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The Two-dimensional Study of the Interaction between Liquid loshing and Elastic Structures

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Abstract: Sloshing phenomenon in the liquid cargo carriers has caught the attention of researchers as the interaction between the sloshing waves and structure is one of the key point and difficulty in the study of sloshing. In this paper, we captured the free surface with a volume of fluid (VOF) method and then calculated the motions and responses of the structure by adopting the Reynolds-averaged Navier–Stokes (RANS) equations for the whole fluid domain. With the use of user defined functions (UDF) in Fluent, the interaction between fluid and structure was then simulated. As a reasonable simplification, the authors studied the response of a single cantilever in a tank under sloshing loads; Further study should pay more attention to the mechanisms of interaction between sloshing waves and elastic structures.
Keywords: Liquid sloshing; Fluent; Deformation; Numerical simulation
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1 Introduction

Sloshing phenomenon in the liquid cargo carriers has caught people's more attention, and the loads and effects induced by sloshing have become one of the most important safety criterions for sailing ships with liquid tanks. In the sail, pressure induced by violent sloshing will have strong impact on the tank walls of the LNG ships, and cause the deformation of the structures. In order to improve the design level and the safety of the sail, we need to establish the mathematic model and use analysis methods to deal with the interactions between the ship movements, liquid sloshing and tank structure deformation, and thus effectively predict the ship movement and sloshing loads of the liquid cargo carriers.

During the last twenty years, many researches have been done for the sloshing phenomenon in the tank, with the combination of the sloshing dynamics and structure dynamics study, and many achievements have been got. The basic methods and techniques are sorted into the following four ones:

(1) Boundary element methods based on potential model for sloshing calculation, finite element methods for structure analysis (Amano. *et al*., 1990; Tian *et al*., 1991; Wang and Troesch, 1997);

(2) Finite element methods based on viscous or inviscid models for sloshing calculation, finite element methods for structure analysis (Ramasway and Kawahara *et al*., 1987; Liu, 1993; Li, 2004; Zhang and Suzuki, 2007);

(3) Finite difference methods based on viscous models for sloshing calculation, finite element methods for structure analysis (Zhu, 2001 *et al*., 2004; Zhu *et al*., 2006);

(4) Sloshing loads based on experimental results, finite element methods for structure analysis (Mateusz *et al*., 2007).

The studies show that the interaction between the sloshing fluid and the structure is important and shouldn't be ignored, and most of the time, the interaction is multi-coupling. So far the research on the coupling interaction based on the combination of the sloshing, tank deformation and the ship's global movement is in its prime, and the paper on this topic has not ever been published.

We did some primary research on the interaction between the elastic structure and the fluid during the sloshing. First we programmed the solver for the governing equations of the structure movement according to the theorem of the structure dynamics with the C programming language, then linked the solver with the software FLUENT, controlling the structure deformation by the dynamics mesh technique in the FLUENT, and realize the simulation of the coupling between the fluid and structure at last.

2 Numerical calculation model

2.1 Governing equations for liquid sloshing

For the transportation of the general incompressible inviscid fluid, the RANS equations should be satisfied, which can be found in the general CFD books, such as the literature by Mateusz *et al*. (2007). We deal the free surface with the VOF method as follows:

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$$\frac{\mathrm{d}F}{\mathrm{d}t}=\frac{\partial F}{\partial t}+(\boldsymbol{v}\cdot\nabla)F=0 \tag{1}$$

where $F(x,y,t)$ is the fluid volume fraction, which is defined as follows:

$$F(x,y,t)=\begin{cases}1, & \text{fluid element}\\ 0\sim 1, & \text{surface element}\\ 0, & \text{empty element}\end{cases} \tag{2}$$

2.2 Governing equations for structure movement

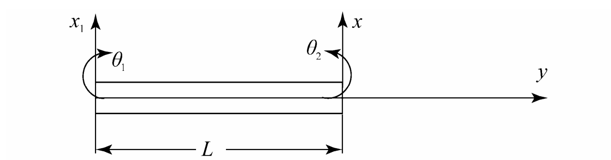


Fig. 1 Mechanical analysis of the beam

According to the literatures by Jin-Xian Ding, 2007; Shang Da-zhong *et al*., 2005; Zhang Zi-ming *et al*., 2008, the beam unit was analyzed, as shown in Fig.1, and the dynamics equations of the simple beam structure was established as follows:

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(\boldsymbol{t})+\boldsymbol{K}\boldsymbol{u}(\boldsymbol{t})=\boldsymbol{F}(\boldsymbol{t}) \tag{3}$$

