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# Numerical simulation of viscous liquid sloshing by moving-particle semi-implicit method

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**Abstract:** A meshless numerical simulation method, the moving-particle semi-implicit method (MPS) is presented in this paper to study the sloshing phenomenon in ocean and naval engineering. As a meshless method, MPS uses particles to replace the mesh in traditional methods, the governing equations are discretized by virtue of the relationship of particles, and the Poisson equation of pressure is solved by incomplete Cholesky conjugate gradient method (ICCG), the free surface is tracked by the change of numerical density. A numerical experiment of viscous liquid sloshing tank was presented and compared with the result got by the difference method with the VOF, and an additional modification step was added to make the simulation more stable. The results show that the MPS method is suitable for the simulation of viscous liquid sloshing, with the advantage in arranging the particles easily, especially on some complex curved surface.

**Keywords:** sloshing; liquid tank; viscous fluid; incompressible fluid; free surface; meshless; moving-particle semi-implicit method (MPS)
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## 1 Introduction

Liquid sloshing is the to-and-fro motion of a partially filled tank. With the ship's movement (rolling, pitching and so on), the ballast tank, oil tank of the ship will show sloshing phenomenon. The liquid sloshing loads action on the wall of tank, and that can cause local structural damage, some can influence the stability or maneuverability of the ship[1-2].

Recently, with the development of the LNG, LPG and VLCC, except the ballast tank and oil tank, more tanks of ship need to be considered, so more attention are paid to the sloshing of the liquid tanks in ship. In the last century, many researches used mesh to study the liquid sloshing, resolving the free surface with Marker and Cell (MAC) or Volume of Fluid (VOF), others used experimental methods by virtue of the potential flow theory for the liquid sloshing. Numerical simulation plays an important role in the liquid sloshing study.

In recent years, the viscous CFD technology has been developed, and many meshless methods have been put forward, such as smoothed particle hydrodynamics (SPH), Moving-Particle Semi-implicit Method (MPS), and so on. These meshless methods provided new tools for studying the hydrodynamic phenomena, which have the advantage of arranging the particles on some complex curved surface more easily than mesh methods.

MPS is a new fully Lagrangian meshless method[3], which substitutes particle for mesh in traditional methods, so MPS is called particle method too. Some ocean engineering problems have been studied by MPS method in Japan[4-6]. In this paper, MPS is used to simulate the liquid sloshing and demonstrate the possibility that MPS is suitable for simulating the liquid sloshing.

## 2 MPS method

The continuity and the Navier-Stokes equations are used as governing equations for incompressible flow:
Continuity equation:

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho\nabla \boldsymbol{U} . \tag{1}$$

Navier-Stokes equation:

$$\frac{\mathrm{D}\boldsymbol{U}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla \boldsymbol{P} + \nu\nabla^2 \boldsymbol{U} + \boldsymbol{F} . \tag{2}$$

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In Eqs.(1) ~ (2), $\rho$ is the density of fluid, $t$ the time, $\boldsymbol{U}$ the velocity vector, $\boldsymbol{P}$ the pressure and $\boldsymbol{F}$ the acceleration of body forces.

### 2.1 Kernel function

In MPS method, the particles' relationships substitute for the differential operators in traditional methods. The kernel function is used for a particle's interaction with others. This concept has been used in SPH, another meshless method. Study shows that the kernel function plays a very important role in simulations. In this paper, 5 different functions are employed for simulations of sloshing (see Fig.1 and Table 1).

With these different functions, particles only interact with a finite number of neighboring particles. The range of interaction is determined by parameter $r_e$.

