Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering
OMAE2008
June 15-20, 2008, Estoril, Portugal

OMAE2008-57460

Validation Study of MPS (Moving Particle Semi-implicit Method) for Sloshing & Damage Stability Analysis

GUILHERME E. RUEDA [1]
(guilherme@tpn.usp.br)

MÁRCIO MICHIHARU TSUKAMOTO [1]
(michiharu@tpn.usp.br)

HIGOR F. MEDEIROS [1]
(higorfm@gmail.com)

CHENG LIANG YEE [2] PCC
(cheng.yee@poli.usp.br)

KAZUO NISHIMOTO [1]
(knishimo@usp.br)

[1]Department of Naval Architecture and Ocean Engineering
University of São Paulo
São Paulo, SP, Brazil

[2] Department od Civil Construction Enginnering
University of São Paulo
São Paulo, SP, Brazil

ABSTRACT

The aim of this paper is to present validation studies of a CFD code based on MPS (Moving Particle Semi-implicit Method). In MPS method the fluid is represented by particles, and the particle interactions are governed by continuity and Navier-Stokes equations. It is a meshless method to simulate incompressible flow and it is able to simulate large surface distortion, fluid fragmentation and non-linear dynamics.

For the validation studies, two cases with complex hydrodynamic phenomena were selected for experimental measurements in towing tank. The first one is the dynamics of a floating body in waves with an internal tank partial filled with water. In this way sloshing effects on the motion of the model can be evaluated. Usually, dynamics of the floating body and sloshing are calculated separately, by neglecting their coupling effects; the body's motion is determined without sloshing and that motion is used to excite the liquid tank. Since the sloshing generates forces and moments, which may change the movement of the hull, sloshing forces and moments may act as a roll absorption device or can enlarger it. In MPS this coupled phenomena can be easily simulated, just by using particles representing water of the internal tank, water of the towing tank and structural particles representing the hull, the walls and the wave maker.

The second phenomenon is the motions of a damaged hull from the moment soon after suffering damage until reaches the equilibrium position. This is an initial step of a validation study of the motion of a damage hull in waves, which will be compared with physical experiments.

The comparisons between the numerical results obtained by the MPS with the experimental and theoretical ones show very good agreement, reinforcing the potential of MPS.

KEYWORDS:

MPS, sloshing, damage stability, particle method

INTRODUCTION

MPS (Moving Particle Semi-implicit Method), developed by Koshizuka [1] is meshless lagrangean method to simulate incompressible flow. It is able to simulate large surface distortion, fluid fragmentation and non-linear dynamics easier than other traditional CFD methods that uses grid.

There are also several studies of dynamics of floating body motions in waves performed by Naito and Sueyoshi [2] and [3] using the MPS. The study showed that, although the computational time is quite large, the results presented by MPS explained well the hydrodynamic phenomena.

The TPN lab group of USP has been evaluating the MPS and implemented in the large computer cluster system that allows to perform several huge offshore dynamic systems coupling floating body motions, mooring line system, riser system, [4] , and now sloshing effect performed by MPS and Finite Difference Method.

In the present paper, MPS method is extended and applied to the study of two complex hydrodynamic phenomena. The first one is the dynamics of a floating body in waves with an internal tank partial filled with water. In this way sloshing effects on the motion of the model were evaluated. The second phenomenon is the motion of a floating hull after suffering structural damage until reaches the equilibrium position.

MPS FOR FLOATING BODY DYNAMICS WITH SLOSHING PHENOMENA

The governing equations of incompressible flows are mass conservation equation and Navier-Stokes equation.

$$\frac{D\rho}{Dt} = -\rho(\nabla \cdot \vec{u}) = 0 \qquad (1)$$

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

In MPS, all the operators are evaluated by numeric models based on interaction between particles that is determined by the kernel function:

$$w(r) = \begin{cases} \frac{r_e}{r} - 1 & r < r_e \\ 0 & r \geq r_e \end{cases} \qquad (3)$$

where, r is the distance between particles and r_e is the radius that limits the neighborhood.

The particle number density (*pnd*) is the normalization value of the weights and it is proportional to the density that is used to guarantee the incompressibility condition.