Where: $$\boldsymbol{M}=\begin{bmatrix}\boldsymbol{m}_1 & 0 & 0 & \cdots & 0\\ 0 & \boldsymbol{m}_2 & 0 & \cdots & 0\\ 0 & 0 & \boldsymbol{m}_3 & \cdots & 0\\ \vdots & \vdots & \vdots & \ddots & \vdots\\ 0 & 0 & 0 & \cdots & \boldsymbol{m}_n\end{bmatrix}$$

$$\boldsymbol{K}=\begin{bmatrix}\boldsymbol{k}_1+\boldsymbol{k}_2 & -\boldsymbol{k}_2 & 0 & \cdots & \cdots & 0\\ -\boldsymbol{k}_2 & \boldsymbol{k}_2+\boldsymbol{k}_3 & -\boldsymbol{k}_3 & 0 & \vdots & \vdots\\ 0 & -\boldsymbol{k}_3 & \boldsymbol{k}_3+\boldsymbol{k}_4 & \ddots & \ddots & 0\\ \vdots & 0 & \ddots & \ddots & -\boldsymbol{k}_{n-1} & 0\\ \vdots & \vdots & \ddots & -\boldsymbol{k}_{n-1} & \boldsymbol{k}_{n-1}+\boldsymbol{k}_n & -\boldsymbol{k}_n\\ 0 & \cdots & \cdots & 0 & -\boldsymbol{k}_n & \boldsymbol{k}_n\end{bmatrix}$$

$\ddot{\boldsymbol{u}}(t)=(\ddot{\boldsymbol{u}}_1,\ddot{\boldsymbol{u}}_2,\ddot{\boldsymbol{u}}_3,\cdots\ddot{\boldsymbol{u}}_n)^{\mathrm{T}}$, $\boldsymbol{u}(t)=(\boldsymbol{u}_1,\boldsymbol{u}_2,\boldsymbol{u}_3,\cdots\boldsymbol{u}_n)^{\mathrm{T}}$, $\boldsymbol{F}(t)=(\boldsymbol{F}_1,\boldsymbol{F}_2,\boldsymbol{F}_3,\cdots\boldsymbol{F}_n)^{\mathrm{T}}$. Where, $\boldsymbol{M},\boldsymbol{K}$, $\boldsymbol{F}(\boldsymbol{t})$, $\boldsymbol{u}(\boldsymbol{t})$, $\ddot{\boldsymbol{u}}(\boldsymbol{t})$ are the matrices of mass, stiffness, loading, displacement, acceleration separately; $\boldsymbol{m}_i$, $\boldsymbol{k}_i$, $\boldsymbol{u}_i$, $\ddot{\boldsymbol{u}}_i$, $\boldsymbol{F}_i$ are the columns of mass, stiffness, loading, displacement, acceleration separately.

2.3 Initial conditions and boundary conditions

(1) Initial conditions: the stagnant tank is under the action of an external excitation, so, at the initial time, when $t=t_0$ the initial velocity and displacement are zero, the initial pressure is the static pressure, and the initial load on the structure is zero too.

(2) Boundary conditions: there are two kinds of boundaries for the viscous fluid, i.e. solid wall and free surface. On the solid wall, there are no-slip and impermeable boundary condition (Zhu, 2001); for the elastic structure, there is boundary restriction condition; in this paper, the cantilever beam is considered, so the linear and angle displacements are zero at the fixed end, while the angle displacement is zero at the free end.

3 Numerical calculation and analysis

3.1 Research object

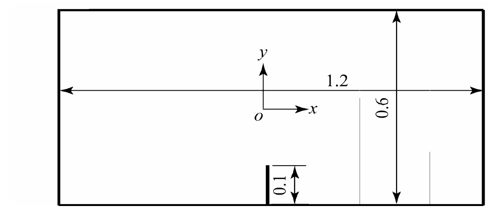


Fig.2 The geometric model / m

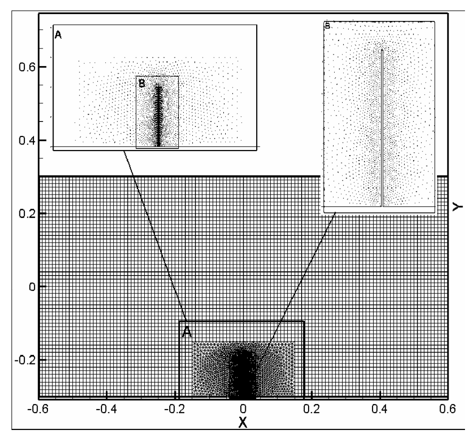


Fig.3 The mesh at zero

The geometric model for calculation is shown in Fig.2, where the thick solid line of 0.1 meter is in the rectangular domain, which is the calculation domain standing for the elastic cantilever beam. During the calculation, the density of beam was set to $7.89\times10^3\,\mathrm{kg/m^3}$, and the elastic modulus to $2\times10^{11}\,\mathrm{N/m^2}$.

