J. Marine. Sci. Appl. (2013) 2: 163-169
DOI: 10.1007/s11804-013-1181-2

# Two-dimensional Numerical Simulation of an Elastic Wedge Water Entry by a Coupled FDM-FEM Method

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**Abstract:** Hydroelastic behavior of an elastic wedge impacting on calm water surface was investigated. A partitioned approach by coupling finite difference method (FDM) and finite element method (FEM) was developed to analyze the fluid structure interaction (FSI) problem. The FDM, in which the Constraint Interpolation Profile (CIP) method was applied, was used for solving the flow field in a fixed regular Cartesian grid system. Free surface was captured by the Tangent of Hyperbola for Interface Capturing with Slope Weighting (THINC/SW) scheme. The FEM was applied for calculating the structural deformation. A volume weighted method, which was based on the immersed boundary (IB) method, was adopted for coupling the FDM and the FEM together. An elastic wedge water entry problem was calculated by the coupled FDM-FEM method. Also a comparison between the current numerical results and the published results indicate that the coupled FDM-FEM method has reasonably good accuracy in predicting the impact force.

**Keywords:** elastic wedge water entry; coupled FDM-FEM method; volume weighted method; CIP method; THINC/SW scheme; hydroelastic behavior

**Article ID:** 1671-9433(2013)02-0163-07

## 1 Introduction

Hydroelastic phenomena, such as springing and whipping often appear in ocean engineering, especially in rough sea conditions. In this study, the main focus was on the whipping phenomena. In the whipping phenomena, seriously transient hull vibration often appear due to bottom slamming, bow flare impact and green water impacting on the deck. Extremely large impulsive impacting force arises in whipping phenomena and it can result in serious fatigue damage of ship hull. Therefore, the study of whipping phenomenon is a very important research topic in modern ocean engineering applications.

Ship hull bottom slamming is a typical kind of whipping phenomenon, and it has been investigated extensively. Earlier studies of hydroelastic behavior in bottom slamming based on the Wagner theory can be found in Meyerhoff (1965) and Wilkinson *et al*. (1968). Great progress on the hydroelastic slamming problem analysis based on the Wagner theory has been conducted by Korobkin and his co-workers (Korobkin, 2000; Khabakhpasheva and Korobkin, 2003). The effect of the deadrise angle in hydroelastic behavior was investigated by previous researchers, using a method that combines the Wagner theory with an Euler beam theory. The impacting force was calculated by the Wagner theory, while the normal mode method is applied to analyze the structural deformation. To extend the method for more complicated structure analysis, Korobkin *et al*. (2006) developed a method that combines the Wagner theory with the FEM. Structural deformation is calculated by the FEM. As a result, it overcomes the limitation of the modal expansion method in practical applications. Another method based on the potential theory for hydroelastic slamming has also been developed by Faltinsen (1997). In his method, the impacting force was obtained with classical potential theory and the structure was treated as an Euler beam. Some relative works on hydroelastic slamming were summarized by Faltinsen in his review article (Faltinsen, 2000). A coupled Boundary Element Method and Finite Element Method (BEM-FEM) had been proposed by Lu *et al*. (2000) to analyze the hydroelastic slamming of an elastic wedge. The flow field was solved by the BEM, which was based on the potential theory. The bottom of the elastic wedge was treated as a beam and its deflection is calculated by the FEM. The effects of deadrise angle and structural thickness in hydroealsticity were discussed in details.

