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Numerical Simulation of Free Surface Flow Impacting on an Elastic Plate

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Highlights:

- A coupled FDM-FEM method has been developed for numerical analysis of strongly non-linear interaction between free surface flow and elastic structure.
- Numerical simulation is carried out on an experimental case of dam-breaking with an elastic plate. Reasonable good comparison has been obtained.

1.Introduction

In rough sea conditions, marine structures such as ship, platform, etc. frequently experience wave impacts, which give rise to a shudder or elastic vibration and extreme forces on structures. Investigation of wave impact problems is of considerable importance in engineering application and has attracted much attention. In this study, we focus on the strongly non-linear phenomenon in wave impact problems. A series of experiments on dam-breaking with an elastic plate have been done in our laboratory of RIAM in Kyushu university. In the experiment, we found a very interesting strongly non-linear phenomenon. At the initial impact stage, the structural deformation is increased from zero to its maximum value rapidly and smoothly due to the extreme impulsive impact force. In this stage, structural first-order vibration modes is excited. And then, with time advancing, structural second-order vibration modes appears. Lower side of the free surface begins to oscillate due to structural vibration, as shown in Fig.1. During the experiment, three cases with different initial water column height (H0=0.4m, 0.3m and 0.2m) have been carried out. We also found that appearance of structural second-order vibration modes depends on the initial water column height.

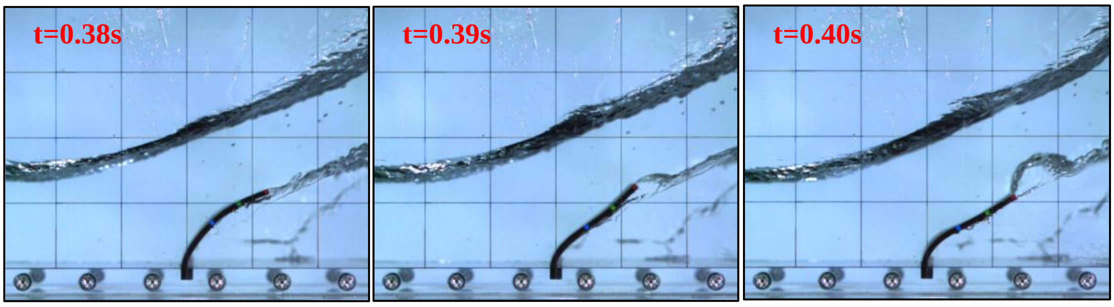

Fig.1 Structural second-order vibration modes

In this study, we simulate this interesting strongly non-linear phenomenon based on numerical method.

2.Numerical Method

Wave impact problem is a typical kind of fluid-structure interaction problem, which involving strongly non-linear interaction between free surface flow and elastic structure. In recent years, numerical methods based on solving Navier-Stokes equations become an important way for analyzing this kind of problem. Most of the established methods [1][2][3][4] are based on Arbitrary Lagrangian-Eulerian (ALE) method with conforming-mesh. As we know, time consuming in mesh updating is a great drawback of methods based on the ALE scheme. Therefore, an efficient and robust partitioned approach by coupling Finite Difference Method (FDM) and Finite Element Method (FEM) has been developing in our group since 2009.

In the coupled FDM-FEM method, a conservative momentum forcing exchange method, based on Immersed Boundary (IB) method [5], is adopted to couple the FDM and the FEM. Flow field is solved by the FDM in which Constraint Interpolation Profile (CIP) method is applied and Tangent of Hyperbola for Interface Capturing with Slope Weighting

(THINC/SW) scheme [6] is used for capturing free surface. The FEM is used for solving structural deformation. The coupled FDM-FEM method has been applied for numerical analysis of a benchmark problem [7], i.e., sloshing with an elastic plate, in our previous research work (IWWWFB 2011) [8]. As shown in Fig.2, the coupled FDM-FEM method has reasonable accuracy in simulating strongly non-linear interaction between free surface flow and elastic structure. In this study, it is applied to simulate an experimental case of dam-breaking with an elastic plate.

