SLOSHING IN A RECTANGULAR STORAGE TANK WITH A HORIZONTAL PERFORATED PLATE - NUMERICAL STUDY FOR 2–D PROBLEMS -

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SUMMARY

The liquid sloshing in a moving partially filled rectangular tank with horizontal perforated plate is investigated assuming inviscid, incompressible and irrotational flows. Inner structures can be used to restrain liquid sloshing and prevent tank damage. The liquid fill level and length of those baffles affecting the sloshing masses and liquid motion are also investigated in details. In order to assess the effects of the perforated plate, a rectangular tank with an inner perforated plate was excited under different rolling amplitudes and frequencies. The maximum pressures were examined. A numerical algorithm based on the volume of fluid technique (VOF) is used to study the non-linear behavior of liquid sloshing. The numerical model solves the complete Navier-Stokes equations in primitive variables by using of finite difference approximations with the moving coordinate system. The ratio of the baffle height to the initial liquid depth has been chosen as hP / h = 1/3, 1/2 and 2/3. The effect of the perforated plate height to reach the roof of the tank have been investigated. The numerical results indicate that the perforated plate can significantly restrain resonant sloshing in the tank under rolling excitation.

Keywords: Sloshing, Two-dimensional free surface flow, Volume of fluid technique, Finite difference method, Horizontal perforated plate.

1. Introduction

Liquid sloshing, in partially filled containers under external excitations, has been a crucial engineering issue, which involve the performance, stability, and structural integrity problems in many discipline such as aerospace vehicles, road tankers, liquified natural gas carriers, elevated water towers and petroleum cylindrical tanks, etc. Ibrahim (2005) has brought together a large deal of past research dedicated to liquid sloshing in a book. He has covered almost all of the research contents in the field at avail until its publication date by a comprehensive review. Hydrodynamic forces acting on tank walls as a result of the liquid sloshing may damage the container, thus the sloshing dynamic loads should be restricted in order to avoid structural failure because of undesirable dynamic behaviors. The inherent liquid viscosity is not sufficient to reduce the sloshing forces on the dynamic characteristics of liquid storage tanks. Therefore, other methods should be introduced to suppress the sloshing dynamic loads. Among them, baffles have been devised as effective internal components to increase the hydrodynamic damping ratio and consequently decrease the slosh forces in most of the practical engineering problems. Fluid motion in partially filled tanks can cause large structural loads and unexpected instability of engineering structural system if the period of tank motion is close to the natural period of fluid inside the tank. Furthermore, the caused failure may be a tremendous loss of human, economic, and environmental resources. The amplitude of the slosh, in general, depends on amplitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry. These parameters have direct effects on the dynamic stability and performance of moving tanks. Vertical baffles and perforated plates are useful for suppressing resonant sloshing by changing the lowest resonant frequency to a higher frequency range.

There has been a considerable amount of work on investigating the effects of baffles on liquid sloshing by using analytical, experimental and numerical methods. But, still it is of great importance for further research on the understanding of the complex sloshing dynamics and the techniques for sloshing damping using baffles. The analytical and semi-analytical mathematical models have been used to study the liquid sloshing characteristics in a baffled or un-baffled half-full horizontal cylindrical containers of elliptical or circular cross section, rectangular containers, vertical circular cylindrical tanks subjected to arbitrary external forces. Some of these studies, e.g. Gavrilyuk et al. (2006), Maleki and Ziyaeifar (2008), Hasheminejad et al. (2014), and Wang et al. (2013), are carried out to approximate the linearized problem on fluid sloshing by using some techniques such as the appropriate eigenfunction expansions, a weakly nonlinear modal theory, an asymptotic modal method, a powerful conformal mapping technique, etc. Developing an analytical model with acceptable accuracy for determination of baffle damping could provide useful means for design of the baffle geometric characteristics and arrangements. On the other hand, analytical methods have not been useful anymore with complexity of the tank geometry.

Experimental investigations are necessary for evaluating the actual dynamic characteristics of the liquid sloshing with different baffles. On the other hand, there are not enough information on the experimental investigation of the suppression of sloshing behavior using baffles in published literature and some problems in the extension of their results to the full scale real world problems due to scaling effects. In recent years, Goudarzi and Sabbagh-Yazdi (2012) carried out the experimental measurements to evaluate the efficiency of three types of baffles (upper and lower mounted vertical baffles as well as horizontal baffles) on hydrodynamic damping of the liquid motion. Akyildiz et al. (2013) conducted the experiments to analyze liquid sloshing in a cylindrical tank at a model scale with various fill levels and ring baffles under the excitation of roll motion. The experimental results of Xue et al. (2013) for the liquid sloshing in a rectangular liquid tank with perforated baffle considered to be an effective baffle arrangement in tanks on reducing the sloshing amplitude. The accuracy of the experimental systems was validated against the numerical results from an in-house robust CFD code. An experimental rig was developed by Zheng et al. (2013) to study non-linear sloshing in a baffled and un-baffled tank of rectangular dimension. Nayak and Biswal (2015) investigated experimentally the hydrodynamic damping potential of three different configurations of centrally installed internal baffles perpendicular to the direction of lateral excitation in a rectangular tank partially filled with water. It can be found that the damping coefficient increases with relative baffle height, and baffles can be used effectively to damp liquid sloshing near resonance conditions.

