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A Mesh-Free Particle Based Method to Study the Fluid Flow Characteristics in Tuned Liquid Dampers

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Abstract

Tall structures are built in urban areas to accommodate large number of populations because of land constraint issue. These types of structures are susceptible to strong ground motions of varying frequency contents. Many researchers have developed various mechanisms to minimize the vibration of tall and slender structures subjected to strong ground motions. Tuned liquid damper is one of the passive damping devices attached to the structure to reduce the vibration. Various numerical methods have been developed to analyze the fluid flow behavior inside the tuned liquid damper. The mesh-based methods fail to capture the complex nonlinear fluid flow behaviour inside the damper and the related phenomena. The present study proposes a particle-based method for the analysis of fluid flow behaviour inside the tuned liquid damper. The proposed method is validated with the results of earlier established studies. Results showed that the moving particle semi-implicit method is one of the robust numerical methods used now-a-days to capture the wave breaking phenomenon inside the tank, wave impact on the side walls of the tank and free board in a consistent manner.

Keywords

Mesh-free particle method, strong ground motion, tuned liquid damper, wave breaking phenomena

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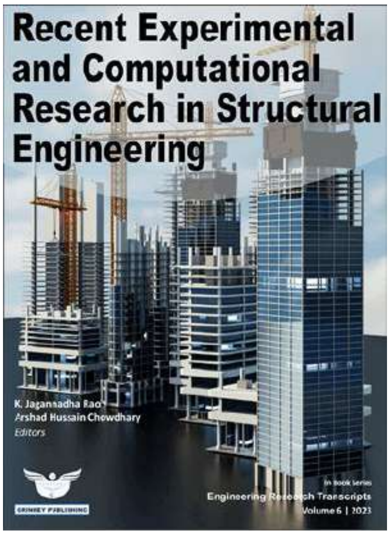


1. Introduction

The construction of tall building structures has developed a growing trend all over the world due to limitation of habitable space. These structures have also become the architectural impression with the advancement in use of light weight and high strength materials. Such kinds of structures are highly flexible and possess very low inherent damping property. Essentially, these two dynamic characteristics such as low stiffness and damping increase the vulnerability of tall structures to external excitations such as wind and earthquakes [1]. Vibrations and other dynamic disturbances during the catastrophic events increase the possibility of complete failure or collapse of the tall structure systems. Hence, the research attention is focused on the use of control systems to prevent the failure of such structures in case of dynamic loading events.

Liquid damper is one kind of the passive control devices which possesses several potential advantages such as low cost, easy installation in existing structures having limited space, non-restriction to unidirectional excitation and minimal maintenance. It is called as tuned liquid damper (TLD) since the fundamental sloshing frequency of the liquid in the container is tuned to the first natural frequency of the primary structure housing the device [2]. It works on the concept of absorbing and dissipating the vibration energy through the sloshing of liquid and free surface wave breaking inside the partially filled container attached rigidly with the primary structure so as to control the structural response in the incident of strong ground motions.

Sloshing is a phenomenon displaying the unrestrained free surface oscillation in partially filled liquid containers. In the field of civil engineering, the problem of liquid slosh dynamics establishes a great importance while studying the influence of strong ground motions. Sloshing induced wave impact force which may cause failure of the complete system. The hydrodynamic forces resulting off sloshing in the event of strong ground motions produce large scale adverse effects on the dynamic behaviour of ground supported and elevated liquid-filled tanks [2, 3]. In this context, it is a major concern to study comprehensively the liquid slosh dynamics in partially filled containers while dealing with the design of liquid container structural systems. The studies non-linear sloshing analysis is limited. It is highly essential to incorporate the nonlinear model in the analysis when the excitation frequency and fundamental frequency of sloshing liquid are very close or the amplitude of excitation is large [4].

The semi-analytical methods remain efficient in analysing slosh dynamics in the event of roof impact but have limitation on studying wave breaking and free-surface fragmentation problems. In order to overcome these difficulties, the present research work proposes a mesh-free particle technique to study the complex violent sloshing phenomena involving wave breaking, wave impact in tanks subjected to external sinusoidal excitation and strong ground motions of varying frequency content.

2. Theoretical formulation

The moving particle semi-implicit (MPS) method was developed to investigate incompressible flow with a free surface [2]. Liquid sloshing in an exciting tank is analyzed in a tank-fixed (non-inertial) coordinate system. The present research uses the Navier-Stokes equation for an incompressible fluid in a non-inertial coordinate system (rigidly fixed with the tank).