Table 1 Two computational cases with different mesh size

Number of element	Thickness of plate [m]	Case	Grid	Minimum mesh size [m]
10	0.004	Case 1	400×230	Δx=Δy=0.001
		Case 2	600×330	Δx=Δy=0.0005

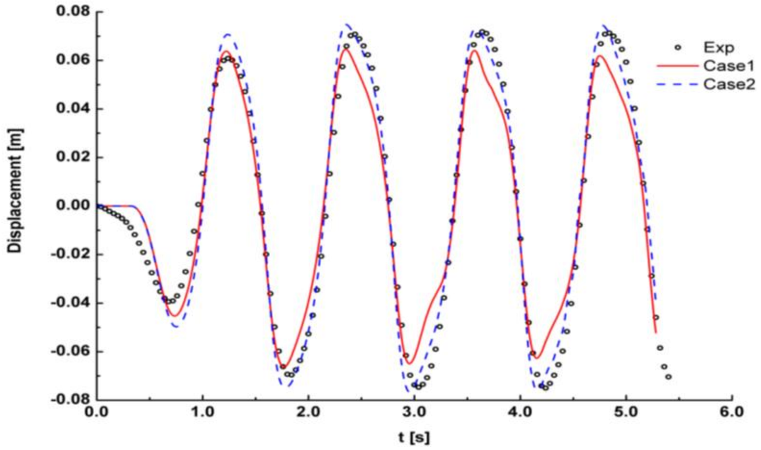

Fig.2 Comparison of experimental data and numerical results

3.Results and Discussions

A series of experiments on dam-breaking with an elastic plate have been done in our laboratory of RIAM in Kyushu university. Experimental setup is shown in Fig.3. An elastic plate is installed at the right-hand side bottom of a water tank. Three cases with different initial water column height (H0=0.4m, 0.3m and 0.2m) have been carried out. Free surface motion and structural deformation are recorded by a high-speed digital video camera system. Structural deformation are then obtained by analyzing a series of video images. Detailed parameters of the elastic plate are listed in Table 2.

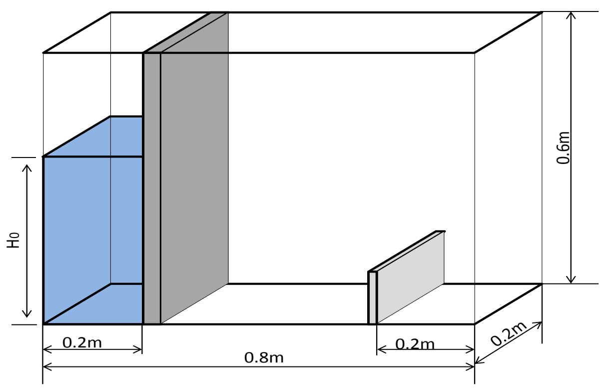

Fig.3 Experimental setup

Table 2 Parameters of the elastic plate

Material	Density [kg/m^3]	Young's modulus [MPa]	Thickness [m]
Rubber	1161.54	3.50	0.004

In this study, the coupled FDM-FEM method is applied to simulate the interesting strongly non-linear phenomenon, which is observed during the experiment. It should be mentioned that numerical simulation is carried out in 2D case. In the computation, time interval is initialized as 2.0×10^{-4}s, and it can be adjusted by Courant-Friedrichs-Lewy (CFL) conditions. Computational grid number is 220×145. Number of structural element is 10. Comparisons of structural displacement in X-direction at tip point A between experimental data and numerical result are shown in Fig.4. It can be seen that numerical results of all the three cases (H0=0.4m, H0=0.3m and H0=0.2m) are in good agreement with the experimental data at the initial impact stage. It means that the coupled FDM-FEM with reasonably fine mesh has good accuracy in predicting the impulsive impact force at the initial stage. According to numerical results in Fig.4, the structural deformation is increased rapidly and smoothly at the initial impact stage. It means that only the structural first-order vibration modes is excited in this stage. With time advancing, track of the structural tip point A shows oscillation. It is obvious that the structural second-order vibration modes is excited. In addition, we can also see that in case of H0=0.2m (Fig. 4(c)), the structural second-order vibration modes is not obvious. It means that appearance of the structural second-order vibration modes depends on the impact force. In summary, main feature of the strongly non-linear phenomenon that observed in the experiment has been captured successfully. However, numerical accuracy needs to be improved, especially after free surface front arriving at the right-hand side wall of the water tank. As shown in Fig.4, there is an obvious difference between experimental data and numerical results after the free surface front arriving at the right-hand side wall. The possible reason is that, in 2D case, an air cavity is formed when the free surface front arriving at the water tank right-hand side wall. The violent motion of the air in the cavity can disturb the flow field greatly. As shown in Fig.5, when free surface front arriving at the right-hand side wall of the water tank (t=0.35s), the free surface profile begins to be different from the experiment image due to the violent air motion in the cavity. As a result, hydro-force acting on the plate is also influenced. Therefore, track of the structural tip point A shows obvious difference between numerical results and experimental data. This problem will be studied in details in our ongoing research work.