The methods, which are based on the Wagner theory or the potential theory, are commonly only valid in the initial impact stage. Those methods do not work when the free surface becomes violent. With the development of computational techniques, numerical simulation based on directly solving Navier-Stokes equations becomes a hopeful way in studying hydroelastic slamming problems. Arai and Miyauchi (1998) investigated the hydroelastic behavior of a cylinder impacting on water surface. A computational fluid dynamic (CFD) tool was applied for solving the flow field, and a modal expansion method was used to solve the structural deformation. Coupling between the flow solver and the structural solver

**Received date:** 2012-07-27.
**Received date:** 2013-03-31.
**Foundation item:** Grants-in Aid for Scientific Research (B), MEXT (No. 21360433)
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was achieved by adding a source term in the continuity equation. Maki *et al*. (2011) proposed a method, which combines the CFD tool with modal expansion method, to study the impact of an elastic wedge onto a calm free surface. The fluid domain was solved with the open source CFD library OpenFOAM, which was based on the finite volume method (FVM). Modal analysis was used to express the response of the wet structure, and the modal equations of motion are integrated to obtain the response in the time domain. A one-way coupling scheme was applied to information transferring at the interface between the fluid domain and the solid domain. It means that the flow solver is carried out based on a rigid body, transferring the fluidic force to the structural solver. Other research works on hydroelastic slamming problem based on the coupled CFD tools and FEM, in which one-way coupling scheme is used, can also be found in the references (Schellin and el Moctar, 2007; Oberhagemann *et al*., 2009; Luo *et al*., 2010; Luo *et al*., 2012; Panciroli *et al*., 2012; Panciroli *et al*., 2013).

In FSI simulation, the one-way coupling method cannot describe the interaction between the fluid domain and the solid domain exactly. In this study, a coupled FDM-FEM method, which is a two-way coupling scheme, was developed to investigate the hydroelastic slamming problem. Concept of the coupled FDM-FEM method is shown in Fig. 1. The flow solver, based on the FDM, was performed using a fixed regular Cartesian grid system, while the structural solver, based on the FEM, was carried out in a moving Lagrangian grid system. A volume weighted method, which was based on the IB method (Peskin, 1972), was adopted for coupling the flow solver and the structural solver together.

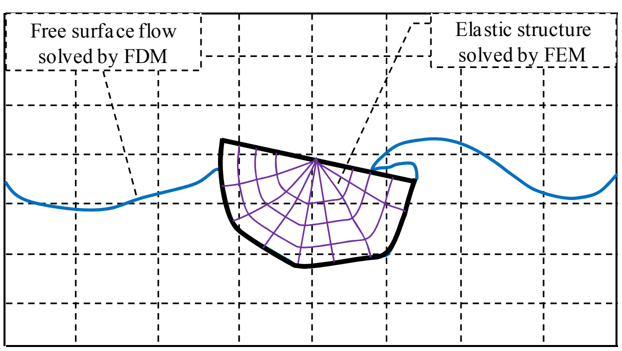


**Fig. 1 Concept of the coupled FDM-FEM method**

In this study, we are studying the hydroelastic behavior of an elastic wedge impacting on calm water surface. The flow field is solved by FDM, in which the CIP method is applied. Free surface flow is captured by the THINC/SW scheme (Xiao *et al*., 2011). The bottom of the elastic wedge is treated as a beam, and its deformation is calculated by the FEM. Coupling between the flow solver and the structural solver is carried out by a volume weighted method, which is based on the IB method. Information exchanging at the interface between the fluid domain and the solid domain is done with a two-way coupling: with the known structural nodal displacement and velocity, the flow solver is carried out to obtain the hydrodynamic force. The hydrodynamic force is then used as the external force for structural solution. New structural nodal displacement and velocity are then obtained by the structural solver. These new nodal displacement and velocity are used as boundary condition for the flow solver in the next time step.

The remaining sections of the paper were organized as follows. Numerical method including the flow solver, structural solver and coupling scheme are briefly summarized in section 2. In section 3, the coupled FDM-FEM method was applied to study the wedge water entry problem. Both the rigid case and the elastic case were calculated and discussed. Conclusions are provided in the final section 4 of the paper.

## 2 Numerical method

The flow solver, structural solver and coupling scheme are described and discussed in this section.

### 2.1 Flow solver

The flow solver for multi-phase flows is considered to be a FDM, which was solved in a fixed regular Cartesian grid system. In order to reduce the numerical diffusion at the inner interface, the CIP method (Takewaki *et al*., 1985), was adopted in the FDM due to the high order upwind scheme with a compact structure. The CIP method has been greatly improved by Yabe *et al*. (1991; 2001), and applied to FSI problems in ocean engineering by Hu and Kashiwagi (2004; 2009).