2.1 Mathematical formulation

The continuity equation and the Navier-Stokes equation for incompressible viscous flows are as follows [2]:

$$\frac{D\rho}{Dt}=0 \tag{1}$$

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P + \upsilon \nabla^2 \vec{u} + \vec{F} \quad (2)$$

Where,

ρ : constant density

t: time

$\vec{u}$: velocity vector

∇ : gradient

'P' is pressure

υ : kinematic viscosity

$\vec{F}$ is external force.

The continuity equation, i.e. Eq. (1) is written with respect to the density. The left hand side of Navier-stokes equation, i.e. Eq. (2) denotes Lagrangian differentiation including convection terms. This is directly calculated by moving particles in a Lagrangian manner. The right hand side consists of pressure gradient, viscous, and external force term.

2.2 Modifications over original MPS

The original MPS method involves large-scale pressure fluctuation in spatial and time domain. Such numerical oscillation of pressure results in predicting the unreal behaviour of the associated physical parameters [5]. Hence, it is essential to eliminate such pressure oscillation to simulate the free surface flow problems precisely. The present numerical model implements five modifications to the original MPS method [6]. The suggested alterations are enlisted as follows.

2.3 Modified Poisson's pressure equation

The addition of both the coefficients used in modified PPE is taken to be unity.

$$\nabla^2 P_i^{n+1} = \alpha_1 \frac{\rho}{\Delta t}\nabla \cdot u^* - \alpha_2 \frac{\rho}{\Delta t^2}\frac{n_i^* - n^0}{n^0} \quad (3)$$

Identification of free-surface particles

Free-surface particles are recognized by using the conditions proposed in modifications.

$$N_i < \beta' N^0 \quad (4)$$

β' is a free-surface parameter selected amid 0.80 and 0.99.

2.4 Structure-TLD interaction model

A multi-storey shear building attached with a TLD atop is considered in this study. The dynamic analysis of the building structure under horizontal ground motion is carried out. The mass ratio of the TLD is considered as follows.

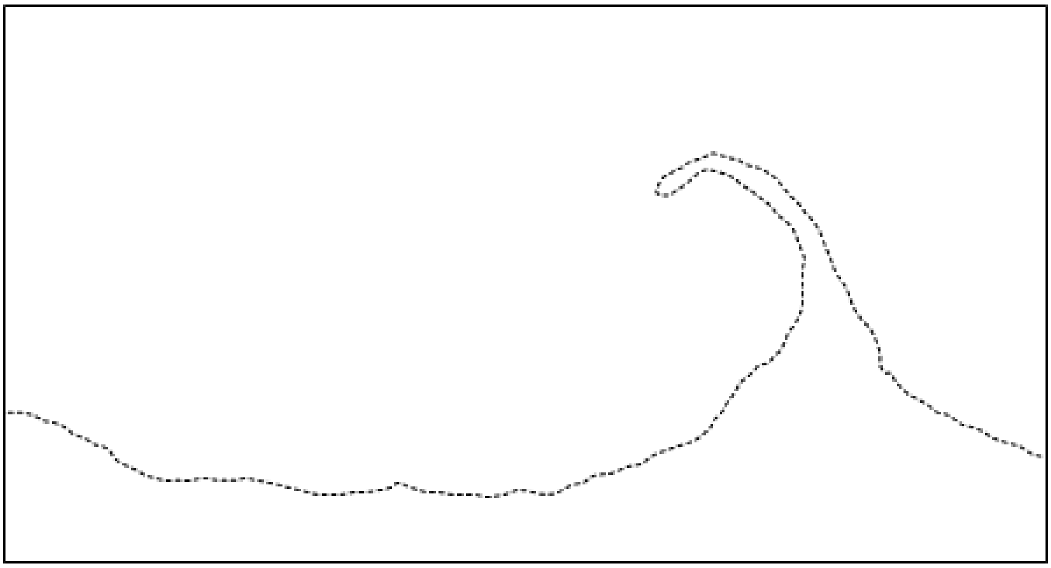
$$\text{Mass ratio of the TLD } (\mu) = \frac{\text{Mass of water in TLD}}{\text{Mass of the structure}}$$

In the present study, one (01) number of tuned liquid damper (TLD) is located at the top of the 10-storey building.