The MPS method uses a semi-implicit algorithm. Except the pressure gradient, all the terms at the right side of the Navier-Stokes are estimated explicitly from instant *(t)* and Poisson equation of pressure is solved implicitly for the instant *(t+Δt)*. This Poisson equation can be obtained using implicit conservation of mass and the implicit pressure gradient:

$$\left\langle \nabla^2 P \right\rangle_i^{t+\Delta t} = -\frac{\rho_0}{\Delta t^2}\frac{pnd_i^* - pnd^0}{pnd^0} \qquad (4)$$

Where *pnd** is the particle number density calculated in the explicit part. Replacing the left hand side of the equation by the Laplacian model, a system of linear equation is obtained.

For 2D simulations, the value of r_e used to calculate pressure gradient is 2.1 the distance between particles, according the studies published by Koshizuka and Oda [1] On the other hand, to calculate Laplacian, r_e is set as 4.0 times the distance between particles.

Dynamics of Floating Bodies in waves with Sloshing phenomena

In MPS, a floating body is modeled by as a set of particle that defines the geometry of the body.

The water pressure on the outside of the hull should not affect the water from inside the hull. So it is necessary put a double layer of auxiliary particles without pressure between the layers that define the outer hull and the interior tank, as shown in Figure 1 and Figure 2. As the radius of action of each particle is 2.1 times the distance between particles, it ensures that the outer layer does not interfere at the inner layer.

Force and moment acting on the hull are calculated by integrating the pressure on both external and internal sides of the body. The elementary area of the wall is defined as the half distance between a hull particle and one of its neighbor particles. Each area has its normal orienting to the fluid side. Figure 3 shows an example of hull particles, their elementary areas and normal.

The force on the hull and the moment applied at the center of gravity are as follows:

$$F = \sum_i P_i \cdot \left(S_{i1} \cdot \vec{n}_{i1} + S_{i2} \cdot \vec{n}_{i2}\right)$$

$$M = \sum_i P_i \cdot \left(S_{i1} \cdot \vec{n}_{i1} + S_{i2} \cdot \vec{n}_{i2}\right) \times \left(\vec{r}_i - \vec{r}_{CG}\right) \qquad (5)$$

Where, S_{i1} and S_{i2} are the areas of particle i; P_i is the pressure of particle i; $\vec{n}_{i1}$ and $\vec{n}_{i2}$ are the normal vectors of S_{i1} and S_{i2}, respectively; $\vec{r}_i$ is the position vector of particle i and $\vec{r}_{CG}$ is the position vector of center of gravity of the floating body.