3.2 Grid model and method for numerical calculation

(1) Grid computing model: the grid model for numerical calculation is shown in Fig.3. Because the deformability of the cantilever beam, the motion of the structure and the change of the surrounding fluid domain need to be controlled by the dynamic mesh, the domains around the elastic structure adopt unstructured meshes, while other domains adopt structured meshes.

(2) Numerical calculation methods: the discretization and solution of the fluid governing equation are based on finite volume method, and the convective and the diffusion terms are discrete with the 2nd-order Upwind scheme, and the coupling between pressure and velocity adopts the PISO

method, which is suitable for the transient problem. The turbulent model adopts the $k-\varepsilon$ model. The free surface is dealt with the VOF model. The solution of the structure's state equation adopts the Newmark method. The algorithms are realized through the C programming language, and linked with the software FLUENT to realize the coupling between fluid and structure.

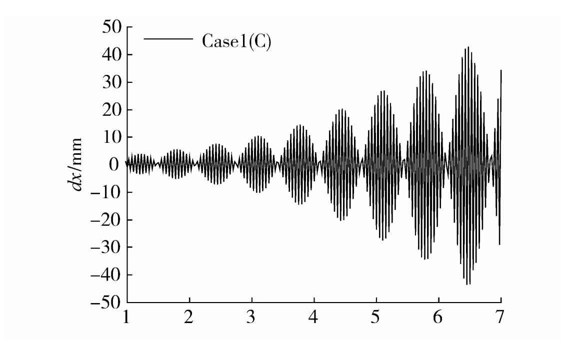
(3) Realization of the coupling between fluid and structure: in the sloshing procedure. The cantilever beam will move together with the tank, whose motion is formed under the action of external excitation, as well as deformative motion under the dynamic loadings. In order to reduce the inconvenience during the programming, we calculated the response of the stagnant cantilever beam under the action of the uniform inflow, and monitored the dynamic load acting on the elastic structure at the same time, and then calculated the deformation and the transient dynamic response of the cantilever beam under the monitored loads by the software Ansys, and compared the results with that got from FLUENT to validate the programs. After that, we consummated the C programs and calculated the deformation and response of the cantilever beam under the action of the sloshing loadings in Case 2.

3.3 Case1

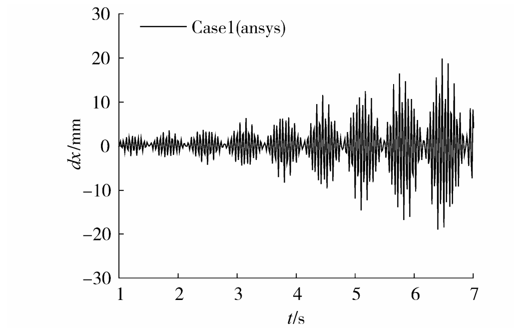
Table 1 Calculation cases

No.	Cantilever beam stiffness / ($N\cdot m^{-1}$)	Velocity of inlet / ($m\cdot s^{-1}$)
Case1	10.42	0.1m/s
Case2	40.02	0.2cos(4.47t)
Case3	21.6	0.1

The geometric model is shown in Fig.2, the fluid in the calculation domain is water, the top and bottom of the domain are solid walls, and the left side of the domain is velocity's inlet, and the right is velocity's outside. Calculation cases are listed in Table 1.



(a)Results of the C program

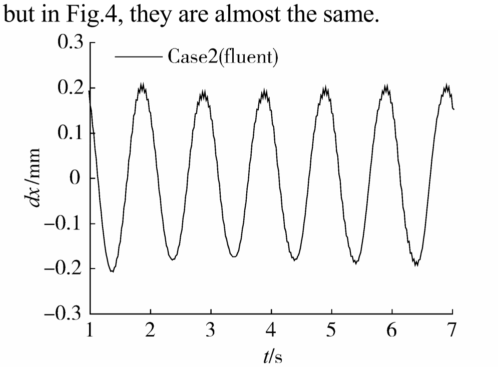


(b) Results of the ANSYS

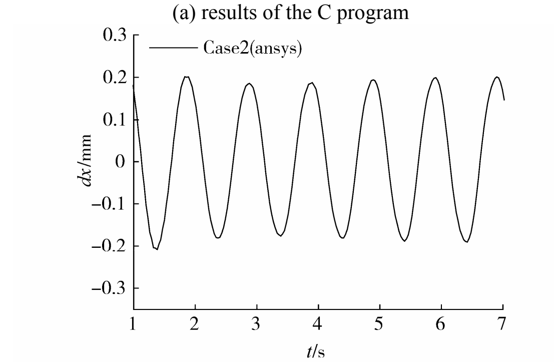
Fig.4 The displacements at the end of cantilever beam for Case1

Result analysis:

(1) Figs.4 and 5 show the calculated results of Case 1 and Case 2, i.e. the motions of the free end of cantilever beam in different uniform inflow. Compare the results obtained through the C program and ANSYS software. In Fig.3, the numerical results are larger than those of the ANSYS on the whole, but in Fig.4, they are almost the same.