Governing equations of an unsteady, viscous and incompressible flow are as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} + f_i \tag{2}$$

where $u_i$ is the velocity vector in the fixed regular Cartesian grid system, $p$ the pressure, $\rho$ the density, and $\tau_{ij}$ the shear stress tensor, which is given by $\tau_{ij} = \mu(\partial u_i / \partial x_j + \partial u_j / \partial x_i)/2$ . $f_i$ stands for the body force, such as the gravity force.

Time evaluation of Eq. (2) can be divided into three steps in a fractional step solution method: advection step, non-advection step I and non-advection II. In the advection step, the CIP method was applied. Viscous term and body force were considered in the non-advection step I. A Poisson equation of pressure, Eq. (3), was solved in the non-advection step II by the SOR or BiCG method.

$$\frac{\partial}{\partial x_i}\left(\frac{1}{\rho}\frac{\partial p}{\partial x_i}\right) = \frac{1}{\Delta t}\frac{\partial u_i}{\partial x_i} \tag{3}$$

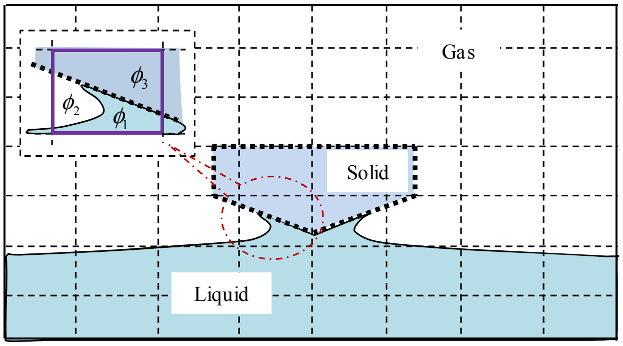


**Fig. 2 Definition of the color function**

In this numerical approach, the whole computational domain was treated as a multiphase field, as shown in Fig. 2. A color function $\phi_m$ (in each computational cell $\sum \phi_m = 1$) was defined for different material phases, where $m = 1,2,3$ represent liquid phase, gas phase and solid phase, respectively. Free surface flow was captured by solving $\phi_1$ with the THINC/SW scheme. $\phi_3$ was used to determine the geometry of a body in the fixed regular Cartesian grid system and can be calculated by using a set of virtual surface particles (Hu *et al*., 2006). $\phi_2$ was calculated by $\phi_2 = 1 - \phi_1 - \phi_3$. Other physical properties of the flow filed, such as density and viscosity can be calculated by $\lambda = \sum_1^3 \phi_m \lambda_m$ for each computation cell after $\phi_m$ for all phases determined.

The Poisson Eq. (3) was assumed valid for the liquid phase, gas phase and solid phase. Solution of Eq. (3) gives a pressure distribution in the whole computational domain. The pressure distribution obtained inside the solid phase was a fictitious one, which satisfies the divergence free condition of the velocity filed (Hu and Kashiwagi, 2004; 2009).

### 2.2 Structural solver

The plate dynamics is described by the following structural dynamic equation:

$$\rho \frac{\partial^2 \boldsymbol{S}}{\partial t^2} = \rho \boldsymbol{f} + \frac{\partial \sigma}{\partial \boldsymbol{X}} \tag{4}$$

in which, $\boldsymbol{S}$ denotes the structural displacements, $\boldsymbol{\sigma}$ stands for the stress tensor of the structure, $\boldsymbol{f}$ is the body force that loaded on the structure and $\rho$ is the structural density.