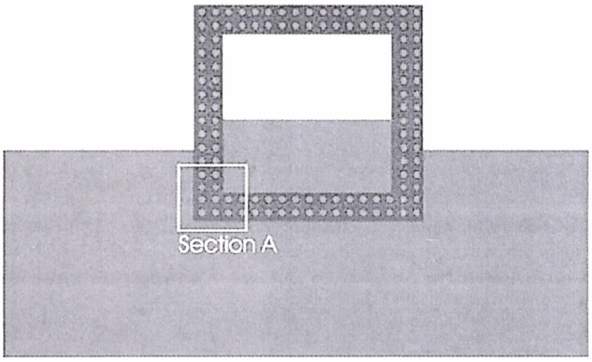

Figure 1 - Hull with internal tank

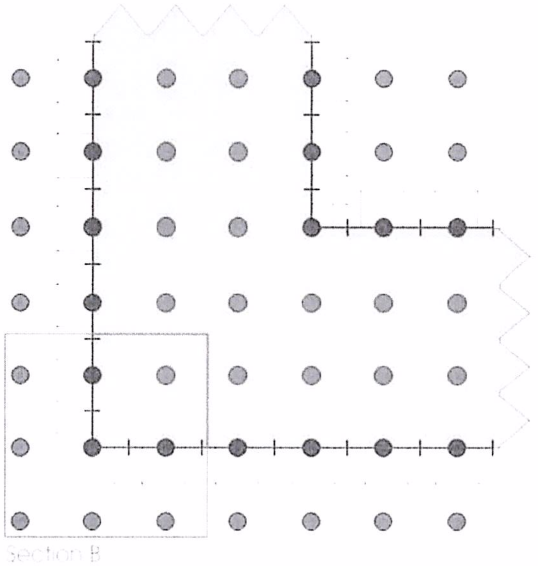

Figure 2 –Sections A – Particles defining a hull with internal tank

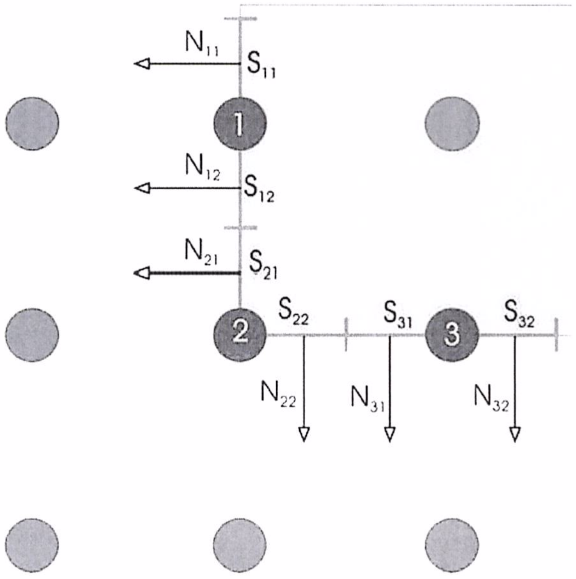

Figure 3 –Sections B – Elementary area and normal vector

With the force and the moment calculated by equations (5), the dynamics of the floating body can be obtained by

$$m\frac{d^2 r_G}{dt^2} = F$$

$$I\frac{d^2\theta}{dt^2} = M$$

Where, m and I are mass and Inertia of rigid body respectively; r_G is the position of the center of gravity and θ is the roll angle;

The time integration method adopted herein was Runge-Kutta 4th order for the linear and angular velocity calculation

MPS VALIDATION OF ROLL MOTION WITH SLOSHING EFFECT

Experimental tests were carried out to obtain data for validation of the roll motion of a floating body. In order to evaluate the effect of liquid sloshing, two conditions were considered: model with internal tank partially filed with liquid cargo and the model with fixed cargo. The characteristics of the tests are listed in the following item.

Characteristics of physical model

The physical model is an acrylic made rectangular box with a double bottom for lead ballast. In order to assure that the sloshing in internal tank occurs only in the transverse direction, i.e. 2D phenomenon, the beam / length ratio of the model is set to be less than 1/2. The Figure 4 shows the physical model and the Table 1 lists the dimensions. The filling of the liquid cargo is 45% of the internal tank capacity. The weight, center of gravity and inertia in the case of the fixed cargo are set to be equal to the liquid one.

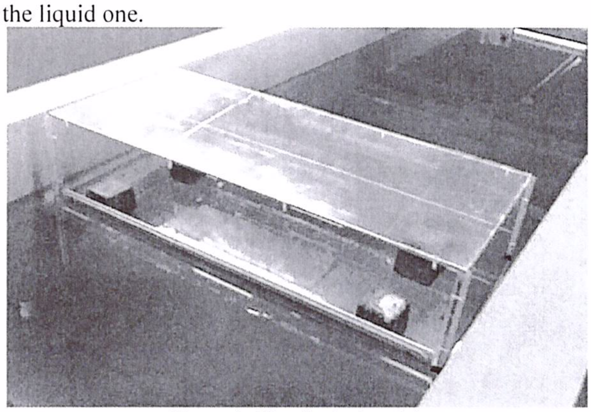

Figure 4 - The physical model.

Table 1 – Dimensions of the physical model

Parameter	Value	Unit
Length	0.920	m
Breadth	0.420	m
Depht	0.315	m
Double Bottom	0.050	m
Mass	89.992	Kg
VCG	0.0941	m
TCG	0.000	m
LCG	0.000	m
Ixx	1.439	Kg.m²

The towing tank has length of 24 meters, including a beach of 3 meters. The width and depth of the tank are, respectively, 1,0 and 0.8 meters. Figure 5 shows the main dimensions of the tank. The wave-maker of the tank is wedge type with vertical movement. The operation range of the wave-maker is 0.5 to 3.0 Hz.