**Table 1 Different kernel functions**

| Kernel function | KF1 | KF2 | KF3 | KF4 | KF5 |
|---|---|---|---|---|---|
| Kernel function formulation | $w(r)=\begin{cases}\frac{r_e}{r}-1, & \\ 0\le r<r_e; & \\ 0, & \\ r_e\le r. & \end{cases}$ | $w(r)=\begin{cases}\exp[-(\frac{r}{\alpha r_e})^2], & \\ 0\le r\le r_e; & \\ 0, & \\ r_e<r. & \end{cases}$ | $w(r)=\begin{cases}1-6(\frac{r}{r_e})^2+8(\frac{r}{r_e})^3-3(\frac{r}{r_e})^4, & \\ 0\le r\le r_e; & \\ 0, & \\ r_e<r. & \end{cases}$ | $w(r)=\begin{cases}\frac{2}{3}-4(\frac{r}{r_e})^2+4(\frac{r}{r_e})^3, & \\ 0\le r\le\frac{r_e}{2}; & \\ \frac{4}{3}-4(\frac{r}{r_e})+4(\frac{r}{r_e})^2-(\frac{4}{3})(\frac{r}{r_e})^3, & \\ \frac{r_e}{2}<r\le r_e; & \\ 0, & \\ r_e<r. & \end{cases}$ | $w(r)=\begin{cases}-(2\frac{r}{r_e})^2+2, & \\ 0\le\frac{r}{r_e}\le\frac{1}{2}; & \\ [2(\frac{r}{r_e})-2]^2, & \\ \frac{1}{2}<r\le 1; & \\ 0, & \\ r_e<r. & \end{cases}$ |
| Reference | [7] | [7] | [7] | [7] | [3] |

The function $w(r)$ depends on the distance $r$ between the two particles. This function only works when distance $r$ is less than $r_e$, the distance is closer, and the function $w(r)$ is biger, which guarantees that two particles cannot hit each other.

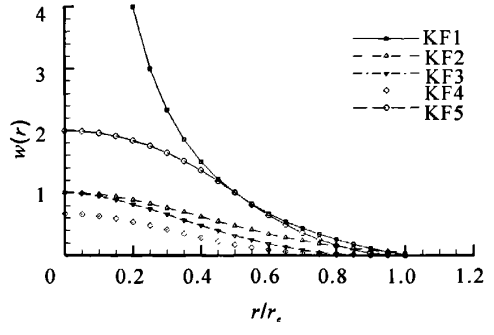



Fig.1 5 different kernel functions

### 2.2 Particle number density

Particle number density is defined as

$$n_i=\sum_{j\neq i}w(|\boldsymbol{r}_i-\boldsymbol{r}_j|). \quad (3)$$

It is the sum of kernel functions of one particle $i$ that works with other particles within the range of particle $i$, the contribution from $i$ itself is not considered. Vectors $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ are the coordinates of particles $i$ and $j$, respectively.

### 2.3 Modeling gradient and laplacian

MPS uses the gradient model and Laplacian model to replace terms of governing equation. These two models only work for one particle in its range $r_e$, which is the same range in kernel functions.

A gradient vector between two particles $i$ and $j$ possessing scalar quantities $f_i$ and $f_j$ at coordinates $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ is given as $(f_j-f_i)(\boldsymbol{r}_j-\boldsymbol{r}_i)/|\boldsymbol{r}_j-\boldsymbol{r}_i|^2$. For one particle $i$, it needs to calculate the gradient vectors with any combination of two particles which are in the range $r_e$ of particle $i$. The gradient vectors between particle $i$ and its neighboring particles $j$ are weighted by the kernel function and added to obtain the gradient vector of particle $i$:

$$<\nabla f>_i=\frac{d}{n_0}\sum_{j\neq i}\left[\frac{f_i-f_j}{|\boldsymbol{r}_j-\boldsymbol{r}_i|^2}(\boldsymbol{r}_j-\boldsymbol{r}_i)w(|\boldsymbol{r}_j-\boldsymbol{r}_i|)\right], \quad (4)$$

where the number $d$ of space dimensions is 2 for the 2-D space and 3 for the 3-D space. The gradient model is applied in MPS for the pressure gradient term, and $n_0$ is the initial particle number density which can be got by Eq.(3) in the initial step of the simulation, vectors $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ are the coordinates of particles $i$ and $j$ respectively.

The Laplacian model $\nabla^2 f$ can be got by diffusion equation, which simulates the change of the quantities $f_i$ and $f_j$ between particles $i$ and $j$, the kernel function should be considered between the two particles:

$$<\nabla^2 f>_i = \frac{d}{\lambda n_0}\sum_{j\neq i}\left[\left(f_j - f_i\right)w\left(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right)\right]. \quad (5)$$

$\lambda$ in Eq.(5) can be got as follows:

$$\lambda = \frac{\sum_{j\neq i} w\left(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right)\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|^2}{w\left(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|\right)}. \quad (6)$$

Other parameters are similar to Eq.(4).