For numerical solution of Eq. (4), FEM is applied. With the FEM concept, the solid domain can be discretized into elements. The structural dynamic equation (4) in a semi-discrete form can be as follows:

$$[\boldsymbol{M}]\{\ddot{S}\} + [\boldsymbol{C}]\{\dot{S}\} + [\boldsymbol{K}]\{S\} = \{\boldsymbol{F}(t)\} \tag{5}$$

where $[\boldsymbol{M}]$, $[\boldsymbol{C}]$ and $[\boldsymbol{K}]$ are the mass matrix, damping matrix and stiffness matrix, respectively. $\{\boldsymbol{F}(t)\}$ is an external force vector acting on the structure, which depends on the time in the structural dynamic problem. $\{S\}$, $\{\dot{S}\}$ and $\{\ddot{S}\}$ are time-dependent structural nodal displacement, velocity and acceleration vectors, respectively.

In this study, we mainly focus on the two-dimensional elastic wedge water entry problem. Therefore, allowing bottom of a wedge to be treated as a two-dimensional beam. Time evaluation of Eq. (5) was carried out by the Newmark method, which was an unconditionally stable method.

### 2.3 FDM-FEM coupling

#### *2.3.1 Volume weighted method based on IB method*

Validations for the flow solver and the structural solver have been done in the previous work (Liao and Hu, 2012). Numerical results show that either the flow solver or the structural solver as a stand-alone tool has good accuracy. A great challenge is that how to couple them together. The flow solver is carried out in a fixed regular Cartesian grid system, while the structural solver is carried out in a movable Lagrangian grid system. The IB method is used to couple the two solvers.

The IB method was originally proposed by Peskin (1972) to simulate cardiac mechanics and associated flow in a fixed regular Cartesian grid system. The basic idea of the IB method was that a body immersed in a fluid domain was considered as a kind of momentum forcing in the Navier-Stokes equations rather than that treated as complex boundary in the computational domain. Therefore, it was easy to treat either fixed or movable complex geometric boundary in a fixed regular Cartesian grid system, even though the grid system did not coincide with the body surface. Because of its good flexibility on treating complex boundary, the IB method has been extensively investigated and widely used in engineering applications (Peskin, 2002; Mittal and Iaccarino, 2005). In the conventional IB method, an interpolation procedure was commonly required. However, the relationship between a body surface node and its neighbor Cartesian mesh nodes is usually complicated and needs to be treated very carefully, especially in a three-dimensional situation. As a result, the interpolation procedure becomes very complicated for applications. In this study, a volume weighted method, which was based on the IB method, but not considered to be a complicated interpolation scheme, was adopted for coupling the flow solver and the structural solver together.

With the IB method, a momentum forcing was imposed to the Navier-Stokes equations. As a sequence, Eq. (2) can be rewritten as the following:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} + f_i + f_{Bi} \tag{6}$$

in which, an additional momentum forcing term $f_{Bi}$ is added to account for the effect of the existing body that immersed in the fluid domain.

In the present flow solver, a color function $\phi_3$ was determined to distinguish a body in the computational domain. It is calculated by a set of virtual surface particles (Hu *et al*., 2006), as shown in Fig. 3. These particles are moved according to the structural deformation, which was solved by the structural solver. With the color function $\phi_3$, no-slip boundary conditions at the interface between the fluid domain and the solid domain can be described with the volume weighted method as follows:

$$u_i^{n+1} = u_{Bi}^{n+1} \cdot \phi_3 + u_{Fi}^{n+1} \cdot (1 - \phi_3) \tag{7}$$

where $n+1$ stands for the new time step, $u_{Bi}^{n+1}$ is the structural surface nodal velocity, $u_{Fi}^{n+1}$ is the fluid velocity, which is obtained by solving Eq. (2) without considering the effect of a body in the fluid domain.

