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A COUPLED ANALYSIS OF SLOSHING IN FLOATING STRUCTURES BY INTEGRATING MOVING PARTICLE SEMI-IMPLICIT (MPS) METHOD WITH A TIME DOMAIN MULTIBODY DYNAMIC ANALYSIS SOFTWARE

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Abstract. Sloshing effects inside partially filled tanks on LNG carriers and FPSOs motions cannot be ignored. It is necessary to analyze the floating structures motion with the sloshing behavior simultaneously to obtain more accurate stability predictions because the phenomenon may affect the safety and the operability of the vessels in seaways and during loading and offloading process. In the present study, in order to model the coupled effects of platforms motion in waves and the liquid sloshing inside its tank, a hybrid time-domain simulation approach based on the integration of two simulators is proposed. The Numerical Offshore Tank (TPN) simulator, which is a time domain multibody dynamic analysis software, is used for the simulation of open domain hydrodynamic forces. It is able to perform calculations of coupled floating structures motion with the dynamic of mooring and connection lines and risers considering environmental condition such as wave, current and wind. In the other hand, due to the highly nonlinear aspect of the sloshing phenomenon, the Moving Particle Semi-implicit (MPS) method, which demands huge computing resources and it is more suitable to confined domain problems, is used to simulate the sloshing motion and to calculate the loads on the tank walls. The effects due to sloshing is then feed-backed to the TPN simulator as additional force and moment to solve the motion equation of the floating structure. The calculation can be distributed in

a PCs cluster and each sloshing tank is solved in a different node. In this way, it allows the calculation of many tanks without increasing the computational time. Simulations were carried out with and without considering the coupled sloshing motions, and the results were compared to assess the effects of the liquid cargo sloshing on the motion of the floating structure.

1 INTRODUCTION

Liquid sloshing is the violent fluid motion inside partially filled tanks. It is observed and studied in different engineering fields such as storage tanks or containers in trucks, airplanes and ships, missiles and space vehicles. The sloshing hydrodynamic forces and moments may cause damage on the tanks structure or affect the motion of the vehicle, particularly, in the resonance frequency vicinity. There are many studies about sloshing using analytical [1, 2], experimental[3, 4] or numerical[5, 6, 7] approaches.

Recently, concerns about sloshing effects on safety of the Liquid Natural Gas (LNG) carriers increased and recent experimental and numerical studies have shown that significant liquid sloshing loads occurs on these floating bodies [8, 9, 10].

In this study, a multibody time domain simulator, developed to simulate the dynamics behavior of offshore structure such as offshore platforms and its mooring lines and risers, is integrated to a particle based method called Moving Particle Semi-implicit (MPS) method to perform simulation of the sloshing coupled to the ship motion. The integration of the two simulators provided a computational system that is able to predict more precisely the motion of moored floating bodies when sloshing loads are not neglectable. While most of the approaches for sloshing analyzes in the earlier studies were simple linear or weakly non-linear ones, this coupling process is taking advantage of the MPS method capability to analyze linear and non-linear aspects of the sloshing behavior.

Results of a study case is presented showing the dynamics of a floating body interacting to the sloshing in tanks.

2 Numerical Offshore Tank (TPN) SIMULATOR

The Numerical Offshore Tank TPN [11] is a time-domain simulator that aggregates methods and algorithms in a single tool to analyze offshore systems dynamics. This simulator was developed by a research group composed by five different institutions and the Brazilian oil & gas company PETROBRAS. It is able to simulate dynamics of floating units connected to mooring lines and risers under environmental conditions of wave, current and wind.