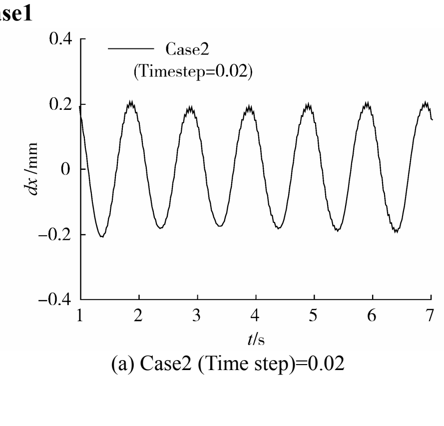


(a) results of the C program

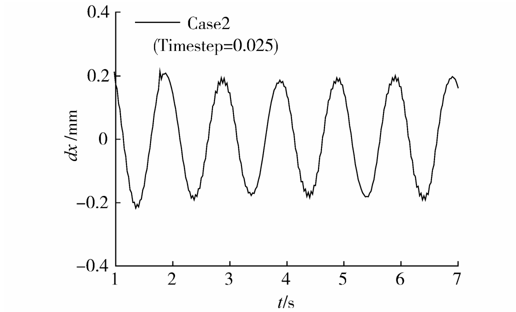


(b) results of the ANSYS

Fig. 5 The displacements at the end of cantilever beam for Case1



(a) Case2 (Time step)=0.02



(b) Case2 (Time Step)=0.025

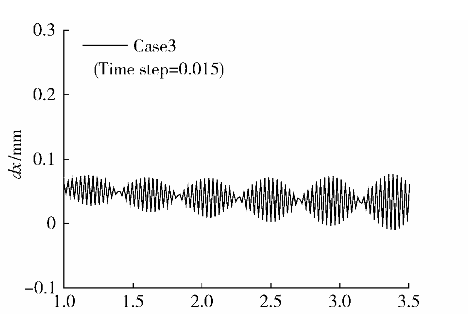
Fig. 6 The displacements at the end of cantilever beam in different time step for Case2

(2) In Fig. 6, take the example of Case 2 to get the relation between the time step and the result. It is shown that there is no difference in the results with different time step.

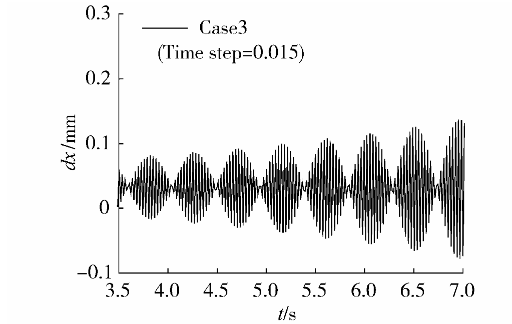
(3) Take an example of Case 3 in Fig. 7, it is shown that the results are sensitive to the time step in this case.

By analyzing those conclusions mentioned above, it can be concluded that firstly, in this paper, we adopt the Newmark-β method to solve the structure's governing equations, the parameters γ and β will affect the precision and stability of the calculation (Xie, 2004). When γ=0.5, β=0.25, the Newmark-β method is unconditionally steady for linear system, but is not true for the non-linear system, which can be seen from Case 1 and Case 3; Secondly, Newmark methods belong to the direct integral method, whose precision and stability are affected directly by the time step. During the calculation, the time step should be small for the structure analysis, but for the fluid calculation too small time step is not good, so compromise is difficult in the solution; furthermore, there is not a complete set of control technique for the dynamic mesh technique, constant debugging is needed in the user's specific calculation process, and the quality of the dynamic meshes also affect the calculation, all of them increase our difficulties in the study.

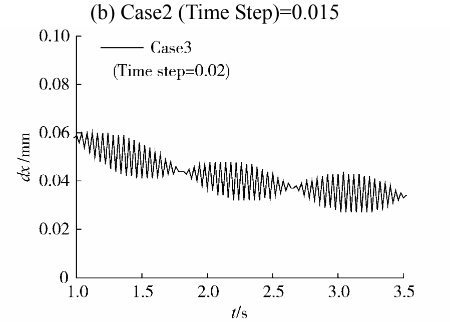
By now, it is shown that it is feasible to study the interaction between the elastic structure and sloshing fluid with the link of C programs and the FLUENT. But during the calculation, comprehensive consideration should be taken based on all of the factors to avoid too large errors.