There are also lots of numerical studies of liquid sloshing with different baffles in the containers with complex geometries, such as finite element methods (FEM), finite difference methods (FDM), boundary element methods (BEM), volume of fluid (VOF) technique, virtual boundary force (VBF) method, and Mesh-less method, etc. Akyildiz (2012) and Jung et al. (2012) examined the effect of the vertical baffle height relative to the initial liquid depth numerically. The critical baffle height to reach the roof of the tank and the baffle height beyond the liquid does not get over the baffle anymore have been investigated. On the other hand, Goudarzi et al. (2012) indicated that an up-mounted vertical baffle is more effective than a low-mounted one and horizontal plates have significant damping effects in slender tanks, whereas vertical plates are more effective in broader tanks. Vertical baffles may reduce the sloshing amplitudes and dynamic impact loads as well as the natural frequency of the tank (Wu et al. 2013; Xue et al. 2012). Additionaly, alternative baffle systems have been analysed in tanks, such as annular baffles and flexible baffles in cylindrical tanks (Biswal et al. 2004), horizontal and vertical baffles in rectangular tanks (Akyildiz, Unal 2005; Akyildiz, Unal 2006; Liu, Lin 2009) and annular baffles in rectangular tanks (Panigrahy et al. 2009). They concluded that, in an increased fill depth; the rolling amplitude and frequency of the tank with or without baffle configurations directly affect the degrees of non-linearity of the sloshing phenomena. Pal, Bhattacharyya (2010) carried out the numerical and experimental studies of liquid sloshing for 2-D problem. The resulting slosh heights for various excitation frequencies and amplitudes are compared with the data obtained numerically. Numerical simulation of liquid sloshing with or without baffles is also examined by Eswaran et al. (2009) and Chen et al. (2009).

The resonant frequency of the tank with a baffle is different from the natural frequency of an unbaffled tank. The resonant sloshing frequencies depend on the solidity ratio (unity minus the porosity), the number of submerged plate gaps, the liquid depth, and the position of the perforated openings relative to the mean free surface. Furthermore, the resonant frequency monotonically decreases as the solid rate increases and the largest amplitude response is at the resonant frequency corresponding to the third-order natural frequency of the unbaffled tank, as the first mode disappeares and the third mode decreases(Faltinsen et al. 2010; Faltinsen et al. 2011; Faltinsen, Timokha 2011). Liu et al. (2007) and Liu, Li (2011) indicated that a proper designed horizontal perforated plate breakwater may have significant wave absorbing performance and decrease wave forces. Therefore, the main purpose of this study is to examine the effect of a horizontal perforated plate on liquid sloshing in a rectangular tank. The maximum pressures on the tank wall with different rolling excitations and the perforated plates in the tank are numerically examined. The effects of the porosity and the relative depth of the horizontal plate on the resonant frequencies are shown. A numerical algorithm based on the volume of fluid technique (VOF) is used to study the non-linear behavior of liquid sloshing. The numerical model solves the complete Navier-Stokes equations in primitive variables by using of finite difference approximations with the moving coordinate system.

2. Mathematical formulation and numerical approach

The fluid is assumed to be homogenous, isotropic, viscous and Newtonian. Tank and fluid motions are assumed to be two-dimensional. The domain considered is a rigid rectangular container partially filled with liquid.

The governing equations (namely Navier-Stokes and continuity equations) are solved simultaneously with the corresponding boundary conditions and free surface kinematics and dynamic boundary conditions in the fluid domain.

$$\nabla \mathbf{U}(u,v) = 0 \tag{1}$$

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} = -\frac{1}{\rho} \cdot \nabla \mathbf{P} + \mathbf{F} + \nu \nabla^2 \mathbf{U} \tag{2}$$

where $\mathbf{U}(u,v)$ is the velocity vector defined in the tank fixed coordinate, and ρ, P, ν and F are the liquid density, pressure, kinematic viscosity and external forces respectively.

In order to include the non-linearity and avoid the complex boundary conditions of moving walls, the moving coordinate system is used. The origin of the coordinate system is at the position of the center plane of the tank and on the undisturbed free surface. The moving coordinate is translating and rotating relative to an inertial system.

The external force consists of gravitational forces, the translational and rotational inertia forces, which can be written as,

$$\mathbf{F} = \mathbf{g} - \frac{d\,\mathbf{V}}{d\,t} - 2\boldsymbol{\Omega} \times \mathbf{V} - \frac{d\,\boldsymbol{\Omega}}{d\,t} \times \mathbf{r} - \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{r}) \tag{3}$$

where $\mathbf{g}$, $\mathbf{V}$ and $\boldsymbol{\Omega}$ are the gravitational vector, the translational velocity and the rotational velocity vector. In addition, is the position vector of the considered point relative to O. On the free surface, both the kinematic and dynamic conditions should be satisfied:

$$\frac{\partial \eta}{\partial t} + \mathbf{U} \cdot \nabla (\eta - z) = 0 \tag{4}$$

$$\text{P} = \text{Patm} \tag{5}$$

where η represents the free surface profile and Patm is the air pressure or ullage pressure inside the tank. The surface tension is ignored in this study. Therefore, a no-shear is needed on the free surface. But, proper wall conditions are necessary on the tank walls and the internal members.

2.1 *Numerical Computation*

For the analysis of the sloshing flow inside a partial filled tank, a finite difference method is applied to the governing equations. A FDM (finite difference method) is useful when there are internal structures inside the tank or the fluid contacts the tank ceiling frequently. As the internal structures exist, the viscous effects may be dominant. In this study, the method concentrates on the global fluid motion, so some local effects, such as turbulence and wave breaking have been ignored. In some cases, these local effects are important, but the simulation of global flow plays a more critical role in many sloshing problems.