The main components of offshore systems can be modeled and analyzed by the TPN simulator. The floating units motion are calculated considering forces of waves, currents, winds and connected lines and solving its motion equation considering six degree of freedom as shown in Eq. 1.

$$M\ddot{x} = F_{ext} \tag{1}$$

Where M is the mass matrix of the body (6×6), $\ddot{x}$ is the acceleration of the body considering 6 degrees of freedom and F_{ext} is the summation of the external forces acting on the center of gravity in six dimensions (6×1). Waves forces are preprocessed by the software WAMIT [12], which is based on Boundary Integral Equation method (BIEM), also known as Panel Method, to obtain the first and second order wave radiation and diffreaction forces. This software also calculates added mass, potential damping, wave first and second order exciting forces to generates memory funtion and impulse response function to be used in in Eq. 1. The current loads can be calculated by cross flow based model, low speed maneuvering model or short wing model [13, 14, 15, 16]. Empirical formula is applied to calculate wind forces. The TPN simulator also considers effects of the interaction between wave and current [17, 18, 19, 20, 21], mooring and riser lines damping [22, 23] and dynamic positioning.

3 MOVING PARTCILE SIMULATION (MPS)

The Moving Particle Semi-implicit (MPS)[24, 25] is a computational fluid dynamics method developed to simulate incompressible flow. It is a Lagrangian meshless method that discretizes the space domain in particles. For the fluid domain, the governing equations are the continuity equation and the momentum equation:

$$\frac{D\rho}{Dt} = -\rho\left(\nabla \cdot \vec{u}\right) = 0 \tag{2}$$

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{u} + \vec{f} \tag{3}$$

In MPS, all operators are derived by particle interaction models based on a weight function that depends on the relative positions between particles. The weight function is given by:

$$w\left(r\right) = \begin{cases} \frac{r_e}{r} - 1, \left(r < r_e\right) \\ 0, \left(r < r_e\right) \end{cases} \tag{4}$$

where r is the distance between two particles and r_e is the effective radius, which limits the region where the interaction between particles occurs.

For a scalar function ϕ, the gradient vector and the Laplacian of a particle i, considering the neighboring particles j, can be represented by:

$$\left\langle \nabla\phi \right\rangle_i = \frac{D}{pnd^0}\sum_{i \neq j}\frac{\left(\phi_j - \phi_i\right)}{\left|\vec{r}_j - \vec{r}_i\right|^2}\left(\vec{r}_j - \vec{r}_i\right) w\left(\left|\vec{r}_j - \vec{r}_i\right|\right) \tag{5}$$

and

$$\left\langle \nabla^2 \phi \right\rangle_i = \frac{2D}{pnd^0 \lambda} \sum_{i \neq j} \left(\phi_j - \phi_i \right) w \left(\left| \vec{r}_j - \vec{r}_i \right| \right) \tag{6}$$

where D is the number of spatial dimensions and λ is given by:

$$\lambda = \frac{\sum_{j \neq i} \left| \vec{r}_j - \vec{r}_i \right|^2 w \left(\left| \vec{r}_j - \vec{r}_i \right| \right)}{\sum_{j \neq i} w \left(\left| \vec{r}_j - \vec{r}_i \right| \right)} \tag{7}$$

and pnd^0 is the initial value of the particle number density, which is denoted as pnd is given by:

$$pnd = \sum_{j \neq i} w \left(\left| \vec{r}_j - \vec{r}_i \right| \right) \tag{8}$$

The MPS method uses a semi-implicit algorithm. The diffusion and body force terms on the right side of the Navier-Stokes equation are calculated explicitly at instant t to obtain the estimates for the velocities and positions and pnd of the fluid particles. Poisson's equation of pressure is solved implicitly at $(t + \Delta t)$. This Poisson's equation can be deducted from the continuity equation and the pressure gradient:

$$\left\langle \nabla^2 \phi \right\rangle_i^{t+\Delta t} = -\frac{\rho}{\Delta t^2} \frac{pnd_i^* - pnd^0}{pnd^0} \tag{9}$$

where pnd^* is the particle number density calculated explicitly. The left side of Eq. 9 is the Laplacian model shown in Eq. 6 and forms a system of linear equations. By using the particle number density as a parameter, particles are considered as free surface when their pnd is smaller than $\left(\beta \cdot pnd^0 \right)$, where β may vary between 0.80 and 0.99 [25].