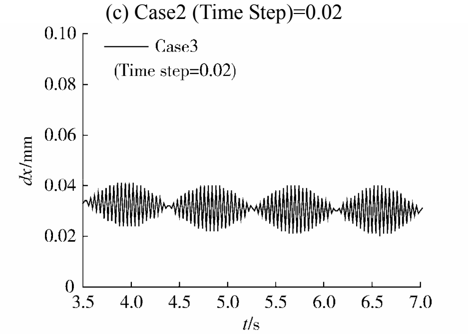
(a) Case2 (Time Step)=0.015



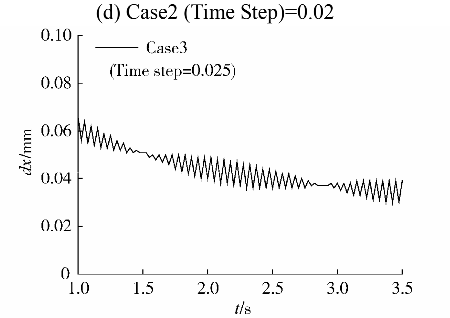
(b) Case2 (Time Step)=0.015



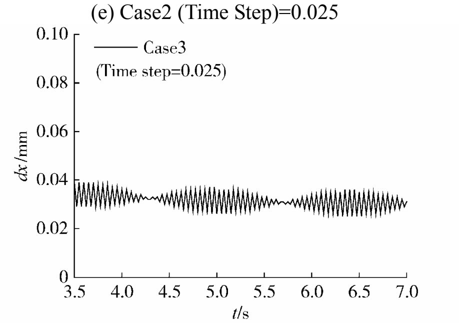
(c) Case2 (Time Step)=0.02



(d) Case2 (Time Step)=0.02



(e) Case2 (Time Step)=0.025



(f) Case2 (Time Step)=0.025

Fig. 7 **The displacements at the end of cantilever beam in different time step for Case3**

3.4 Case 2

The geometric model is shown in Fig.1. The boundary of calculation domain is tank wall, so it's set to rigid wall. The tank is forced to sway, the transverse excitation velocity $V = 0.2\cos(4.47t)\text{m/s}$. The deformation of the cantilever beam is controlled by loading on the UDF (custom code) combined with the dynamic mesh technique. Two monitors P_1 and P_2 are set near the free end, as is shown in Fig.8, where P_1 is 0.625mm away from the free end and P_2 is 1.25mm away from P_1. Table 2 lists some cases for calculation.

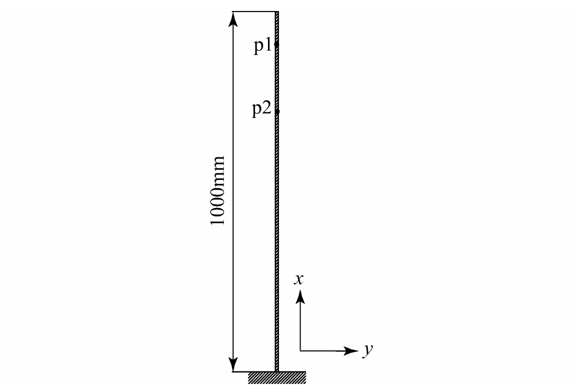


Fig. 8 Schematic diagram of cantilever beam

Table 2 Cases for calculation

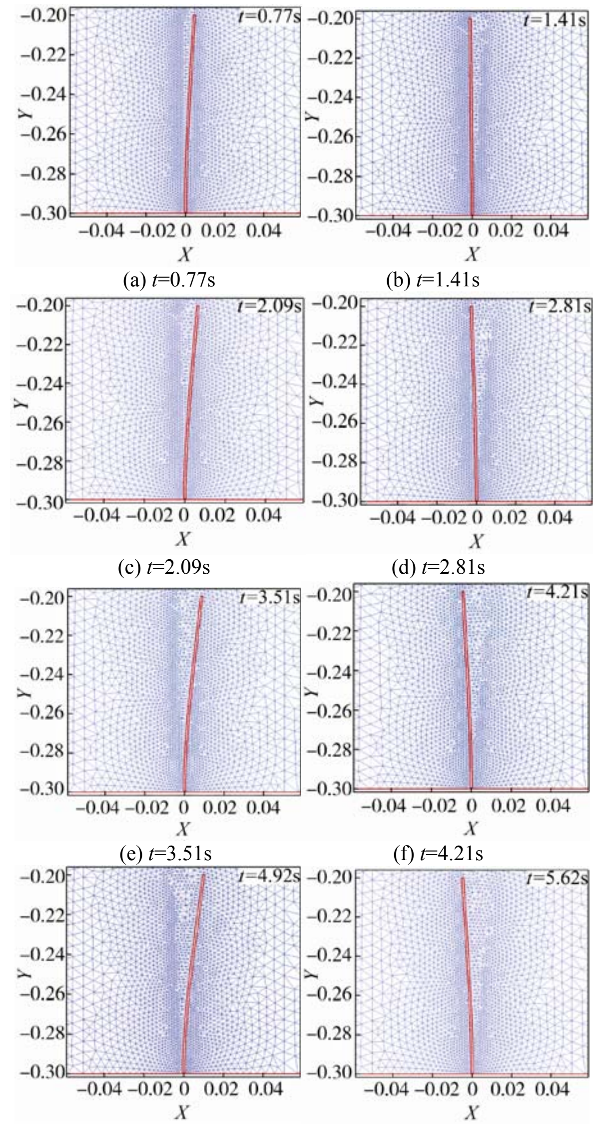
No.	Rigid of the beam / $N\cdot m^{-1}$
Case1	21.6
Case2	40.02
Case3	infinite