The scheme adopted in this study is the SOLA method (Hirt, Nichols 1981). Tank volume is discredited into Cartesian staggered grid cells. The mesh region containing fluid is composed of cells and a single layer of fictitious cells (or boundary cells) surrounds the fluid region. The fictitious cells are used to set the boundary conditions so that the same difference equation can be used in the interior of the mesh.

Fluid velocities are located at the centers of the cell boundaries and pressure (P) and the volume of fluid function (S) are computed at the center of the cell. The volume of fluid function is governed by the Eulerian form of the transport equation in two dimensions. It can be formed by using the incompressible version of the continuity equation.

$$\frac{\partial \mathbf{S}}{\partial t} + \frac{\partial}{\partial x}(u\,\mathbf{S}) + \frac{\partial}{\partial y}(v\,\mathbf{S}) = 0 \tag{6}$$

The volume of fluid function can be defined whose value is unity at any point occupied by fluid and zero otherwise. The average value of (S) in a cell would represent the fractional volume of the cell occupied by fluid. A unit value of (S) would correspond to a cell full of fluid, while a zero value would indicate that the cell contained no fluid. Cells with (S) values between zero and one must then contain a free surface. The solution algorithm works as a time cycle or ‘movie frame’.

The results of the time cycle act as initial conditions for the next one. At each step, suitable boundary conditions must be imposed at all boundaries.
There are two alternatives for the wall conditions; when the viscosity effect on the tank boundary is significant, the no-slip condition should be imposed. However, in most sloshing problems, the viscous effect is not significant and the boundary layer thickness is much less than the cell size. Therefore, the free slip condition is applied in the present study.

2.2 Numerical Stability and Accuracy

Numerical calculations can have quantities that develop large, high frequency oscillations in space or time or both of them. This behavior is usually referred to as a numerical instability. To prevent this type of numerical instability or inaccuracy, certain restrictions must be observed in defining the mesh increments Δx_i and Δy_j, the time increment Δt and the upstream differencing parameter α.

For accuracy, the mesh increments must be chosen small enough to resolve the expected spatial variations in all dependent variables. Once a mesh has been chosen, the choice of the time increment necessary for stability is governed by two restrictions. First, material cannot move through more than one cell in one time step, because the difference equations assume fluxes only between adjacent cells. Therefore, the time increment must satisfy the inequality,

$$\Delta t < \text{Min}\left\{ \frac{\Delta x_i}{|u_{i,j}|}, \frac{\Delta y_j}{|v_{i,j}|} \right\} \tag{7}$$

where the minimum is with respect to every cell in the mesh. When a non-zero value of kinematic viscosity, momentum must not diffuse more than one cell in one time step. In this study, Δt is automatically chosen to satisfy the above inequalities. In order to insure the numerical stability, the parameter α is,

$$1 \geq \alpha \geq \text{Max}\left\{ \frac{u_{i,j} \cdot \Delta t}{\Delta x}, \frac{v_{i,j} \cdot \Delta t}{\Delta y} \right\} \tag{8}$$

2.3 Tank configuration

Fig.1 denotes the 2D-rectangular tank with perforated plate and the locations of the transducers to obtain the pressure distributions with time. For all cases, the fluid depth (*h*) is 75% of the tank height. The baffles are assumed to be rigid. The height of the plate (h_p) is established by the ratio to liquid depth of h_p / h = 1/3, 1/2 and 2/3. The geometrical porosity *GP* is defined as GP = (21×*dx*) / 920 where *dx* is the width of the slot. Therefore, three *GP* values of 1.0, 0.5 and 0.25 were used to analyse the effect of plate porosity on the sloshing motion. The pressure transducers are installed on the left side in the center plane of the beam and one location on the top wall.

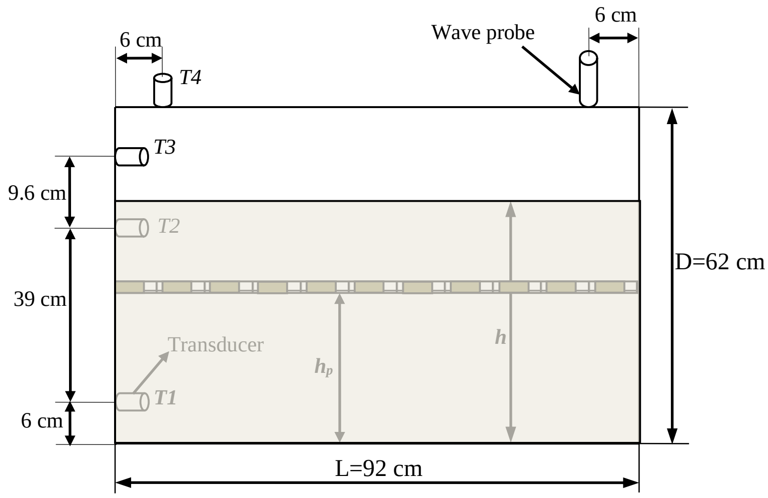

Fig. 1. Schematic diagram of the perforated plate configuration

Present numerical code is set up to handle a simple harmonic forcing function. Thereafter, it advances the velocities in time explicitly using the two momentum equations. First, the angular displacement and its derivatives are calculated. The apparent acceleration terms are then calculated and finally the advective, diffusion and pressure gradients terms are calculated yielding an estimate of the velocity at the new time level. The tank motion is the pitch oscillations about *y*-axis only which follows the sinusoidal function given as $\theta = \theta_0 \sin(\omega t)$ where θ_0 and ω are the rolling amplitude and the frequency, respectively. The rolling amplitude is chosen as 2^0 and 4^0 in this study. The tank natural frequencies are calculated as follows (Lamb 1932):