As dynamic boundary condition of the free surface, the pressure of all free surface particles is set to zero. For cases analyzed herein, r_e is set to $2.1 l_0$ to calculate pressure gradient, the particle number density and Laplacian operator, where l_0 is the initial distance between particles.

In the literature, there are studies validating the MPS method comparing pressure variation measured on sensors positioned at the tank structure caused by sloshing induced by horizontal motion of tanks[26, 27].

4 TPN-MPS COUPLING SCHEME

The main program that controls the main inputs and output and distributes the processes to the computer cluster nodes is the TPN software. In the initialization process, the main program is responsible to start the MPS module and to communicate the input data.

TPN software distributes its processes to solve problems using PCs clusters? The lines dynamics calculated by a Finite Element Method and the sloshing dynamics calculated by the MPS method are the processes that consumes resources the most. Due to this fact, each line and sloshing tank dynamic is calculated in a different process. The processes are distributed to the cluster nodes using a standardized and portable message-passing system called MPI [28] and each sloshing process is parallelized using the node cores based on OpenMP [29], an API that supports multi-platform shared memory multiprocessing programming.

After the initializations, for every calculation time step, the TPN provides the sloshing tanks positions, velocities and accelerations. As the MPS program usually adopts much more smaller time steps when compared to the the TPN's, a sub-cycling strategy is employed in the coupling between TPN and MPS programs: the MPS program considers interpolated motion of the tank provided by TPN. After the MPS calculates the fluid motion, it sends back to the TPN program the information of forces and moments obtained by integrating the pressure on the tanks particles. Figure 1 illustrates how the integrated program distributes the the processes and the data exchanged among the processes.

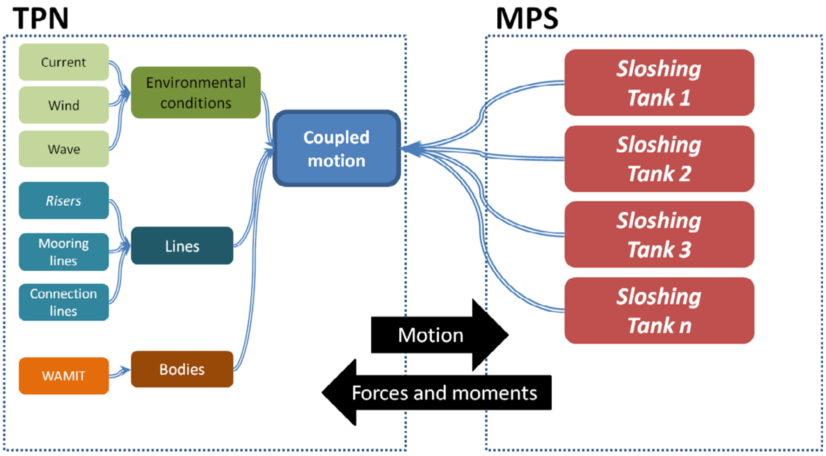

Figure 1: TPN-MPS integrated program scheme and data exchanged.

5 CASE OF STUDY

In order to verify the TPN-MPS integration, a model with two cases were chosen keeping in mind the sloshing induced by the FPSO motion and the effects of the sloshing load on the body motion.

5.1 Model description and simulation conditions

A FPSO with eight tanks partially filled or empty was chosen as the test cases to analyze the coupling between TPN and MPS simulators. The platform has length of $464m$, beam of $71m$, height of $30m$, and the tanks have length of $108m$, width of $33m$, height of $25m$ as described in Fig. 2. The FPSO is moored using a turret configuration concentrating all the lines are connected on a structure positioned at its bow making the floating platform rotates around this structure freely. Initially, the FPSO is heading to 0°.