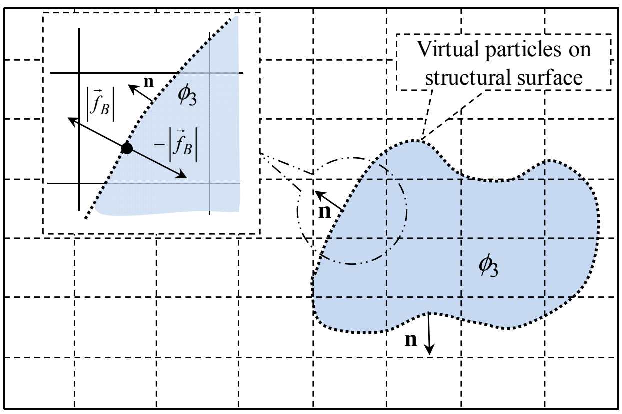


**Fig.3 Schematic of the momentum forcing and virtual particles on the structural surface**

According to Eq. (7), it is obvious that no-slip boundary conditions are satisfied automatically when $\phi_3 = 1$. With boundary conditions, the momentum forcing can be calculated by:

$$f_{Bi} = \phi_3 \frac{u_{Bi}^{n+1} - u_{Fi}^{n+1}}{\Delta t} \tag{8}$$

Substitute Eq. (8) into Eq. (6), we have

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} + f_i + \phi_3 \frac{u_{Bi}^{n+1} - u_{Fi}^{n+1}}{\Delta t} \tag{9}$$

According to Eq. (9), we can see that the volume weighted method was equivalent to the conservative momentum-exchange method, which was proposed by Kajishima *et al*. (2001). Therefore, the conservation of momentum at the interface between the fluid domain and the solid domain was guaranteed (Kajishima *et al*., 2001; Kajishima and Takiguchi, 2002).

*2.3.2 FDM-FEM coupling procedure*

Fig. 4 shows the flow chart of the coupled FDM-FEM method, in which $n$ is the current time step. In the coupled FDM-FEM method, structural nodal displacement $S^{n-1}$ and velocity $\dot{S}^{n-1}$ at the interface were used to give boundary conditions on the fluid domain. Then the flow solver was carried out to obtain the velocity field $u^n$ and the pressure field $p^n$. Subsequently, the hydrodynamic force as external force acting on the structural surface, and structural dynamic equations were solved to get new displacement and velocity. These new structural displacement and velocity were then used as boundary conditions for the flow solver in the next time step.

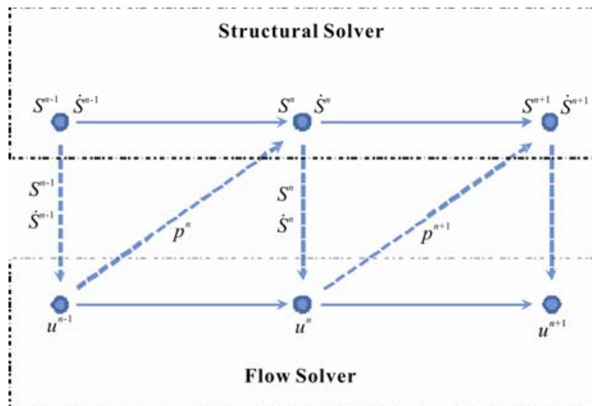


**Fig. 4 Flow chart of the coupled FDM-FEM method**

## 3 Numerical results

The above described numerical method was applied to simulate wedge water entry problem. Geometry of a wedge-shape body is shown in Fig. 5, in which $\beta$ is the deadrise angle and $L$ is the bottom length. Both the rigid case and the elastic case were considered in this study. In the elastic case, the bottoms of the wedge were treated as elastic beam, which were simply supported by a structure (the shaded area), while in the rigid case, very large Young's modulus is used.

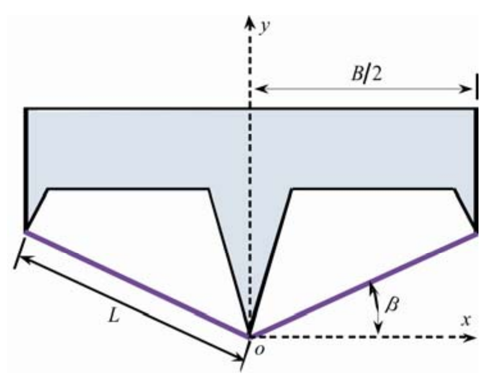


**Fig.5 Geometry of the wedge-shape body**

Parameters of the calculation are listed in Table 1. More detailed parameters can be found in the paper (Lu *et al.*, 2000). In this study, length of the wedge bottom is $L$=0.4m, and the wedge impacts on the calm water free surface with a constant velocity $V$=1.0m/s. It should be noted that the gravity acceleration ($g$=9.82m/s$^2$) was considered in the flow solver, while it was neglected for wedge.