$$\omega_i = \left[g \frac{\pi i}{L} \tanh \left(\frac{\pi i}{L} h \right) \right]^{0.5} \quad i = 1, 2, 3... \tag{13}$$

where ωi is the natural frequency, and g is the gravitational acceleration. Faltinsen et al. [21] indicated that a vertical perforated plate to a water tank may remove the first-order resonant frequency. Thus, the first-order and the higher-order resonant frequencies are considered when studying the resonant effect of sloshing.

When the period and amplitude of excitation are large, the liquid responds violently and causes the numerical solution to become unstable. The instability are related to the instability of the fluid motion, such as the occurrence of turbulence, wave breaking and the transition from homogeneous flow to a two-phase flow. For these situations, the present numerical model is limited to the period prior to the inception of these flow perturbations. On the other hand, in this study, to estimate the limited impact pressure on the tank top and to demonstrate the capability of the numerical code in computing impact-type loads, the slosh of liquid at 75% fill depth with the rolling amplitudes 2^0 and 4^0 are chosen for all cases.

3. Results and discussions

3.1 Maximum pressures at different excitation frequencies

Fig. 2, at T1, denotes the non-dimensionless maximum pressures at different excitation frequencies . It is obvious that the maximum pressure increases based on the time history of the pressures for the unbaffled tank. The resonant effect on the maximum pressure occurs near the natural frequency.

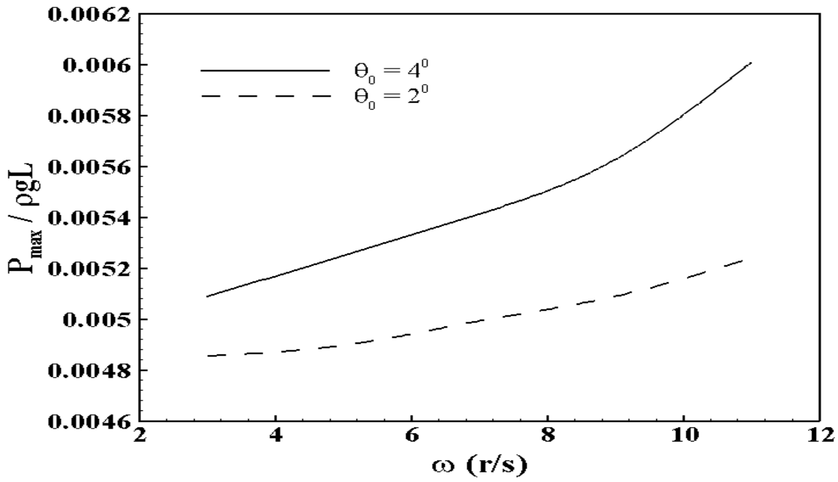

Fig. 2. Maximum pressures for an un-baffled tank at T1.

On the other hand, the resonant effect on the maximum pressures at other frequencies are very small. Since the transducer of T2 locates near the initial free surface height, the values of pressure are obtained by net liquid impact, resulting in the dynamic pressures (Fig. 3).

It can be concluded that the static pressure is mainly predominant over the dynamic pressure as the rolling frequency increases continuously. Additionally, the maximum pressure at T2 is increased near the first-order resonant frequency due to the net impact loads. Figs. 4-9, at T1, also indicate that the horizontal perforated plate with h_P / h = 2/3, 1/2 , 1/3 and GP = 0.25 does not change the resonant frequency significantly. Because, small porosity with the relative submerged depth represents the shallow water effects and the free surface behavior is getting stable slowly due to the inertial forces. On the other hand, as shown in Figs. 10-15, at T2, the horizontal perforated plate shows that the natural frequency is more influenced by the plates for first-order mode than the higher-order modes.

As shown in Figs. 4-9 and Figs. 10-15, among all cases, the maximum pressures at h_P / h = 1/3 with GP = 0.25 are the smallest for the rolling amplitudes of 4^0 and 2^0. Therefore, it is indicated that a suppression effect could be obtained by adjusting either the location or geometric porosity of the horizontal perforated plate. The maximum pressures at T1 do not change very much for other modes of the natural frequencies comparing to the first-order mode when h_P / h = 1/3 and

GP = 0.25. On the other hand, the maximum pressures at T2 change much more for other modes of the natural frequencies due to the net liquid impact. It is indicated that the porosity influences the maximum pressure, and the relative submerged depth changes the period.