### 2.4 Modeling of incompressibility

The continuity equation of governing equation requires that the density of fluid should be constant, MPS keeps $n_0$ as a constant to ensure the fluid's incompressibility. In the simulation, if the number density $n^*$ is not $n_0$, it needs to be implicitly corrected to $n_0$ by

$$n^* + n' = n_0, \quad (7)$$

where $n'$ is the correction value related to the velocity correction value $u'$:

$$\frac{1}{\Delta t}\frac{n'}{n_0} = -\nabla \cdot \boldsymbol{u}'. \quad (8)$$

$\Delta t$ is the increment of time, and the velocity correction value can be derived from the implicit pressure gradient as follows:

$$\boldsymbol{u}' = -\frac{\Delta t}{\rho}\nabla P^{n+1} \quad (9)$$

With Eqs.(7) ~ (9), a pressure Poisson equation is obtained as

$$<\nabla^2 P^{n+1}> = -\frac{\rho}{\Delta t^2}\frac{<n^*>_i - n_0}{n_0}. \quad (10)$$

The pressure Poisson equation can be solved by super over relax method (SOR) or incomplete Cholesky conjugate gradient method (ICCG).

### 2.5 Modeling of free surface

In a full Lagrangian motion of particles, free surface is clear to be traced by:

$$<n^*>_i < \beta n_0. \quad (11)$$

$n_0$ is the initial particle number density calculated in the initial step of the simulation, $<n^*>_i$ is the number density of particle $i$ in any simulation step, $\beta$ can be chosen between 0.8 and 0.99.

## 3 Algorithm of simulation

In each step of simulation, the source terms are explicitly calculated and the temporal velocities $\Delta \boldsymbol{u}_i^*$ are got, then use the temporal velocities to calculate the motion of particles, and temporal coordinates $\boldsymbol{r}_i^*$ are obtained. And then, the number density of each particle is changed. Use the number density and initial number density to set the pressure Poisson equation, then solve the pressure Poisson equation, and then get the pressure of the next step of simulation. Finally, the new velocities and coordinates of the next step of simulation are obtained by adding the pressure gradient terms with the next step pressure values, particularly,

1) Calculate the initial velocities $u^0$ and coordinates $r^0$ of each particle;

2) In one increment of time $\Delta t$, calculate the increment of velocities $\Delta \boldsymbol{u}_i^*$ by

$$\Delta \boldsymbol{u}_i^* = \Delta t\left(\nu\nabla^2 \boldsymbol{u}_i^n + \boldsymbol{F}\right); \quad (12)$$

3) Obtain the temporal velocities $\boldsymbol{u}_i^*$ and $\boldsymbol{r}_i^*$ coordinates by $\Delta \boldsymbol{u}_i^*$:

$$\boldsymbol{u}_i^* = \boldsymbol{u}_i^n + \Delta \boldsymbol{u}_i^*, \quad (13)$$

$$\boldsymbol{r}_i^* = \boldsymbol{r}_i^n + \Delta \boldsymbol{u}_i^* \cdot \Delta t; \quad (14)$$

4) Obtain the new number density of each particle $<n^*>_i$ by Eq.(3) and set the pressure Poisson Eq.(10);

5) With the next step's pressure of each particle, calculate the correction velocities:

$$\boldsymbol{u}_i' = -\frac{\Delta t}{\rho}\nabla P_i^{n+1}; \quad (15)$$

6) With the correction velocities, obtain the new velocities $\boldsymbol{u}_i^{n+1}$ and coordinates $\boldsymbol{r}_i^{n+1}$ of the next step of simulation:

$$\boldsymbol{u}^{n+1} = \boldsymbol{u}_i^* + \boldsymbol{u}_i'; \quad (16)$$

$$\boldsymbol{r}^{n+1} = \boldsymbol{r}_i^* + \boldsymbol{u}_i' \cdot \Delta t. \quad (17)$$

## 4 Numerical results of sloshing

The sloshing of a partially filled tank is presented in this paper. The geometry is depicted in Fig.2. The tank was surging to-and-fro with the frequency of 1.0 Hz, which was close to the first order linear frequency of an ideal fluid (1.008 Hz), the amplitude of the surging

was 0.005 m. Result of this sloshing was compared with the result of the difference method with the VOF[8].

The increment of time $\triangle t$ is a dynamic state in this paper, the fastest particle in each simulation step is chosen, and the velocity of this particle is used in Courant's law for calculation of $\triangle t$:

$$\Delta t = \alpha \frac{l_0}{v_{\max}}. \quad (18)$$

In Eq.(18), $l_0$ is the distance of particles, $v_{\max}$ is the velocity of the fastest particle, $\alpha$ in generalized case is 0.1.