3. Results and discussion

3.1 Validation test

The developed model is validated with experimental results published in previous research work [7-9]. The free surface profile at the instance of 4.64s in the liquid tank is captured by using present model. The results obtained by present model appears similar to the publishd one.



(a)

(b)

Fig.1. Fluid flow patterns at the instance of 4.64s in the liquid tank (a) Experiment (b) Present model

The validation test result of the proposed model is compared with the previously published result. The free surface profile at a particular instant (4.64s) during sloshing motion is captured using the proposed model. The present result is observed to be similar in all aspects with the previously published result. This demonstrates the robustness of the model in simulating the violent sloshing motion in the liquid filled tanks during vibrant external excitations.

3.2 Numerical test

A 10-storey shear building representing a multi degree of freedom structure is considered in this study. The structure is rigidly attached with a TLD. The first natural frequency of the structure is computed as 1.0Hz. The structure-TLD coupled system is subjected to horizontal sinusoidal ground motion. The mass ratio (μ) = 1% is considered in this study. Length of the tank = 0.41m; Depth of liquid = 0.08m; Height of the tank = 0.17m.

3.3 Evaluation of dynamic characteristics of TLD

The dynamic characteristics arising out of the sloshing phenomenon in TLD are manifested as wave elevation, fluid flow pattern in the TLD. The evaluation of free-surface wave in the TLD is of primary interest when its value exceeds the available free board under large structural vibration. The maximum sloshing wave elevations in the TLD container need to be evaluated to ascertain wave impact phenomenon on the tank ceiling. The time-based free-surface wave elevation in the TLD vessel is simulated and shown in the Fig. 2.