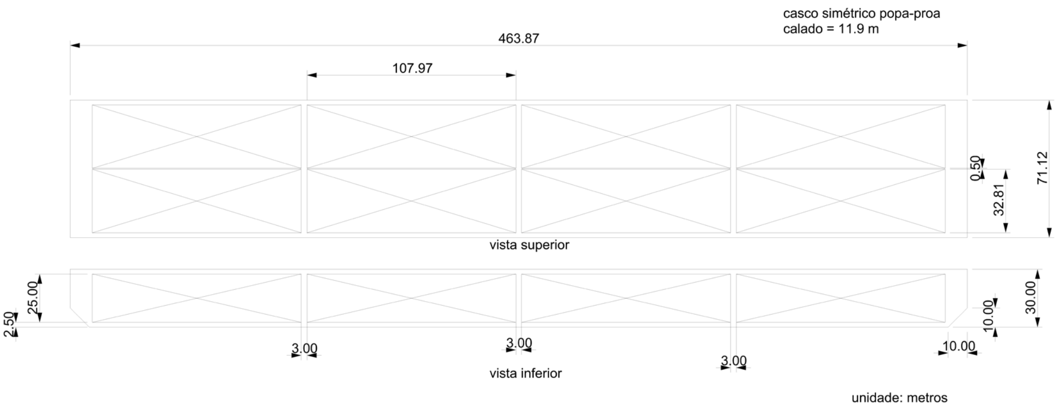

Figure 2: Study case vessel dimensions.

Tanks positions and filling ratios are specified in Tab. 1. The tanks numbered as 1 and 2 are the closest to the bow of the FPSO and tanks number 7 and 8 are the closest to stern of the platform. Odd numbered tanks are positioned on the starboard and even numbered ones are positioned on the port side. The origin of the coordinate system is positioned on the keel in the mid section of the platform and x axis is the longitudinal axis pointing ahead, z axis is the vertical axis point downwards and y axis respect the right handed frame.

Table 1: Tanks positions and filling ratios.

Tank	Position (m, m, m)	Filling Ratio
1	$(166.5, 16.7, 2.5)$	24%
2	(166.5, -16.7, 2.5)	16%
3	(55.5, 16.7, 2.5)	0%
4	(55.5, -16.7, 2.5)	24%
5	(-55.5, 16.7, 2.5)	24%
6	(-55.5, -16.7, 2.5)	0%
7	(-166.5, 16.7, 2.5)	16%
8	(-166.5, -16.7, 2.5)	24%

The simulations were carried out using time step of $0.25s$ and considering irregular wave using a JONSWAP spectra with significant height of $8.0m$, period of $13.0s$, heading from $-60°$, γ of 1.826 and α of 0.009. The wind is heading to $-180°$ with velocity of $35.0m/s$. The current is heading to 180° with top velocity of $3.5m/s$.

The specific mass of the liquid cargo is $476kg/m^3$. The simulations of sloshing using MPS were carried out using time step of $0.01s$ and average distance between particles of $1.0m$.

5.2 Results and analysis

Two cases were simulated using the model and the environmental conditions described in the previous section. The first case was carried out with the TPN software without the MPS integration. Each tank liquid was considered as concentrated mass positioned at the gravity center of each volume. This setup can simulate the FPSO motion without the sloshing effects. The second case was carried out with the MPS integrated to the TPN simulator with the same condition of the first one but the sloshing effect was taken into account.

Figure 3 shows a sequence of images taken from the simulation of the second case when coupled sloshing and the FPSO motions are simulated. This sequence of images was chosen to show sloshing being induced by the body motion. The vessel is represented by a bounding box and the particles representing the tanks structure are not shown. Voids are observed in tanks 3 and 6 because there are empty tanks at these positions. In the Fig. 3, from the observer point of view, the bow is the nearest part of the vessel.

The sloshing induced by the body motion can be observed in Fig. 3 and its effects on the body roll motion is showed in Figs. 4 and 5 and two different time ranges: $800s$ to $1300s$ and $1500s$ to $2000s$. These two samples represent the behaviors observed in all the time history of the roll motion.