An open tank was used for sloshing at first, but it was found that at about 2.0 s of the simulation, one particle spattered out of the tank, with the gravity action, this particle became so fast that the increment of time $\triangle t$ became very little. So a close tank was chosen for sloshing in this paper (see Fig.2).

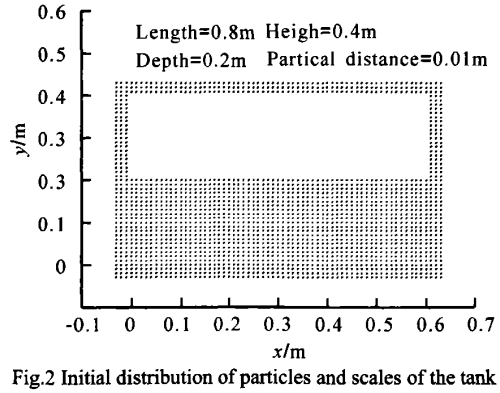
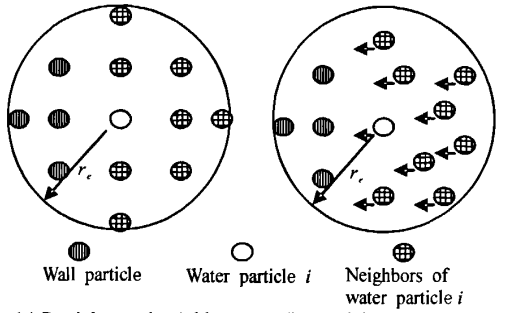



Fig.2 Initial distribution of particles and scales of the tank

At some steps of the simulation, a few of particles were too close and even passed through the wall of tank after the first correction of coordinates in Eq.(14), so the force given by kernel function was very big, and pushed the particle too far, while it could not happen in the real situation. It occurred because after the second correction of the last time step, the number density of each particle went back to the initial number density $n_0$, but it couldn't guarantee the distance of each particle with its neighbors going back to $l_0$, so $l_i^n$ may be less than $0.1l_0$, that caused the pass-through phenomenon in the first correction after Eq.(14) (see Fig.3).




(a) Particle $i$ and neighbors in initial step (b) Particle $i$ and neighbors in some time step

Fig.3 Reason of the pass-through phenomenon

Because of that, an additional modification is added after the correction of coordinates, by choosing a distance parameter. If two particles are close enough, pull them off by this additional modification (see Fig.4).

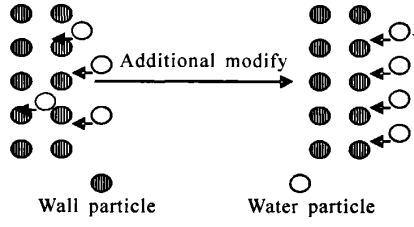



Fig.4 Additional modification step

Although the additional modification step has been taken, some kernel functions still cannot work in simulations, but in other functions, this additional modification step works well.

Five different kernel functions in Table 1 were used for simulation, and in kernel function 2, 3.0 was chosen for $\alpha$. The results show that kernel functions 2 and 5 aren't suitable for simulation of sloshing with 0.005 m surging and 1.0 Hz frequency (see Fig.5). The other three kernel functions can be used in the simulation.

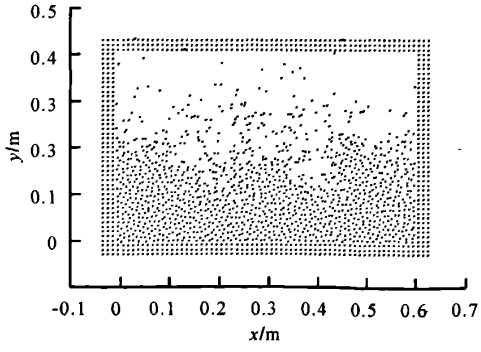



Fig.5 One example of failure

The simulation shows that results of kernel functions 1, 2 and 4 are different in motions on each side of wall, and the results show that the motion of kernel function 3 is the most close to the result of VOF (see Fig.6), so kernel function 3 is the most suitable for simulation of sloshing with 0.005 m surging and 1.0 Hz frequency.