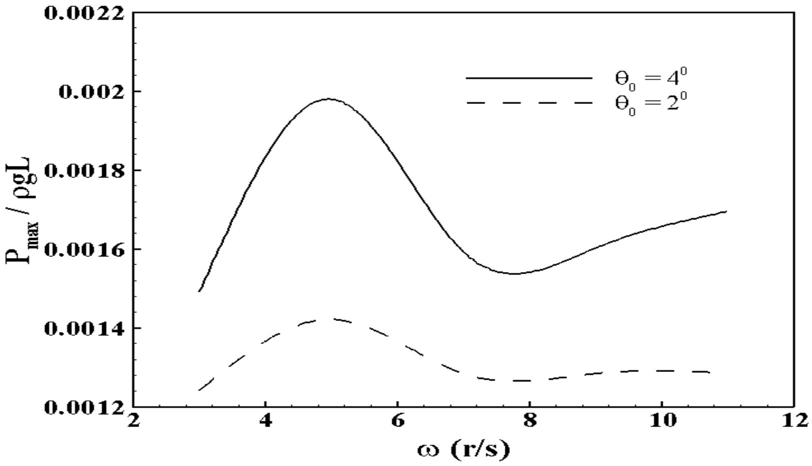

Fig. 3. Maximum pressures for an un-baffled tank at T2.

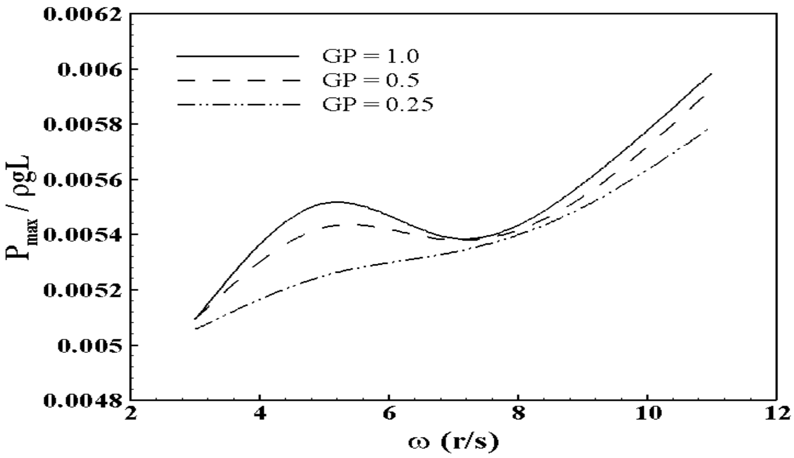

Fig. 4. Maximum pressures at T1. $\theta_0 = 4^0$; $h_P / h = 2/3$.

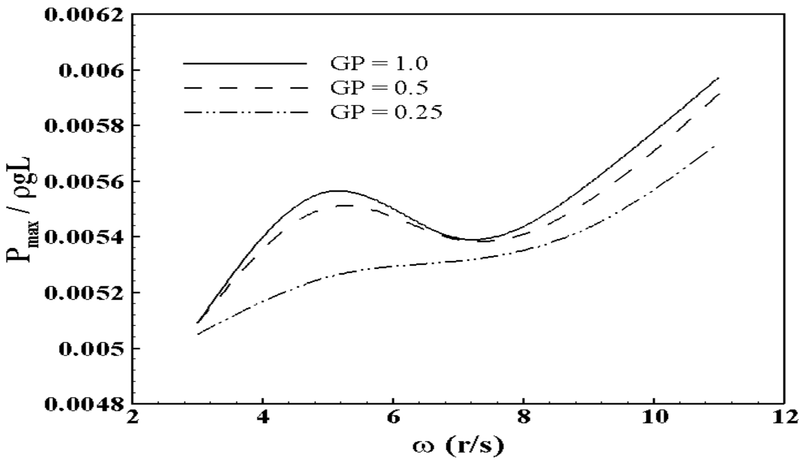

Fig. 5. Maximum pressures at T1. $\theta_0 = 4^0$; $h_P / h = 1/2$.

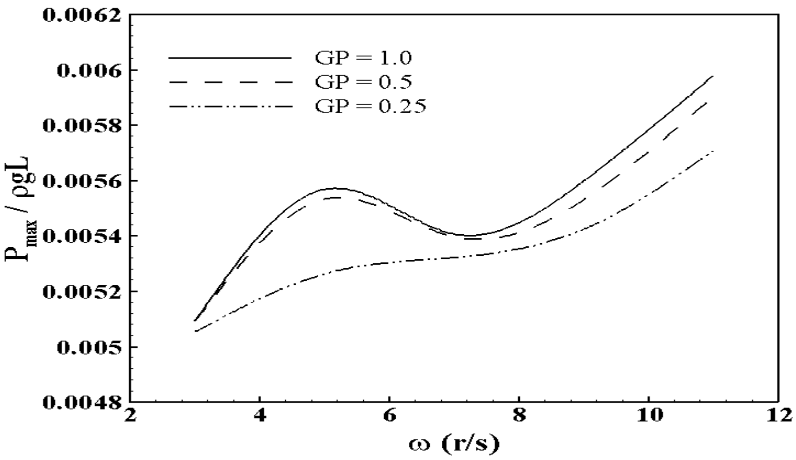

Fig. 6. Maximum pressures at T1. $\theta_0 = 4^0$; $h_P / h = 1/3$.

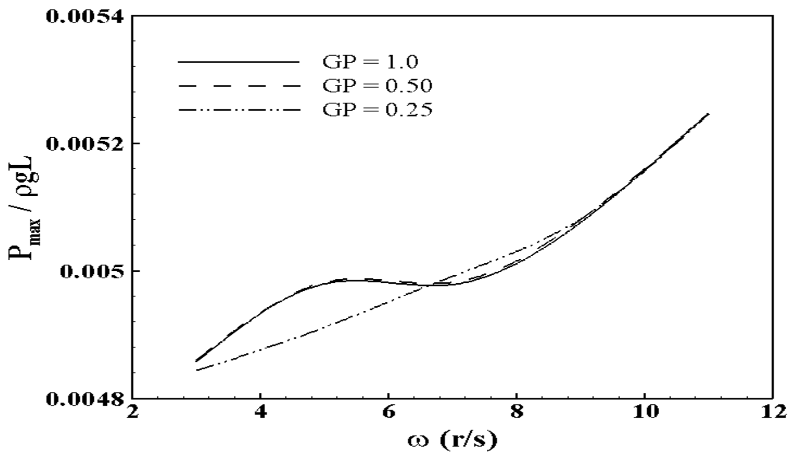

Fig. 7. Maximum pressures at T1. $\theta_0 = 2^0$; $h_P / h = 2/3$.