Result analysis:

(1) Fig.9 shows the change of the dynamic mesh at different time. It can be seen that by adopting dynamic mesh the ambient fluid field which changes as the structure's deformation is under control. However, comparing with the initial mesh, the quality of the meshes after several movements becomes worse. If more attention is paid to the observation, we can notice that some meshes have extreme large curvature, which will affect the precision of the calculation. Further study should be done.

(2) Fig.10 shows the deformation of the cantilever beam at different time. It is shown that the beam sways as the time going by. During the motion the fixed end keeps the states of zero angle and zero displacement, which accords with the basic character of the beam's motion.

(3) Fig.11 shows the streamlines pattern of different time, which is visual to show the fluid current during the sloshing procedure, and is convenient to analyze the character of the flow.



(a) t=0.77s (b) t=1.41s (c) t=2.09s (d) t=2.81s (e) t=3.51s (f) t=4.21s (g) t=4.92s (h) t=5.62s

Fig. 9 The change of mesh

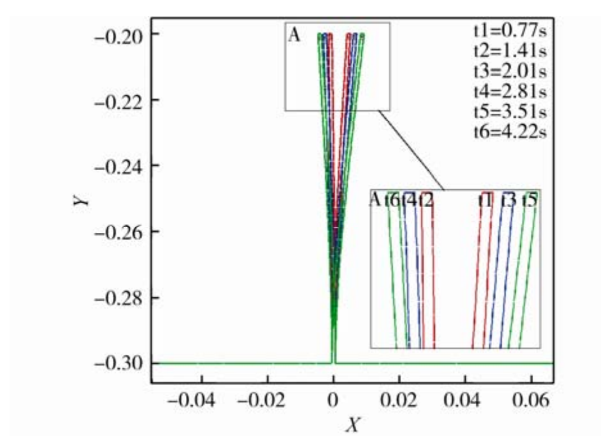
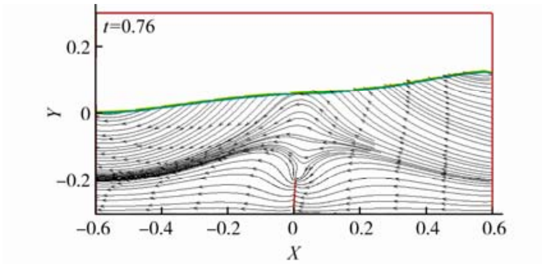
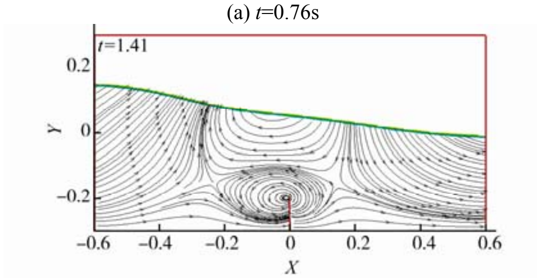


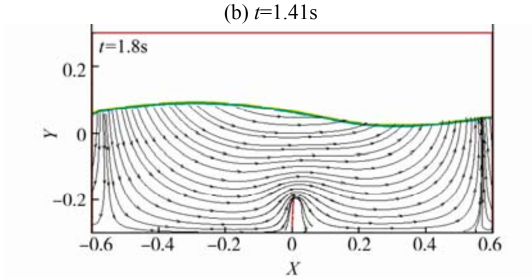
Fig.10 Cantilever beam movement (Case2)