**Table 1 Parameters for calculation**

| Item | Symbel | Liquid | Gas | Solid |
|---|---|---|---|---|
| Density | $\rho$ /(kg·m$^{-3}$) | 1000.0 | 1.225 | 7800.0 |
| Dynamic viscous | $\mu$ /(Pa·s) | 1.0×10$^{-3}$ | 1.0×10$^{-5}$ | ------ |
| Young's modulus | $E$ /(GPa) | ------ | ------ | 200.0 |
| Poisson ratio | $v$ | ------ | ------ | 0.3 |

### 3.1 Rigid case

In hydroelastic slamming analysis, impulsive impact force plays an important role. Therefore, accuracy of a numerical method in predicting the impact force was a key point. In order to check the accuracy of the coupled FDM-FEM method in predicting the impact force, a rigid wedge case was first considered.

Pressure distribution profile on the bottom of a wedge with deadrise angle $\beta = 30^\circ$ is shown in Fig. 6. It was found that, with refining the mesh size, the present result tends to be in good agreement with the result obtained by Lu *et al.* (2000) with the coupled BEM-FEM method. However, the peak value of the pressure distribution was smaller than the published result. The reason was that, in the coupled FDM-FEM method, the flow solver treats the liquid phase, gas phase and solid phase as multiphase flow, and solves them simultaneously. As a result, the air motion can affect the flow behavior near the wedge bottom greatly. Fig. 7 shows the free surface profile when half of the wedge bottom is wetted. It can be seen that, flow separation appears in the front of the free surface due to the effect of gravity and low impact velocity. However, in the coupled BEM-FEM method, a very thin jet was assumed to be along the wedge bottom without any flow separation.

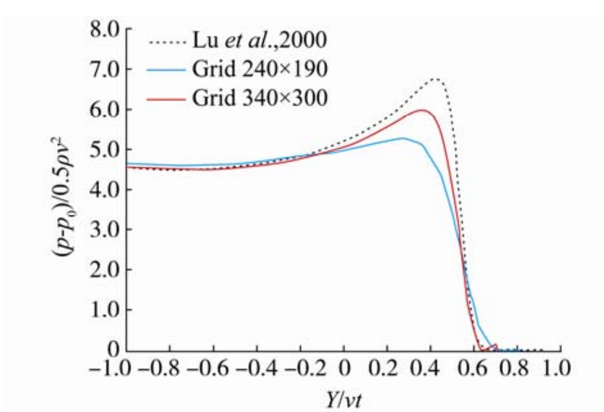


**Fig.6 Pressure distribution along the wedge bottom** ($\beta$=30°)

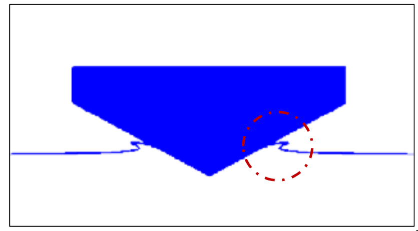

**Fig.7 Free surface front separation (**$\beta$=30°**)**

Other two cases with deadrise angle $\beta = 45^\circ$ and $\beta = 60^\circ$ are also calculated. Comparisons of pressure distribution profile are shown in Fig. 8 and Fig. 9. Numerical results show that the coupled FDM-FEM method has reasonably good accuracy in predicting impact force for wedge slamming case.