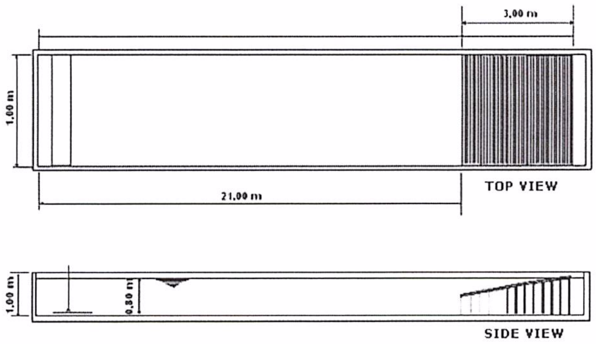

Figure 5 - Size of the physical tank.

Characteristics of numerical model

The length of the tank used in the numerical simulations is 2.92 m, including the beach of 1 m. The slope of the beach is approximately 30 degrees. Squares of 3x3 particles are fixed close to the beach and individual particles are fixed the furthest region. The depth of the tank used in the simulation is 0.50 m, lower than physical tank. This may cause bottom effects, specially the shallow water effect.

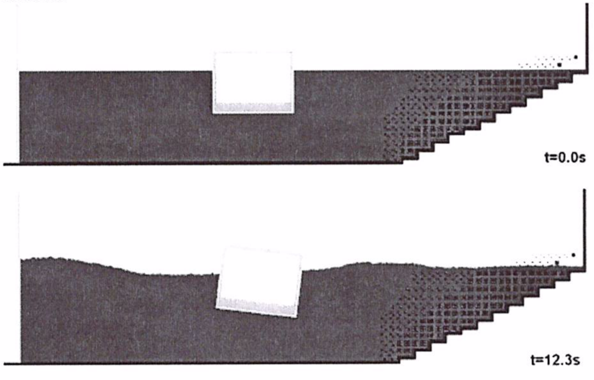

Figure 6 – Simulation snapshots: model with fixed cargo

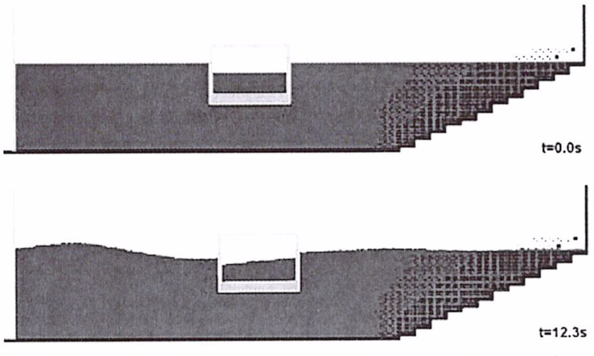

Figure 7 – Simulation snapshots: model with liquid cargo (sloshing effect)

The numerical tank has a plunge type wave generator, which is different to the wave generator of the physical tank, which is wedge type. The range of the motion of wave generator for each period of wave is shown in Table 2:

Table 2 – Motion amplitude of the wave maker for each period of simulated waves in MPS.

Wave Periodo (s)	Wave Frequency (Hz)	Wave Maker smaller amplitude (m)	Wave Maker higher amplitude (m)
0.75	1.333	0.0105	0.0210
0.863	1.159	0.0110	0.0220
0.93	1.075	0.0115	0.0230

The hull used in the numerical simulations has the same characteristics of the experimental model. The characteristics are described in Table 3:

Table 3 – Characteristics of simulated hull

Beam (m)	0.420
Depth (m)	0.315
Initial draft(m)	0.235
Mass (kg/m)	97.817
Inertia (kgm²/m)	1.564
TCG (m)	0.000
VCG (m)	0.0941

In the simulations, 48800 particles were used, with distance between particles of 0.005 m. The time step was 0.0005 s and simulation time is 30.0 s. Each simulation used only one processor of a SGI Altix 330, with 16 Intel Itanium2 1.5GHz processor, 128 GB of RAM shared for 16 processors, Operating System Novell® SUSE® Linux Server with SGI ProPack 4 ™. Each simulation consumed about 134 hours of CPU. Efforts have been done to improve the code performance and parallelization.