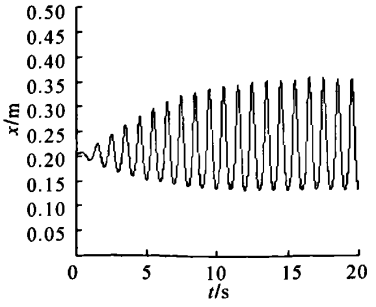
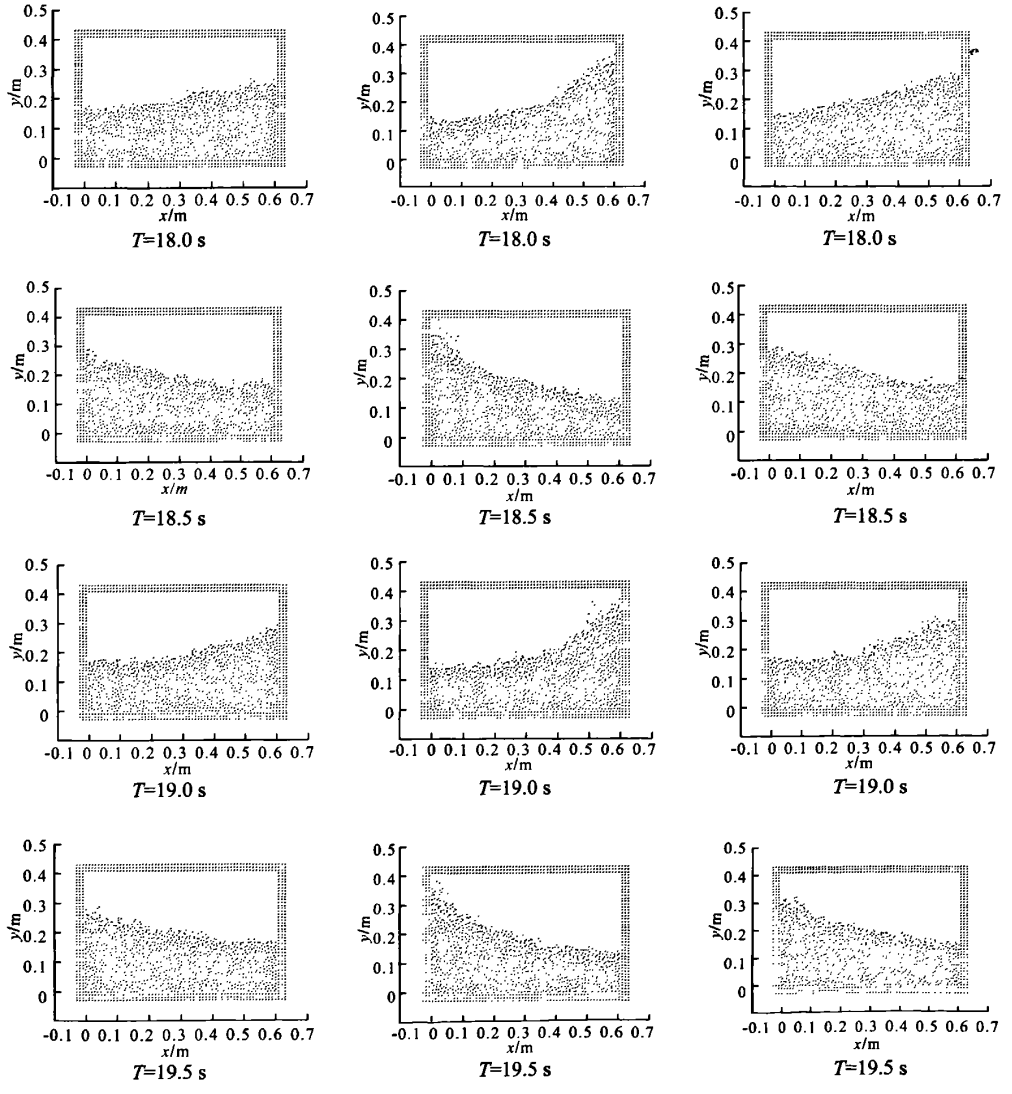



Fig.6 The surface of water on left wall in VOF




(a) Kernel Function 1 (b) Kernel Function 3 (c) Kernel Function 4

Fig.7 Sloshing simulation using different kernel functions

Comparing the result with the difference method with VOF[8], it shows the velocities and coordinates simulated by MPS with kernel function 3 are very close to VOF (see Figs.6~7), and the pressure is acceptable too (see Figs.8~9). In pressure part, there are lots of fluctuation because the random of the

particles' motion and every motion can influence the pressure of corresponding particle.