References

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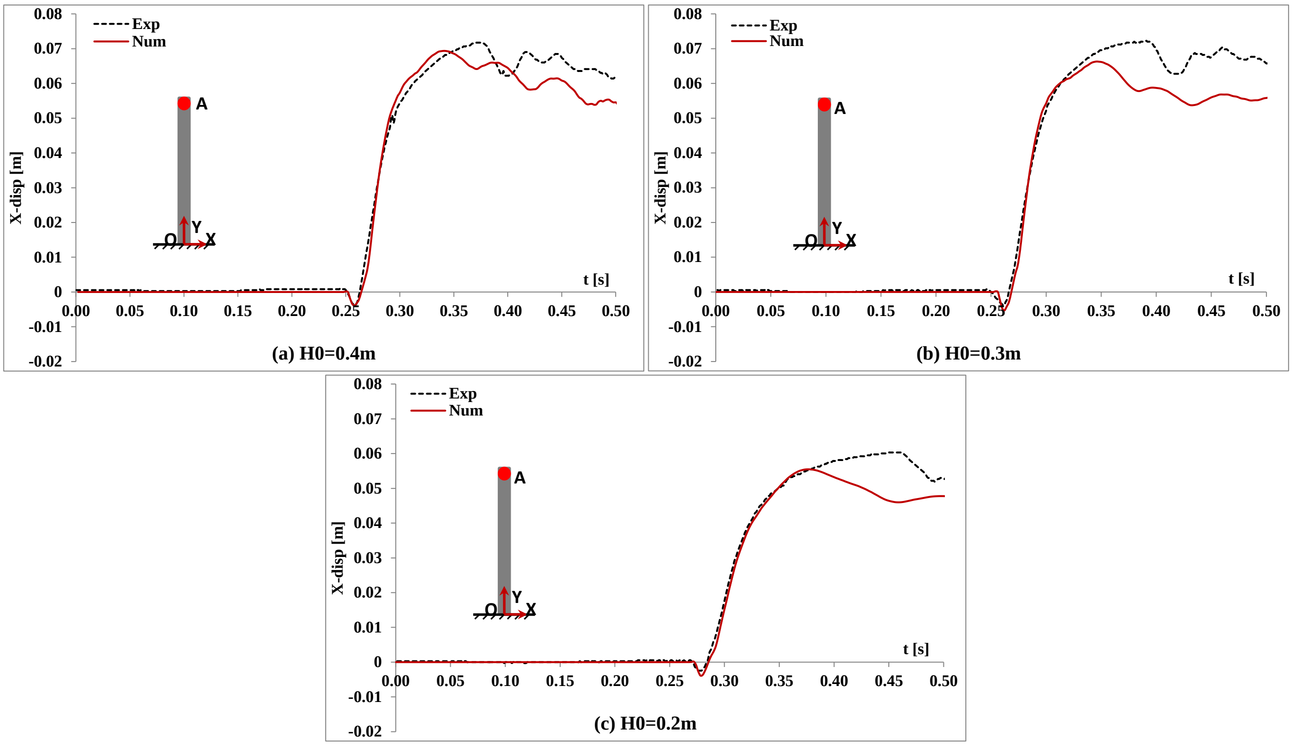