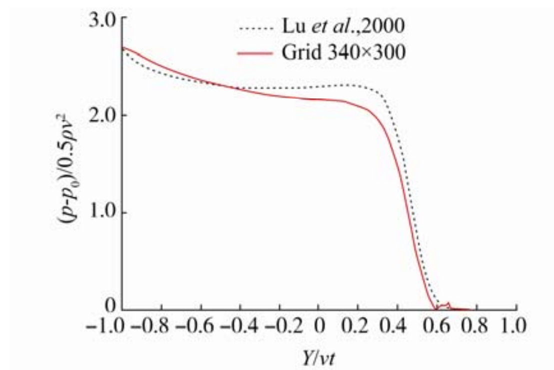


**Fig.8 Pressure distribution along the wedge bottom** ($\beta$=45°)

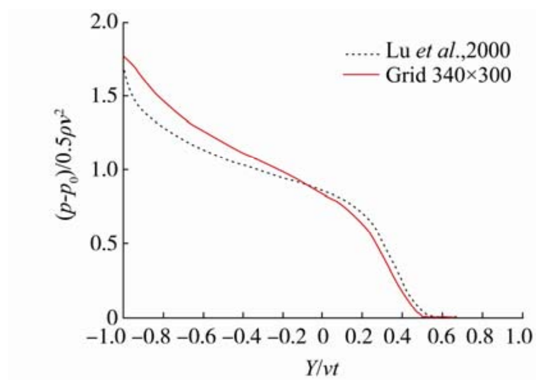


**Fig.9 Pressure distribution along the wedge bottom** ($\beta$=60°)

### 3.2 Elastic case

In the elastic case, an elastic wedge-shape body with deadrise angle $\beta = 30^\circ$ was considered. Three cases with different beam thickness were calculated. In the calculation, a fine mesh (Grid 340×300), which was the same as in the rigid case used.

Fig. 10 shows the structural deflection at the middle point of the wedge bottom, in which thickness of the beam is $b$=0.005m. It can be seen that the trend of the present structural deflection was in good agreement with the coupled BEM-FEM result in the initial impact stage. It means that the coupled FDM-FEM method has good accuracy in predicting the impact force during the impact stage. It can also be seen that there are vibrations at high-order mode in the result obtained by the coupled BEM-FEM method, while the present result was smooth. The possible reason was that the structural deflection was relatively small, and the resolution at the interface between the fluid domain and solid domain was relatively low in the fixed regular Cartesian grid system. Therefore it was difficult to capture the structural high-order mode vibration with the coupled FDM-FEM method. On the other hand, we can see that the coupled BEM-FEM method was only valid in the initial impact stage when the free surface does not roll up and separate. However, the coupled FDM-FEM method can handle that problem even though the free surface flow is extremely violent.

Structural deflection at the middle point of other two cases with thickness $b$=0.008m and $b$=0.011m are shown in Fig. 11 and Fig. 12, respectively. Behavior of the structural deflection was similar to that shown in Fig. 10. According to the comparison of results between Fig. 10, Fig. 11 and Fig. 12, it can be seen that, the vibration frequency increases with the beam thickness increasing.

Free surface profile, pressure filed and structural deformation of case 1 with beam thickness 0.005m at typical time steps are shown in Fig. 13. It should be noted that, in order to present the structural deformation obviously, the output deformation is 100 times of the actual calculated deformation.