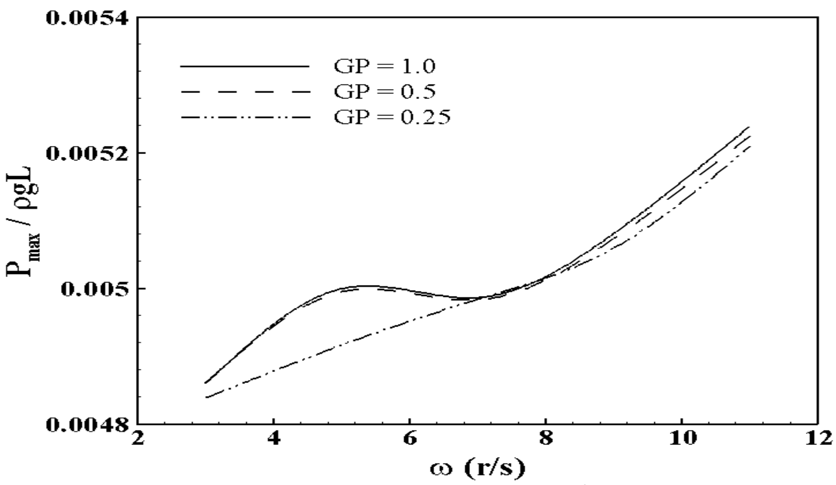

Fig. 8. Maximum pressures at T1. $\theta_0 = 2^0$; $h_P / h = 1/2$.

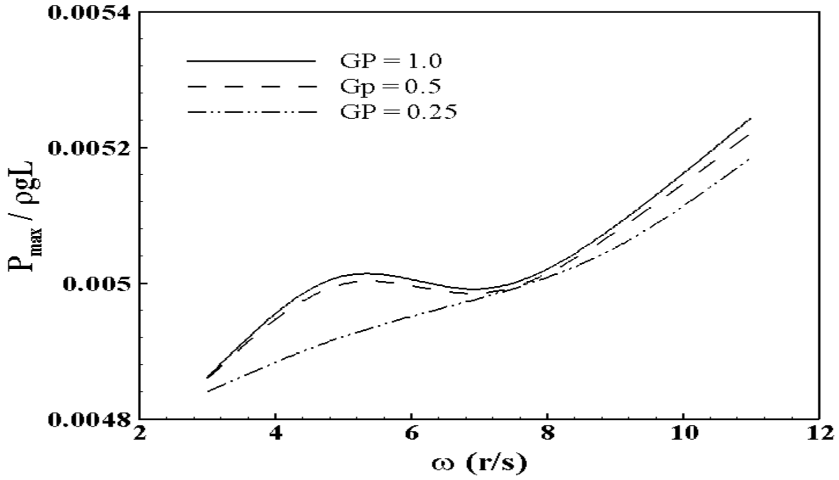

Fig. 9. Maximum pressures at T1. $\theta_0 = 2^0$; $h_P / h = 1/3$.

3.2 The influence factors of the sloshing loads

It can be said that the horizontal perforated plate is useful for restraining the free surface elevations and thereafter the sloshing loads. For the rolling amplitudes of 4^0 and 2^0, the maximum pressures at T1 and T2 decrease with the smaller plate porosity near the first-order resonant frequency. This reduction is also more significant at a smaller relative submerged depth of $h_P / h = 1/3$. Additionally, the resonant frequency is shifted by the horizontal perforated plate at the higher order modes when the plate submerged depth is getting smaller. It is indicated that the relative submerged depth is of great importance in the control of the sloshing loads at a higher mode. It can be recommended that a horizontal perforated plate with smaller porosity is effective for reducing resonant sloshing in a liquid tank. The results also show that the variations at the first-order mode have a trend of moving away diminishingly from the natural frequency with a decrease of porosity and relative submerged depth.

The maximum pressures decrease monotonously with the decrease of GP and h_P / h while the larger pressures appear at the lower mode. This means that the resonant sloshing at the lower mode can be restrained by a horizontal perforated plate with a small porosity and a small relative submerged depth. Furthermore, it suppresses slightly the liquid sloshing because of the hydrodynamic damping and the blockage effects. Then, the rolling motion of the liquid becomes weaker and free surface behavior is getting stable by the shallow water effects. It can be indicated that the effect of restriction is obvious for the first-order mode.

It can also be said that the value of the maximum pressure keeps increasing as h_P / h and the rolling frequencies increase. It is of great importance to know the maximum pressure exerting on the tank wall in the design of the liquid tanks. Thus, the instantaneous peak values in the time histories of the pressure at each transducer have been averaged to obtain the mean maximum pressure according to the height of the perforated plate. Since the transducer of T2 locates near the initial free surface height, the values of pressure are obtained by net liquid impact, resulting in the dynamic pressures. As the rolling amplitude decreases continuously, the maximum pressures decrease. In general, at T1, the static pressure is mainly predominant over the dynamic pressure while the dynamic pressure is mainly predominant over the static pressure at T2.