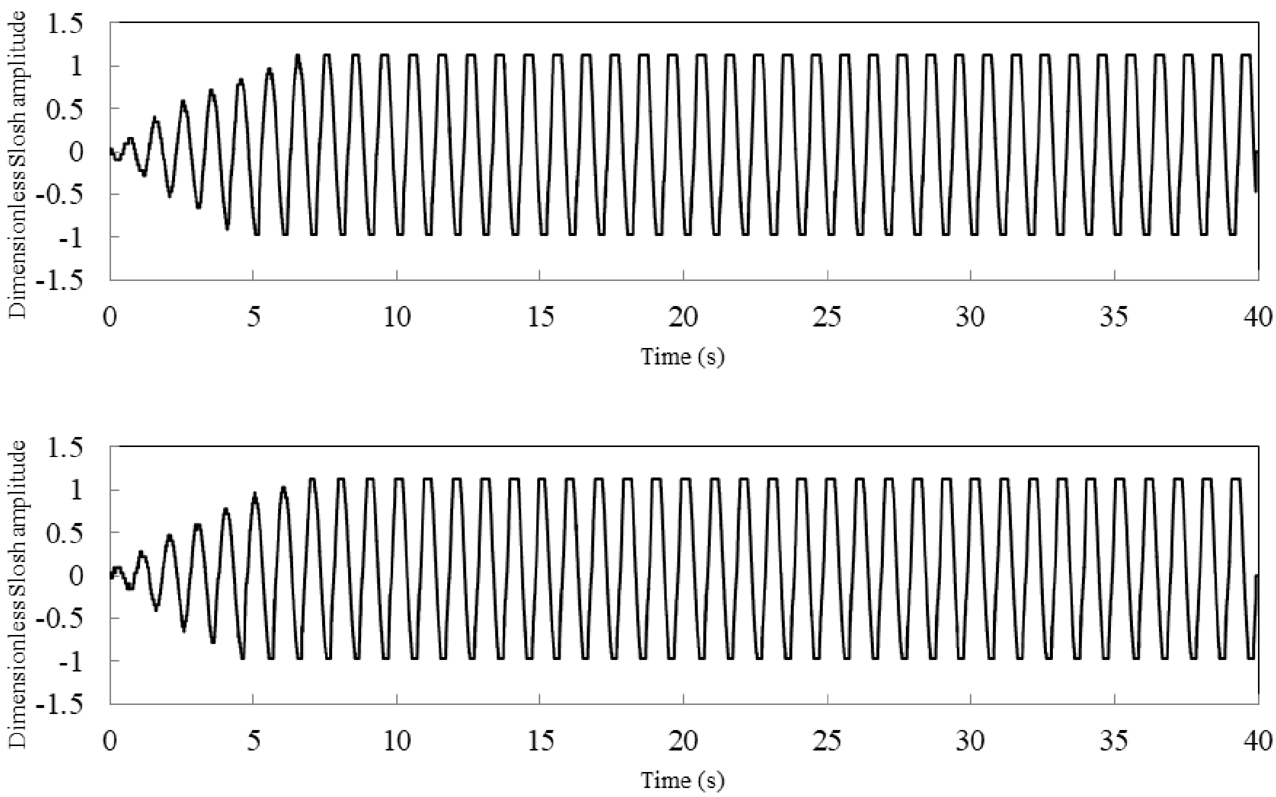


Fig. 2. Time histories of free-surface wave elevation in the TLD container for mass ratio (μ) = 1% (i) At left side wall (ii) At right side wall

The liquid flow patterns were captured through the sloshing motion and the growth of velocity field of fluid particles in the TLD are drawn for a particular cycle of sloshing motion. The wave striking in the left side ceiling as well as right side ceiling of the tank are captured at time instants 10s and 10.5s and presented in Fig. 3.