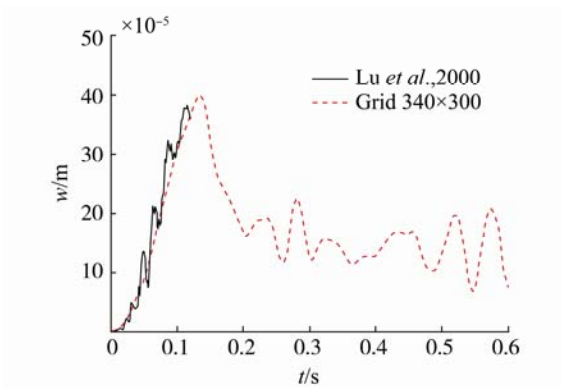


**Fig. 10 Structural deflection at the middle point of the wedge bottom** ($\beta$=30°, $b$=0.005m)

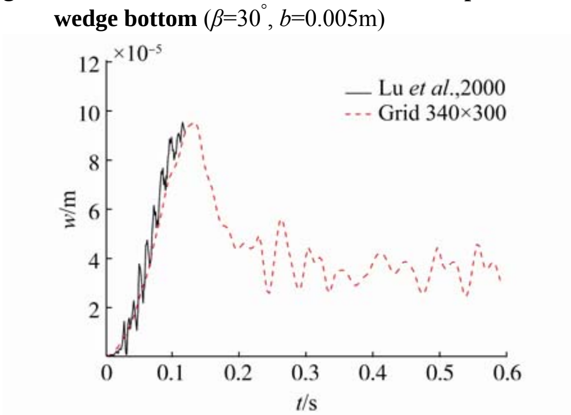


**Fig. 11 Structural deflection at the middle point of the wedge bottom** ($\beta$=30°, $b$=0.008m)

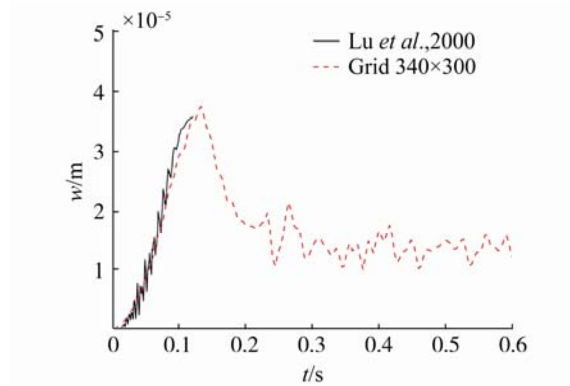


**Fig. 12 Structural deflection at the middle point of the wedge bottom** ($\beta$=30°, $b$=0.011m)

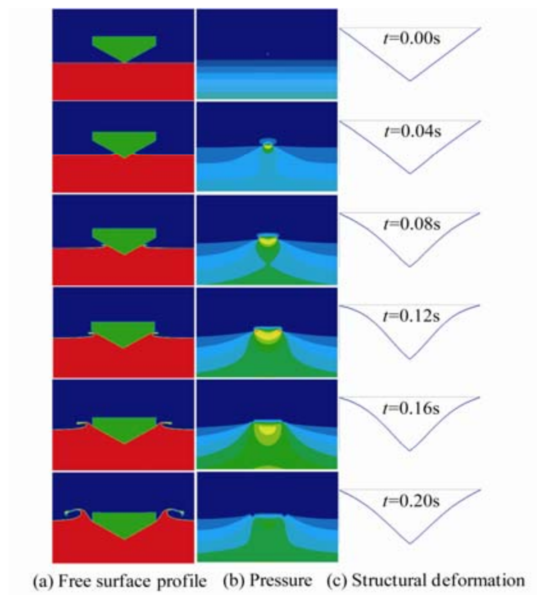


**Fig. 13 Free surface profile, pressure filed and structural deformation at typical time steps** ($\beta$=30°, $b$=0.005m)

## 4 Conclusions

A partitioned approach by coupling FDM and FEM was developed to examine the simulation of hydroelastic slamming problems. In this paper the proposed method was applied to simulate a wedge impacting on calm free surface with a constant speed. Comparisons between the present result and other published result were explored with careful discussion. The result of the rigid wedge case indicates that our method has reasonably good accuracy in predicting the impact force. Also in the case of elastic wedge, the result shows that the proposed coupled FDM-FEM method can handle interaction between violent free surface and elastic structure. The results also illustrate that the proposed method has great potential capability in hydroelastic slamming analysis in ocean engineering.

## Acknowledgement

The authors would like to gratefully thank the support of

Grants-in-Aid for Scientific Research (B), MEXT (No. 24360358). The authors also are grateful and would like to thank Prof. Masashi Kashiwagi of Osaka University and Prof. Xian Chen of Yamaguchi University for their valuable discussions, comments, and support.

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