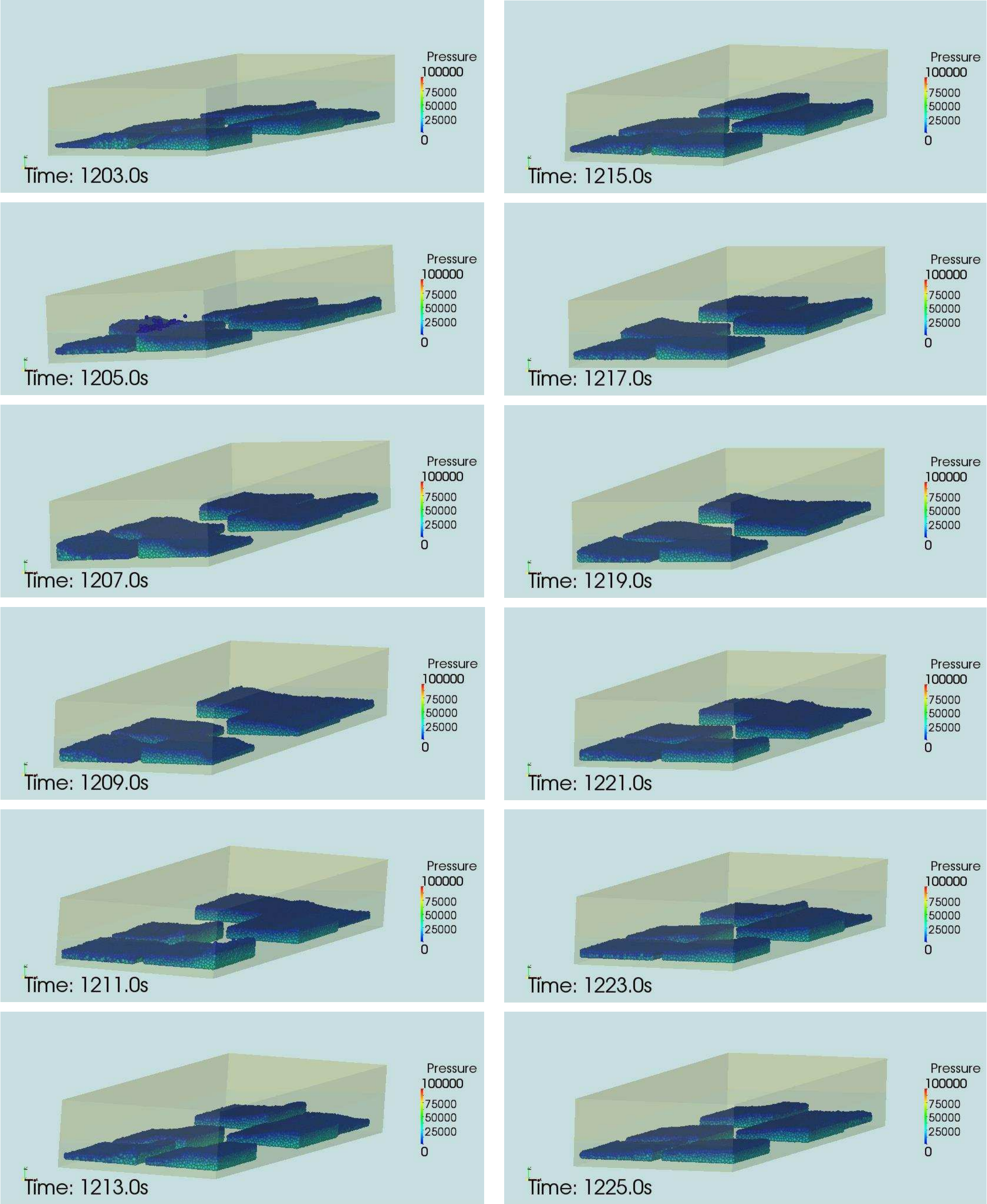

Figure 3: Simulation results obtained by the MPS software integrated to the TPN simulator showing the liquid cargo interacting with the FPSO motion.