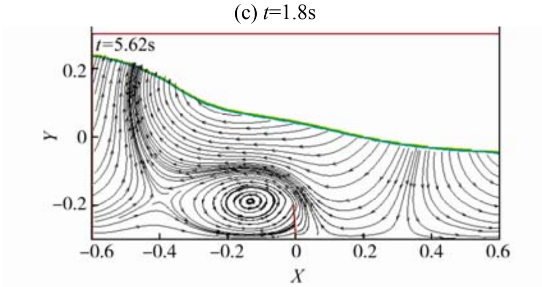
(a) t=0.76s



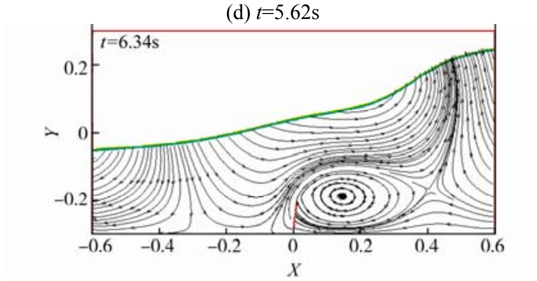
(b) t=1.41s



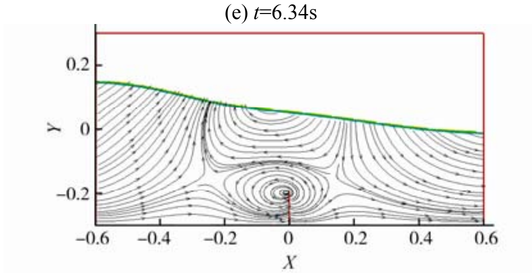
(c) t=1.8s



(d) t=5.62s

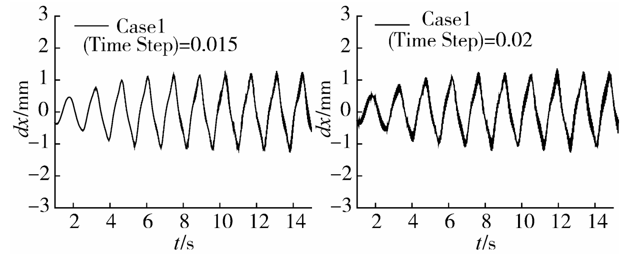


(e) t=6.34s



(f) t=9.15s

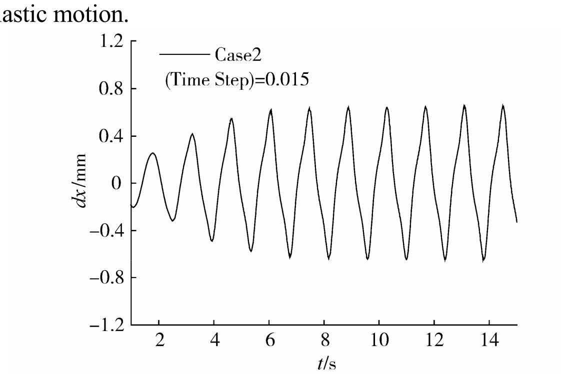
Fig. 11 The streamlines pattern of different time for Case2



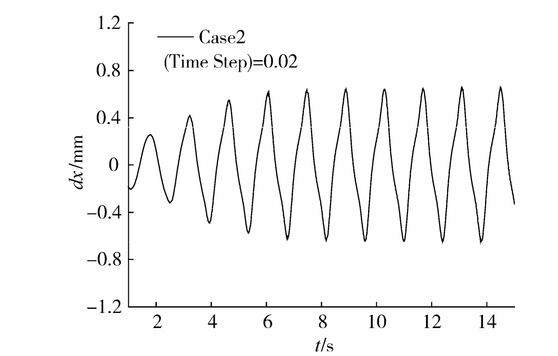
(a) (Time Step)=0.015 (b) (Time Step)=0.02

Fig. 12 The displacements history at P_1 for Case1

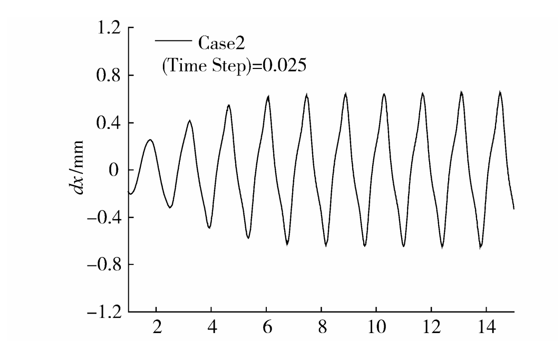
(4) Figs. 12 and 13 show the calculation results of Case 1 and Case 2 separately, mainly comparing the difference between the results with different time steps. It is shown that: after a period of time the results show a periodic change, and the calculation is steady, the time step rarely affect the calculation; with the increase of the rigid of the cantilever beam, the deformation is decreased, which is accordant with the law of elastic motion.