Fig.4 Time history of X-displacement at point A

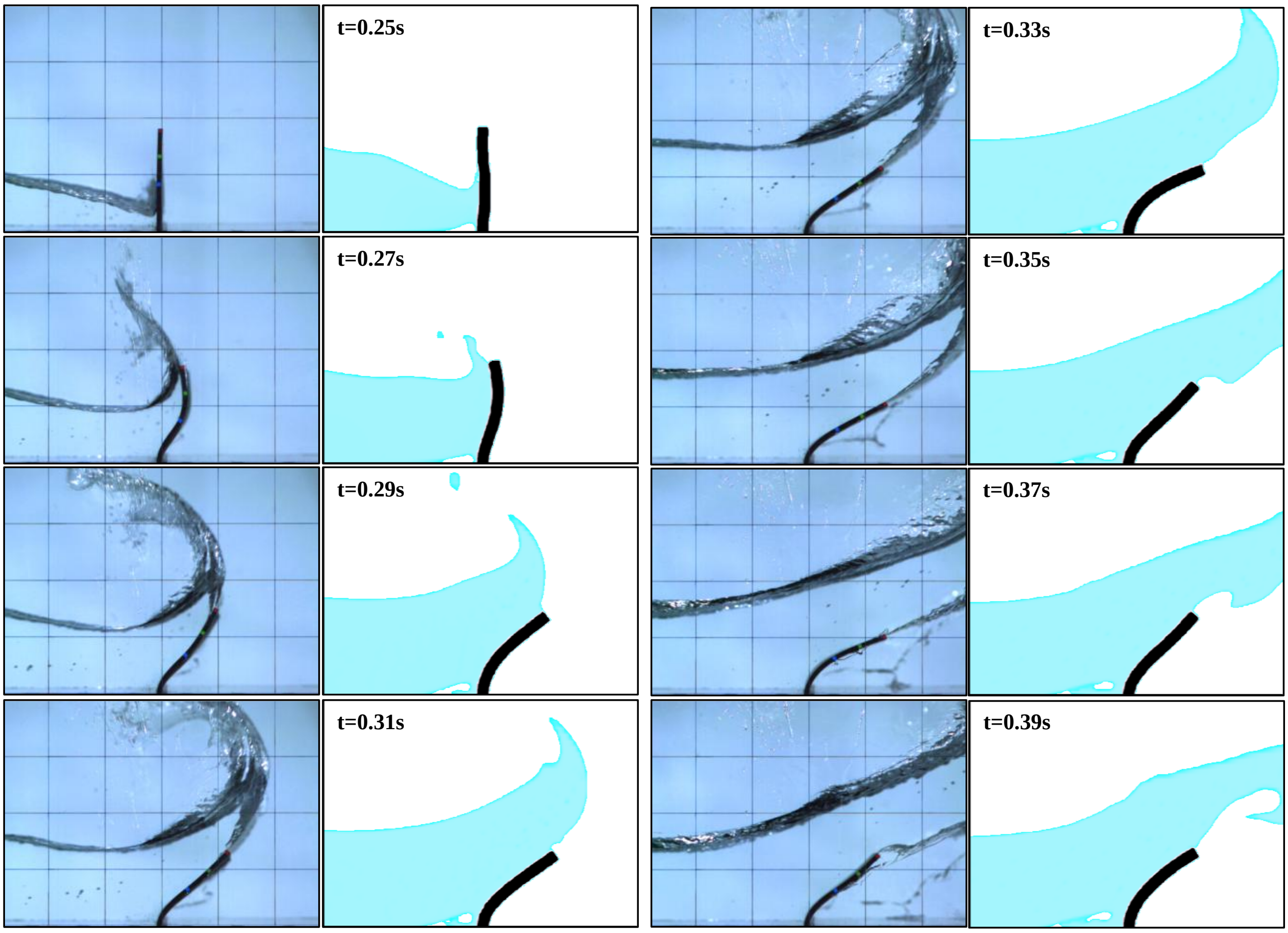

Fig.5 Free surface profile and structural deformation (H0=0.4m)