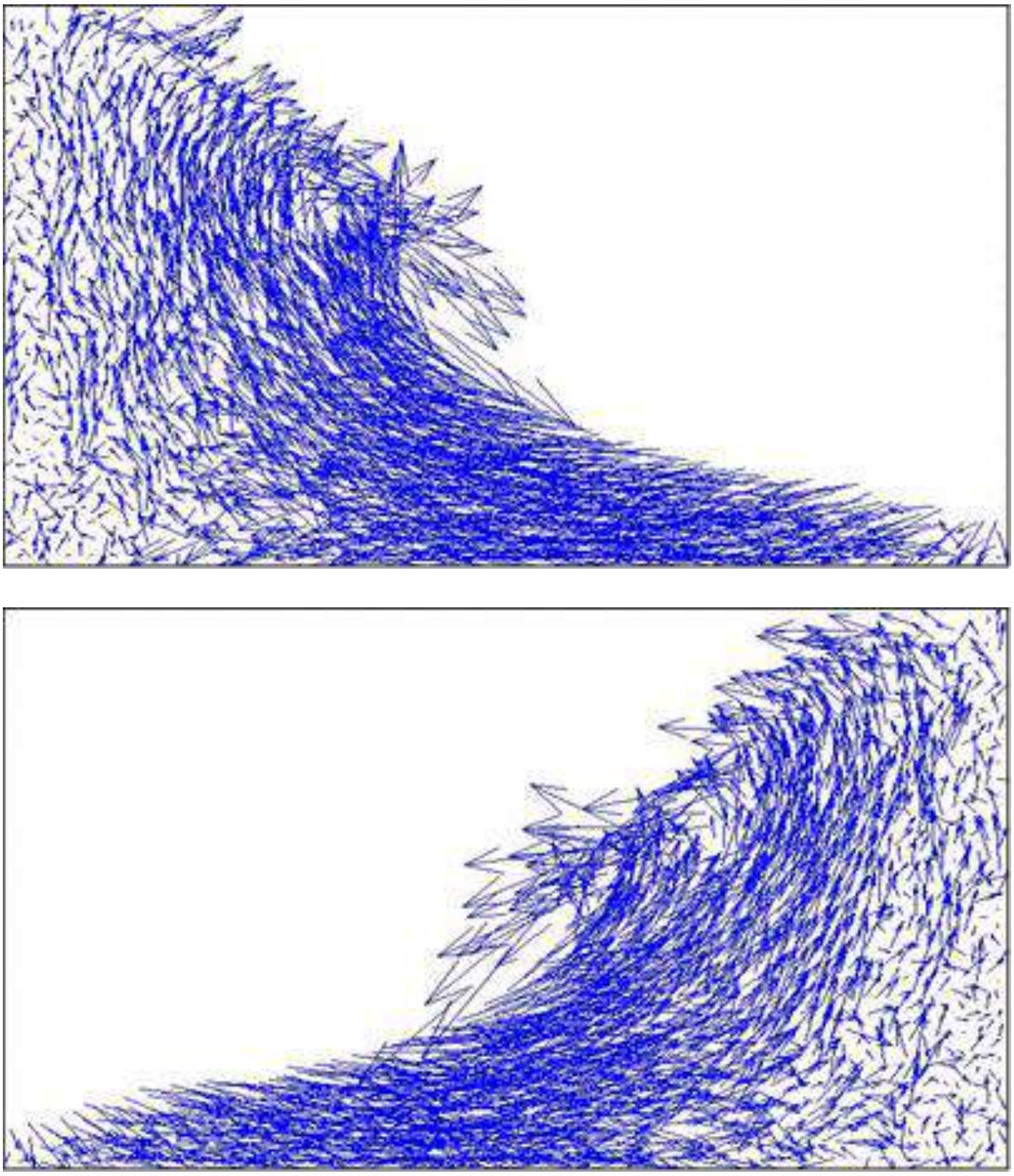


Fig. 3. Velocity field plots of fluid particles inside TLD at 10s and 10.5s

The pressure contour in the left side wall as well as on the right side of the tank wall are computed at time instants 10s and 10.5s and presented in Fig. 4. The x-axis (horizontal axis) represents the length of the tank. The base shear produced due to sloshing in the tank is calculated from the pressure developed at the vertical side walls of the tank. This base shear is utilized in counteracting the force causing the deflection of the structure.