As a full Lagrangian meshless method, MPS can trace the free surface easily and show the water condition in sloshing more easily, which are advantageous than some Eulerian numerical methods, but it's difficult to trace the data of one fixed position, because of the continues moving particles.

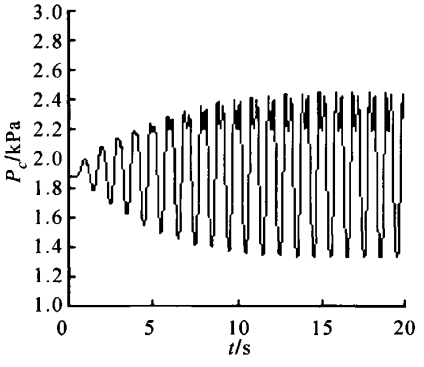



Fig.8 Pressure of left bottom (MPS, Kernel function3)

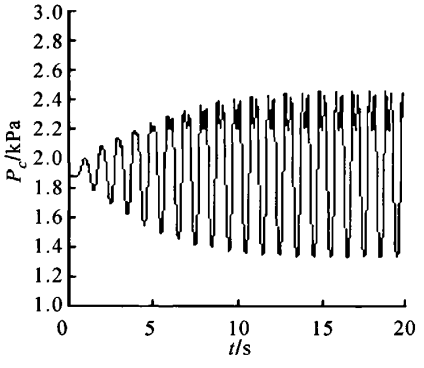



Fig.9 Pressure of left bottom (VOF)

## 5 Conclusions

In this paper, a simulation of liquid sloshing is put forward by MPS and 5 different kernel functions. It is found that kernel function 3 is most suitable for simulation. Result shows that MPS can trace the free surface easily and show the fluid condition in each step. An additional modification step is added to make the simulation more stable.

After comparing with other results, it shows the result of MPS is acceptable, and MPS is suitable for simulating the liquid sloshing. This paper just presents an initial study for the liquid sloshing using MPS, and more complicated sloshing simulations need to be studied based on MPS.

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8. ZHU R Q Time domain simulation of liquid sloshing and itsinteraction with flexible structure 2002

## 相似文献(10条)

1. 外文期刊 A. Kaneshige. N. Kaneshige. S. Hasegawa. T. Miyoshi. K. Terashima Model and control system for 3D transfer of liquid tank with overhead crane considering suppression of liquid vibration

The purpose of this paper is to present a model for and the development of a control system for the three-dimensional transfer of a liquid tank by an overhead crane that considers the suppression of sloshing. The model of sloshing in each transfer direction is built by using a double pendulum model. In addition, it is confirmed that the proposed model can be applied to a two-dimensional transfer. The present paper provides a method to control sloshing with an overhead crane and also discusses the optimal design for the shape and size of a rod tank device is discussed.

2. 期刊论文 朱仁庆. 王志东. 方智勇. ZHU Ren-qing. WANG Zhi-dong. FANG Zhi-yong 液舱内大幅晃荡引起的压强预报 -船舶力学2004,8(6)

本文基于流体体积(VOF)法就部分装载液体的液舱内的晃荡压强进行了二维数值计算.为了模拟大幅晃荡引起的冲击压强,重点对数值计算较为敏感的速度边界条件进行了数值处理.通过对某一矩形液舱内的液体晃荡的计算,得到了自由表面位置和压强的时间历经曲线.计算结果同实验值的比较显示:本方法可以用于计算预报大幅晃荡引起的载荷.

3. 外文期刊 T. Nasar. S. A. Sannasiraj. V. Sundar Wave-induced sloshing pressure in a liquid tank under irregular waves

The sloshing pressures on the side wall and on the top cover plate of a tank partially filled with liquid and rigidly mounted on a barge in irregular waves are investigated through physical model tests. The barge was allowed to oscillate freely in the combined degrees of excitation, i.e. sway, heave, and roll. Four liquid fill levels with aspect ratios h{sub}S/l (where h{sub}s is the static liquid depth and / is the tank length) of 0.163, 0.325, 0.488, and 0.585 are considered for the present study. The effect of peak wave excitation frequencies on the pressure variation is studied in detail, the results of which are herein reported. It is observed that the impact pressure on the top panel of the tank is about 1.6 times the pressure observed on the side wall.

