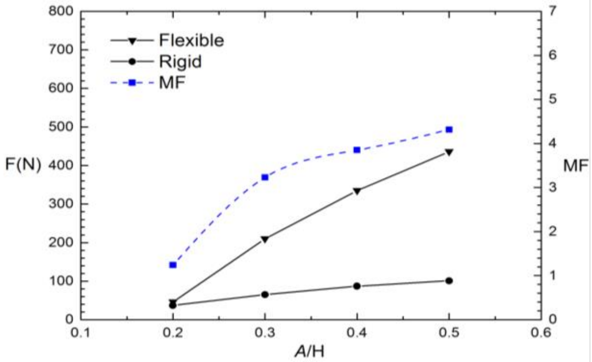


(d) t=2.14s (e) t=2.20s (f) t=2.28s

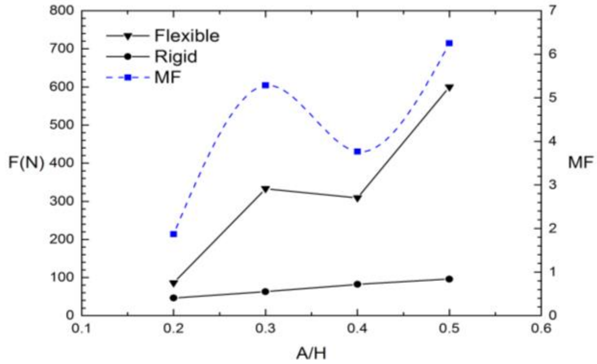
Figure 7. Snapshots of the wave-plate interaction (*A*/H=0.3; *D*/H=0.1; Flexible plate)

It can be observed in Fig. 6(b) that two curves agree well before the first peak (t=1.96s), during which the deformation of plate is not so obvious. After the peak, the curve of the flexible plate drops drastically while it goes through some slight oscillation in the rigid case. Around t=2.14s, the flexible plate encounters severe impacting force which is much greater than the first peak. To find out the reason of this phenomenon, some particular snapshots in the selected simulation are given in Fig. 7. It can be seen that the plate possess an upward velocity after being hit by the solitary wave. As the plate moves upward, it partially separates from the water surface around t=2.02s. After the deformation maximizes, the flexible plate starts to move downward and impacts onto the surface at 2.14 s, leading to an impacting force much greater than the first peak. And the value of the second peak is more than 3 times the value of the first peak.

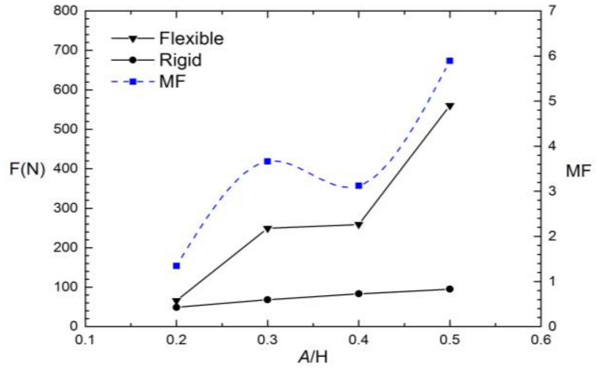
Similar phenomenon can be observed in other cases. To quantitatively analyze the effects of the flexibility on the wave-induced force, the maximum wave-induced force (corresponds to second peak) in the flexible case is collected and then be contrasted with the maximum wave-induced force (correspond to the single peak) in the rigid case. The quantitative comparison is presented in Fig. 8. The enhancement of the maximum wave-induced force with regard to the wave amplitude displays strong nonlinearity. It can be inferred from the figures that the phenomenon of the second impact is not severe for cases of *A*/H=0.2. It is because the resulted deformation of the plate is so small that the impact is much milder. The magnification factor (MF), defined as ratio of the maximum value in flexible case to that in rigid case, in the cases of *A*/H=0.2 is 1.24, 1.87 and 1.35 respectively. For the cases of *A*/H=0.3, the MF (3.23, 5.28 and 3.66) increases as the impact onto the surface intensifies. However, the MF drops when the wave amplitude increases to *A*/H=0.4 in the cases of *D*/H=0.06 and 0.03. After checking the snapshots of the simulation, we find it is because the plate elevation is so small that the water always suffuses the bottom of the plate during the impact, which indicates that the slamming doesn't exist in these cases. As the wave amplitude increases further to *A*/H=0.5, the MF rises to 4.31, 6.25 and 5.89 as a result.



(a) *D*/H=0.1



(b) *D*/H=0.06



(c) *D*/H=0.03

Figure 8. The maximum vertical force and the corresponding MF

III. CONCLUSIONS

In this paper, the interaction between the solitary wave and the horizontal plate is investigated using the proposed MPS-FEM coupled method. The numerical wave profile is contrasted with the theoretical solution, which shows a good agreement. In the simulation of the wave-plate interaction, both the rigid and flexible cases are considered. The wave amplitude (A/H=0.2, 0.3, 0.4 and 0.5) and plate elevation (D/H=0.1, 0.06 and 0.03) are altered to study their effects on the interaction. The results indicate that the maximum vertical force is in proportion to the wave amplitude, while it is not sensitive to the elevation within the D/H=0.03~0.1. The collected maximum vertical forces are also compared with the experimental results from Seiffert et al. [19]. Two curves show the same trend and the relative difference ranges from 1.8% to 19%.

In the flexible cases, the maximum vertical force increases at various levels compared with the result from rigid case. It can be observed that the maximum vertical force in the flexible case corresponds to the second peak of the curve. By analyzing the vertical force history and the snapshots from the case of A/H=0.3 and D/H=0.1, we find that the deformed plate possesses a downward velocity around the 2nd peak which intensifies its impact with the surface. The maximum vertical force in both the flexible and rigid case is collected in order to investigate the magnification effects of the flexibility. Compared with the relatively large-amplitude wave, the magnification effect (MF=1.24, 1.87 and 1.35) is not much evident for small-amplitude wave (A/H=0.2). Besides, in the cases of D/H=0.06 and 0.03, the magnification factor drops as the wave amplitude increases from A/H=0.3 to 0.4. It is found that in the low-elevation case (D/H=0.03) the water suffuses the plate bottom during the impact, which indicates that the slamming doesn't happen. In conclusion, the motion of the flexible plate exerts a complicated influence on the vertical wave-induced force.

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