(a)(Time Step)=0.015



(b) (Time Step)=0.02



(c) (Time Step)=0.025

Fig. 13 The displacements history at P_1 for Case2

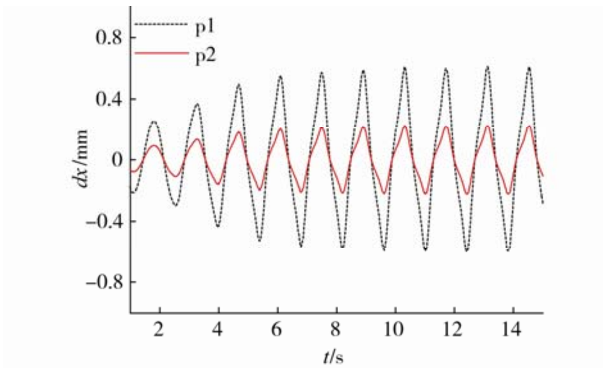
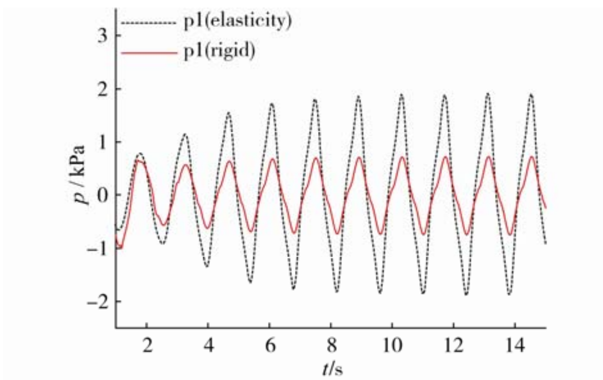
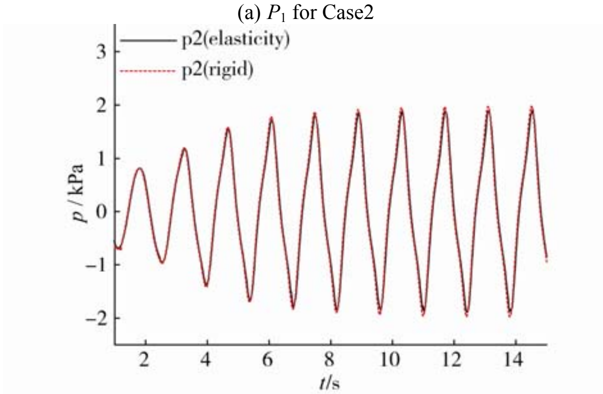


Fig. 14 The responses at P_1 and P_2 for Case2



(a) P_1 for Case2



(b) P_2 for Case2

Fig.15 Pressure history at $P_1$and P_2 for Case2

(5) Fig.14 takes the example of Case 2 to show the motion morphing of the cantilever beam at P_1 and P_2. It is shown that P_1 has larger deformation than P_2, which validates that P_1 is closer to the open end than P_2.

(6) Fig.15 takes the example of Case 2 and Case 3 to compare the pressures of the rigid beam and elastic beam at P_1 and P_2. Combining Fig.14, it can be seen that the elastic beam suffers larger pressures than the rigid one, the larger the deformation, the larger the pressure.

(7) Fig.16 shows the velocity vector of the rigid beam and elastic beam, which validates that the motion of the structure changes the motion of the fluid.

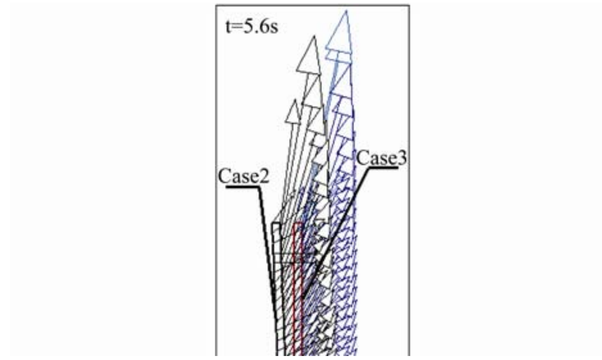


Fig. 16 Vector of velocity of cantilever beam

4 Conclusions

In this paper, we give a brief introduction to the method to study the interaction between the elastic anti-sloshing structure and the fluid in the sloshing tank. Validate the C programs with some simple cases, calculate and analyze the motion and response of the elastic anti-sloshing structure under the action of the sloshing loads. It is shown that it is feasible to study the interaction between the elastic structure and sloshing fluid with the link of C programs and the FLUENT. Further study should be focused on the interaction between the elastic tank and sloshing liquid.

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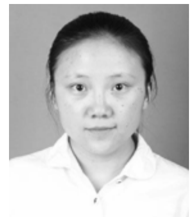

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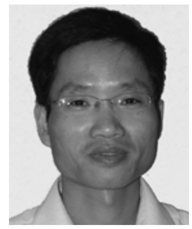

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