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wave excitation frequencies on the pressure variation is studied in detail, the results of which are herein reported. It is observed that the impact pressure on the top panel of the tank is about 1.6 times the pressure observed on the side wall.

5.外文期刊 Miao Guo-ping.H. Ishida.T. Saitoh ANALYTICAL SOLUTIONS FOR THE SLOSHING LOADING ON CIRCULAR CYLINDRICAL LIQUID TANKS WITH INTERIOR SEMI-POROUS BARRIERS

The estimation of sloshing loading on liquid tanks is offundamental importance due to the wide and impor- tant applicationsof liquid tanks in various engineering aspects. Analytical solutionsfor the sloshing loading on circular cylin- Drical liquid tanks withan interior concentric vertical thin Semi-porous barrier undereternal excitations are presented. And the extensions of thesolutions to the elastic vibrations And to the high frequency limitto count for the earthquake re- Sponse are also included.

6.外文会议 Y. P. Xiong.J. T. Xing.W. G. Price THE INTERACTIVE DYNAMIC BEHAVIOUR OF AN AIR-LIQUID-ELASTIC SPHERICAL TANK SYSTEM

The dynamic behaviour of an air-liquid-elastic spherical tank interaction system is investigated. The tank is fully filled with a non-viscous liquid and air and supported at four equally spaced persitions around the outer shell. The governing equations describing this system are presented. A mixed displacement-pressure finite element method is developed adopting the dynamic pressure in the liquid/air and the displacement in the elastic solid as variables to initiate a numerical model incorporating a substructure-subdomain approach. Numerical simulations are presented based on a developed computer program FSIAP. The natural sloshing frequencies and the corresponding vibration modes of the coupled system are derived. To reveal different interactive mechanisms, four cases are investigated. Namely, 1) liquid sloshing in a rigid tank; 2) air-liquid interactions in a rigid tank; 3) liquid-elastic tank interactions; 4) three phase air-liquid-tank interactions. The numerical results obtained demonstrate the complex coupled behaviour of the system. This study provides information for the design of liquid/gas filled tanks in which structure sloshing behavious is of interest.

7.外文会议 Y.P. Xiong.J.T. Xing.W.G. Price THE INTERACTIVE DYNAMIC BEHAVIOUR OF AN AIR-LIQUID-ELASTIC SPHERICAL TANK SYSTEM

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8.外文会议 Y.P. Xiong.J.T. Xing.W.G.Price.American Society of Mechanical Engineers; THE INTERACTIVE DYNAMIC BEHAVIOUR OF AN AIR-LIQUID-ELASTIC SPHERICAL TANK SYSTEM

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9.外文期刊 Shin Hyung Rhee Unstructured Grid Based Reynolds-Averaged Navier-Stokes Method for Liquid Tank Sloshing

The present study is concerned with liquid tank sloshing at low filling level conditions.The volume of fluid method implemented in a Navier-Stokes computational fluid dynamics code is employed to handle the free-surface flow of liquid sloshing.The geometric reconstruction scheme for the interface representation is employed to ensure sharpness at the free surface.The governing equations are discretized by second order accurate schemes on unstructured grids.Several different computational approaches are verified and numerical uncertainties are assessed.The computational results are validated against existing experimental data,showing good agreement.The capability is demonstrated for a generic membrane-type liquefied natural gas carrier tank with a simplified pump tower inside.The validation results suggest that the present computational approach is both easy to apply and accurate enough for more realistic problems.

10.外文期刊 Ikeda T. Nonlinear parametric vibrations of an elastic structure with a rectangular liquid tank

The nonlinear coupled vibrations of an elastic structure and liquid sloshing in a rectangular tank partially filled with liquid, are investigated. The structure on which the liquid tank is attached is vertically subjected to a sinusoidal excitation when the natural frequency of the structure is equal to twice the natural frequency of one of the sloshing modes. In the theoretical analysis, the modal equations are derived by taking nonlinear fluid force into account. Responses of the structure and the liquid surface are presented as resonance curves using the harmonic balance method. From this theoretical analysis the following predictions are obtained: (a) due to the nonlinearity of the fluid force, harmonic oscillations appear in the structure, while subharmonic oscillations occur on the liquid surface; (b) the shapes of the resonance curves markedly change depending on the liquid level; and (c) when the tuning condition is slightly deviated, amplitude modulated motions and chaotic oscillations appear during a certain range of the excitation frequency. These were qualitatively in agreement with the experimental results. [References: 37]