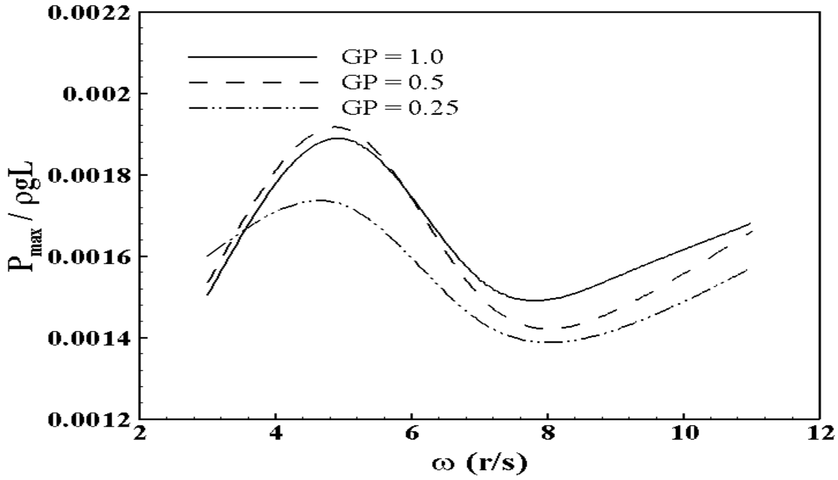

Fig. 10. Maximum pressures at T2. $\theta_0 = 4^0$; h_P / h = 2/3.

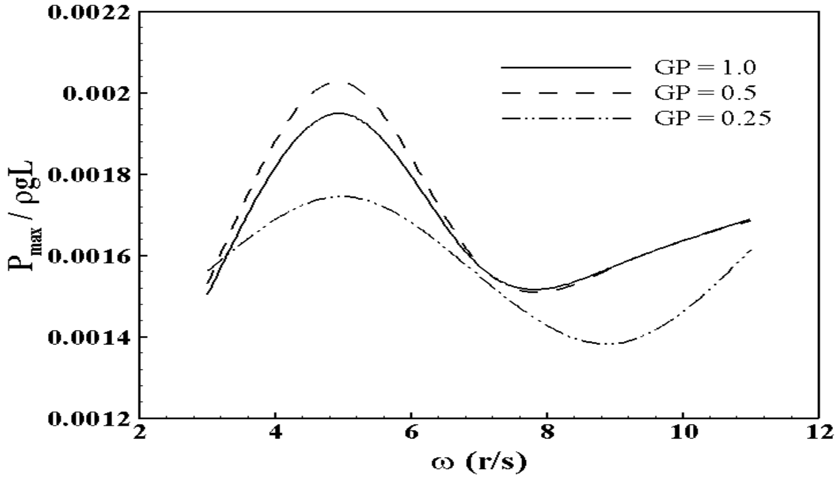

Fig. 11. Maximum pressures at T2. $\theta_0 = 4^0$; h_P / h = 1/2.

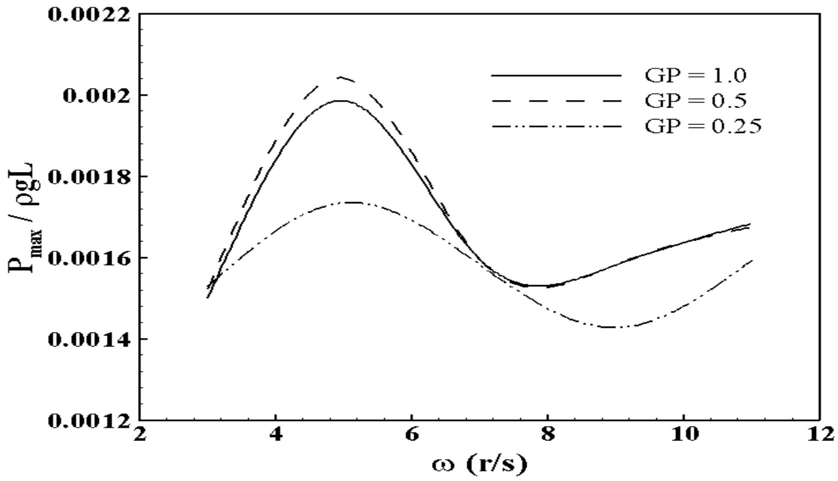

Fig. 12. Maximum pressures at T2. $\theta_0 = 4^0$; $h_P / h = 1/3$.

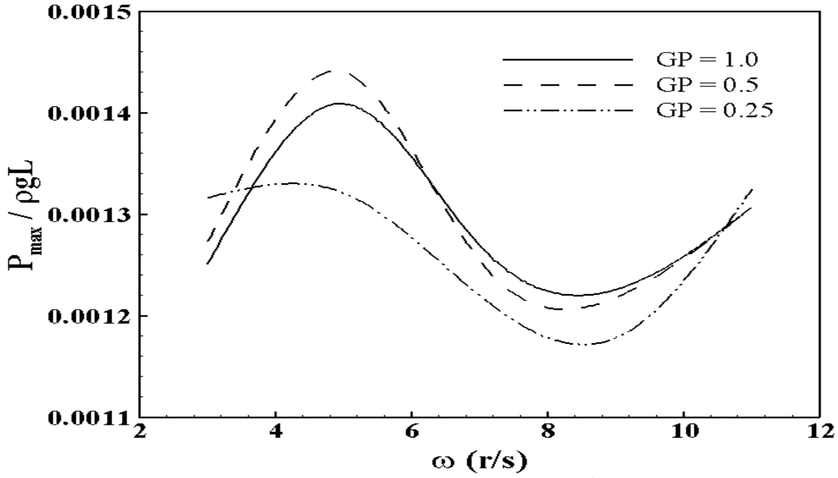

Fig. 13. Maximum pressures at T2. $\theta_0 = 2^0$; $h_P / h = 2/3$.