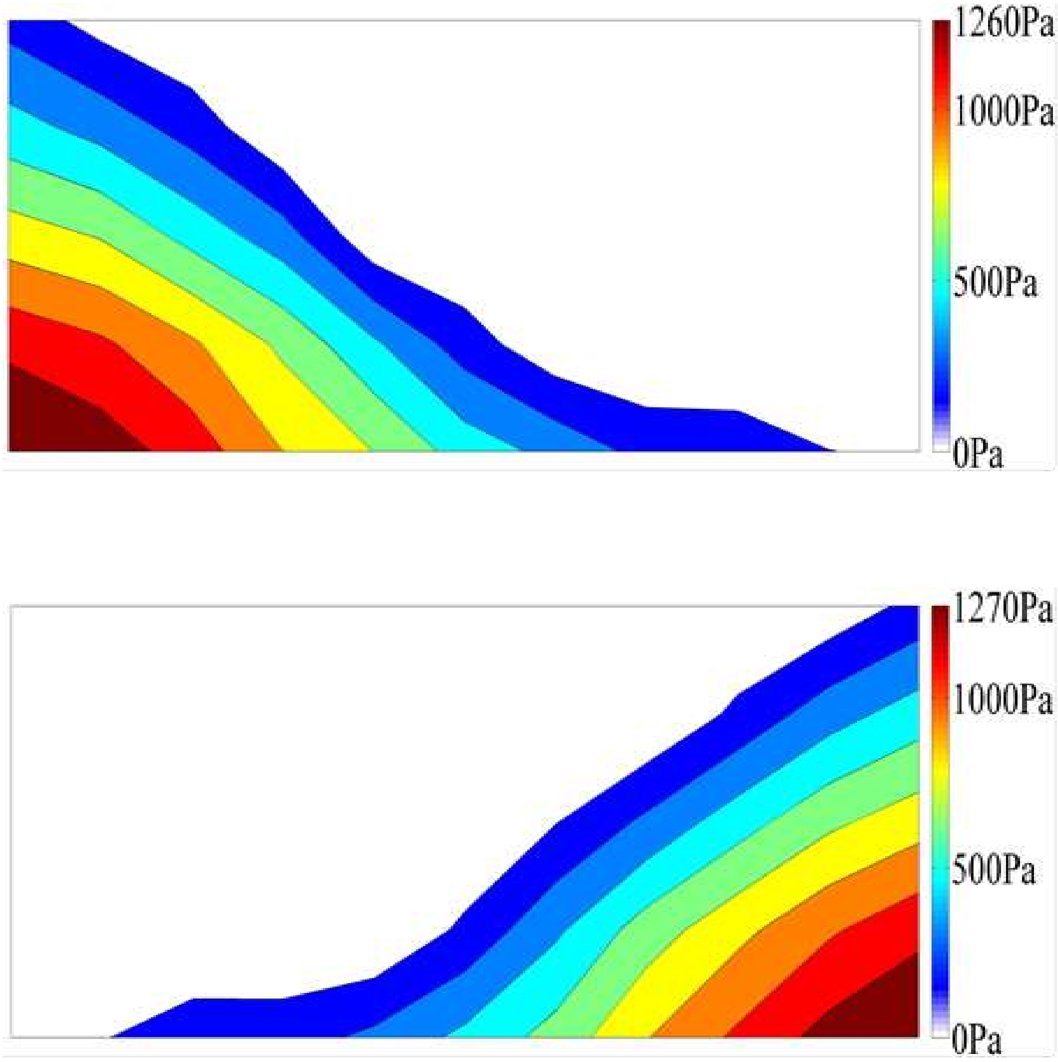


Fig. 4. Pressure contour in the fluid domain inside the TLD at 10s and 10.5s

The result of the present study contains free surface wave elevation, the liquid flow pattern and the pressure contour inside the tuned liquid damper during the external excitation. The external excitation is of sinusoidal in nature and the time period of external excitation is 1sec and the present results demonstrate all the three features such as free surface wave elevation, the liquid flow pattern and the pressure contour inside the TLD precisely at two-time instants. These two-time instants represent the beginning and midway of one cycle of motion. The results preferably represent the flow behaviour of liquid arising out of sloshing in both the left and right side of the container at regular time intervals. This trend of results confirms the consistency of the proposed structure-interaction model.

4. Conclusion

An integrated structure-TLD interaction model comprising of a MPS based model is used to simulate the violent sloshing motion inside the TLD container. The model is applied to a ten-storey shear building supporting a TLD subjected to a sinusoidal ground excitation. The fluid flow dynamics in the TLD considering the structure-TLD interaction effects are determined for a specific cycle of motion. A relatively lower mass ratio for the TLD is considered and violent sloshing with wave breaking phenomenon is observed and captured. The present model is found to be an efficient numerical tool in investigating the complex flow dynamics in the TLD.

References

[1] P. Banerji, M. Murudi, A. H. Shah, N. Popplewell, Tuned liquid dampers for controlling earthquake response of structures, Earthquake Engineering and Structural Dynamics. 29 (2000) 587-602. https://doi.org/10.1002/eqe.129.

[2] S. Koshizuka, A. Nobe, Y. Oka, Numerical analysis of breaking waves using the moving particle semi-implicit method, International Journal for Numerical Methods in Fluids. 26 (1998) 751-769. https://doi.org/10.1002/(SICI)1097-0363(19980415)26:7<751::AID-FLD671>3.0.CO;2-C.

[3] K. P. McNamara, B. N. Awad, M. J. Tait, J. S. Love, Incompressible smoothed particle hydrodynamics model of a rectangular tuned liquid damper containing screens, Journal of Fluids and Structures. 103 (2021) 103295. https://doi.org/10.1016/j.jfluidstructs.2021.103295.

[4] B. H. Lee, J. C. Park, M. H. Kim, S. C. Hwang, Step-by-step improvement of MPS method in simulating violent free-surface motions and impact-loads, Computer Methods in Applied Mechanics and Engineering. 200 (2011) 1113-1125. https://doi.org/10.1016/j.cma.2010.12.001.

[5] M. Tanaka, T. Masunaga, Stabilization and smoothing of pressure in MPS method by quasi-compressibility, Journal of Computational Physics. 229 (2010) 4279-4290. https://doi.org/10.1016/j.jcp.2010.02.011.

[6] A. Ashasi-Sorkhabi, H. Malekghasemi, A. Ghaemmaghami, O. Mercan, Experimental investigations of tuned liquid damper-structure interactions in resonance considering multiple parameters, Journal of Sound and Vibration. 388 (2017) 141-153. https://doi.org/10.1016/j.jsv.2016.10.036.

[7] A. H. Kashani, A. M. Halabian, K. Asghari, A numerical study of tuned liquid damper based on incompressible SPH method combined with TMD analogy, Journal of Fluids and Structures. 82 (2018) 394-411. https://doi.org/10.1016/j.jfluidstructs.2018.07.013.

[8] C. H. Hu, M. Kashiwagi, Z. R. Kishev, Numerical simulation of violent sloshing by CIP method, In Proc. of the 19^{th} IWWWFB, Cotona, Italy, 2004.

[9] Z. R. Kishev, C. H. Hu, M. Kashiwagi, Numerical Simulation of Violent Sloshing By CIP Method With Experimental Validation, In: Proceedings of the Fifteenth International Offshore and Polar Engineering Conference, Seoul, Korea, 2005.