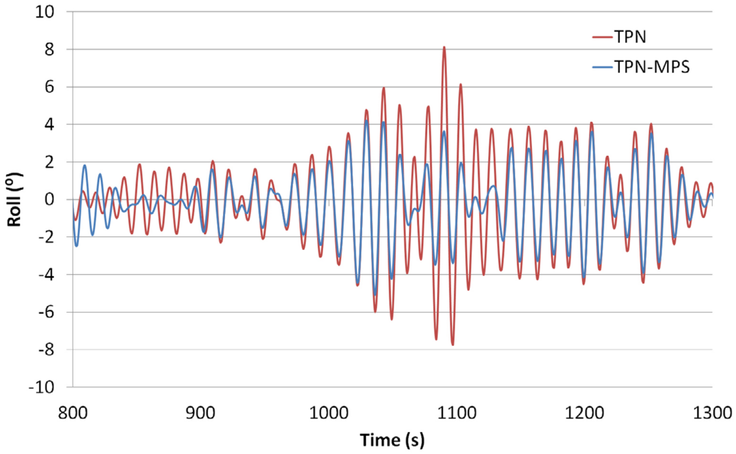

Figure 4: Roll motion of the main vessel time history calculated with and without considering sloshing effect between 800s and 1200s.

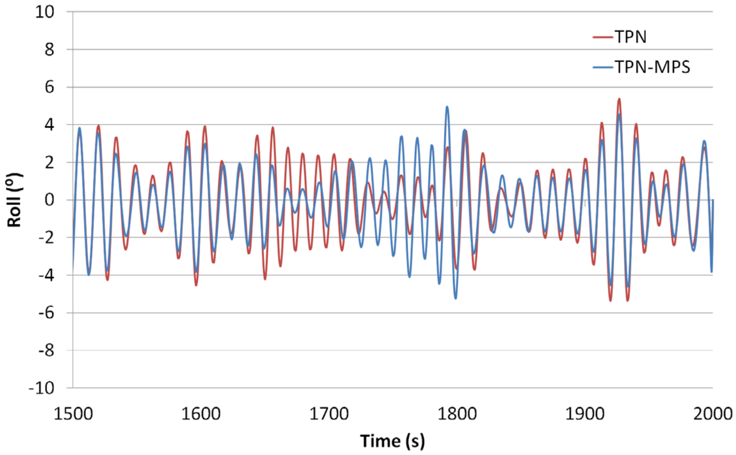

Figure 5: Roll motion of the main vessel time history calculated with and without considering sloshing effect between 1500s and 2000s.

These graphics show the roll motion time history running the TPN considering only the liquid mass and the TPN coupled to the MPS considering sloshing loads. These two time windows shows two distinct behavior of this TPN-MPS integration. When considering the sloshing on the vessel motion compared to the results without the integration, the amplitude of the roll motion is smaller because of the sloshing consideration at most of the simulation time as shown in Fig. 4. However, there are situations that the sloshing loads amplifies the roll motion. This can be observed in the roll motion time history between 1720s and 1800s as shown in Fig. 5 when there a synchronization of the phases between the sloshing loads and the body motion. The large difference between these two cases between $830s$ and $900s$ and between $1050s$ and $1120s$ showed in Fig. 4 occurs when there are high sloshing wave amplitude before these intervals followed by the inversion of the phases between the sloshing loads and the body motion.

6 CONCLUSIONS

In the present paper, the MPS based simulator was integrated to the TPN simulator to analyze the behavior of platforms when considering the sloshing in large liquid tanks. By adopting an architecture in which the MPS runs as a module for sloshing simulation, the integrate system is able to perform a parallel computing with several tanks simultaneously.

As an example of the application of the integrated simulator, the results of the study case showed that the sloshing loads can affect the motion of the vessel and it cannot be neglected.

In the next steps, the TPN-MPS coupled software will be validated with physical experiments.

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