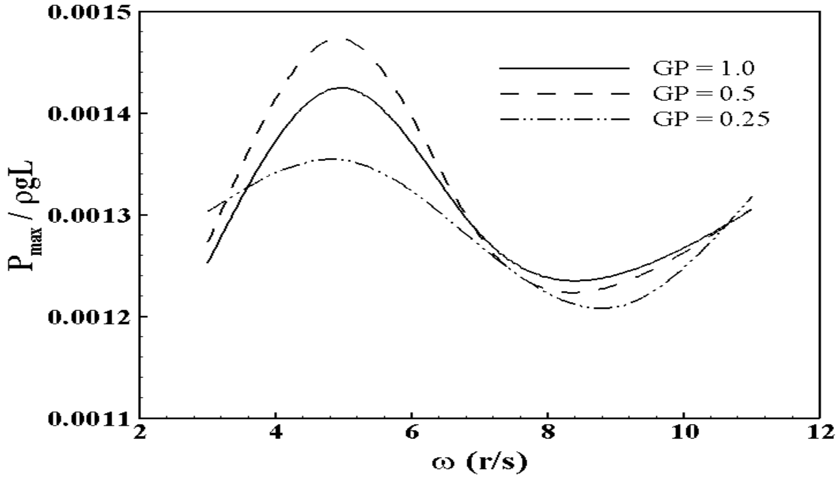

Fig. 14. Maximum pressures at T2. $\theta_0 = 2^0$; $h_P / h = 1/2$.

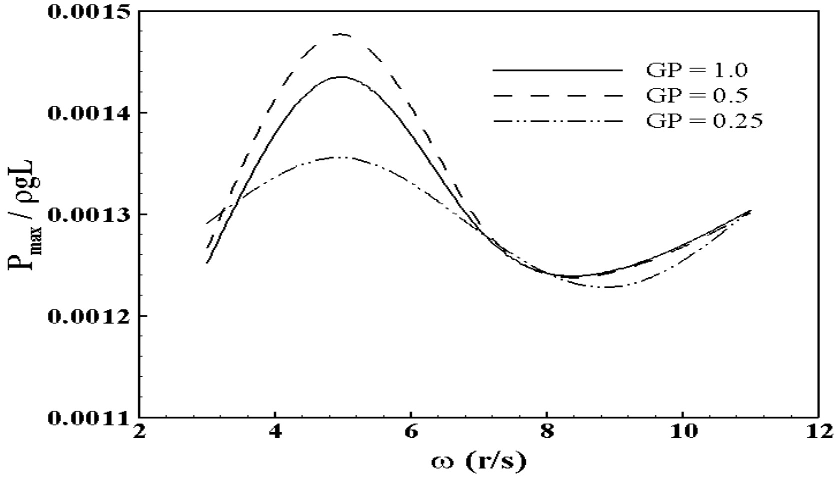

Fig. 15. Maximum pressures at T2. $\theta_0 = 2^0$; $h_P / h = 1/3$.

4. Conclusions

In this study, the effectiveness and characteristics of the tank have been investigated numerically with different horizontal perforated plates under different excitation amplitudes and frequencies in a moving partially filled 2D-ractangular tank. The present study is limited to the frequency prior to the inception of flow perturbations such as turbulence and two-phase flow considering the global sloshing loads. The horizontal perforated plates are useful for restraining violent sloshing effects in a rectangular tank under rolling excitation. The characteristics of the tank with a horizontal perforated plate showed that the natural frequency is more influenced by the plates for first-order mode than the higher-order modes. Thus, the characteristics of this tank system offers a large damping effect to reduce the sloshing loads, ensuring that the tank resonant sloshing could be activated by the natural frequency and dissipate energy significantly.

In the numerical calculations, GP = 0.25 and hp / h = 1/3 are the best choice. Moreover, as a general conclusion, the plates need to be placed under the water surface to ensure proper activity and the better the restraining effect it can offer. The total area of the perforations should be determined by taking into account the strength of the plates in drilling the slots.

The effect on the maximum pressure at the excitation frequencies away from the first-order mode is small. It has an obvious variation of the maximum pressure that is decreased when GP decreases. The maximum pressure, at T1, increases and is greater than the unbaffled tank at the first-order resonance. Furthermore, the maximum pressure, at T2, increases and is greater than the unbaffled tank when hp / h = 1/2 and hp / h = 1/3 especially for GP = 0.5.

The numerical calculations showed that the amplitude of excitation, the intensity of nonlinearity and the sloshing damping influenced the frequency responeses in different ways. But the amplitude of excitation played a much more role in affecting the sloshing motion than the other factors. To be more precisely, the amplitude of excitation influences greatly on the sloshing phenomenon and the maximum pressure by increasing or decreasing the amplitudes of sloshing motion.

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