Results of the simulation

Figure 6 and Figure 7 show the animation of the simulation with model filled with fixed and liquid cargo, respectively, and the wave period is 0.86 s. The Figure 8 shows the time series of wave height and roll motion obtained experimentally for the same wave. In order to assess the amplitudes of the wave and the motion, two methods were considered: the analysis of peaks, for calculating the amplitude of the wave, and the power spectrum, through FFT (Fast Fourier Transformation). The intervals selected for the analysis are shown in red. The Figure 8 shows the results obtained by MPS simulation with the same wave.

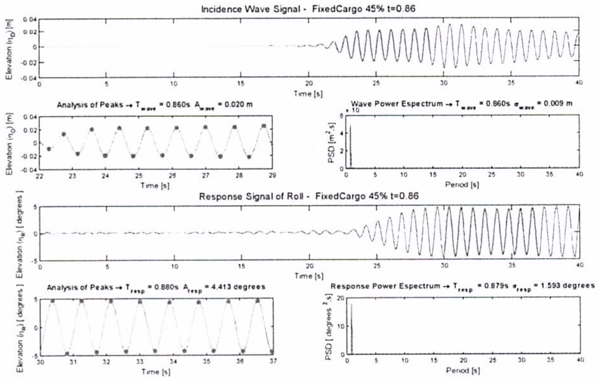

Figure 8 – Experimental results of incident wave and roll response with fixed cargo (T=0.86s)

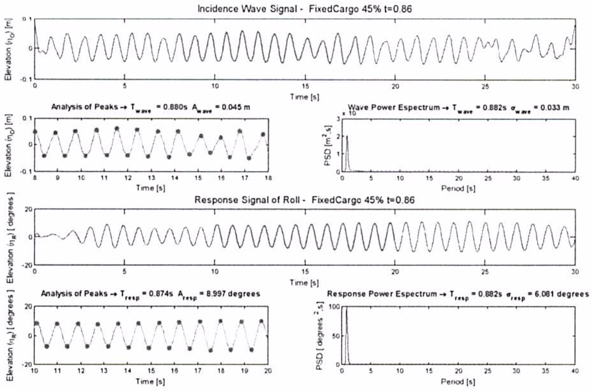

Figure 9- MPS simulation results of incident wave and roll response with fixed cargo (T=0.86s)

The Figure 10 shows, the RAO obtained experimentally and numerically. The RAO is the magnitude of the linear transfer function between the forcing function (wave) and the response function (roll) in frequency domain. The comparison shows that the numerical results agree well with experimental ones when the model is loaded with fixed cargo.

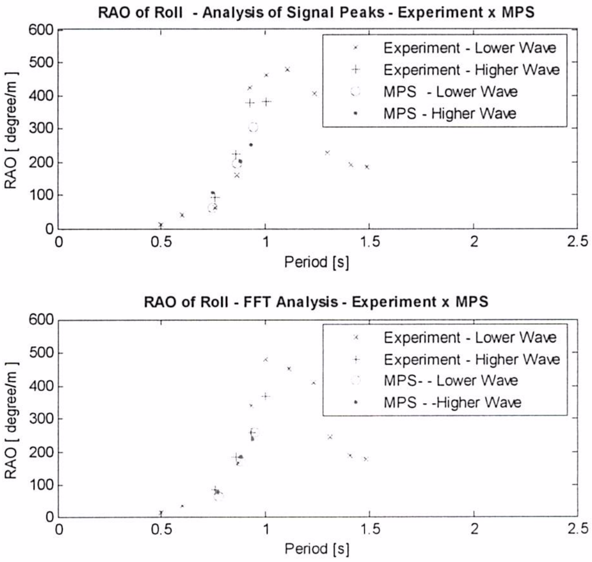

Figure 10 – RAO of fixed cargo – Simulation at MPS and experimental test.

Figure 11 shows the experimental results obtained with liquid cargo for incident wave of T=0.86s and internal tank with 45% filling. Figure 12 shows the numerical results obtained with the same wave period.

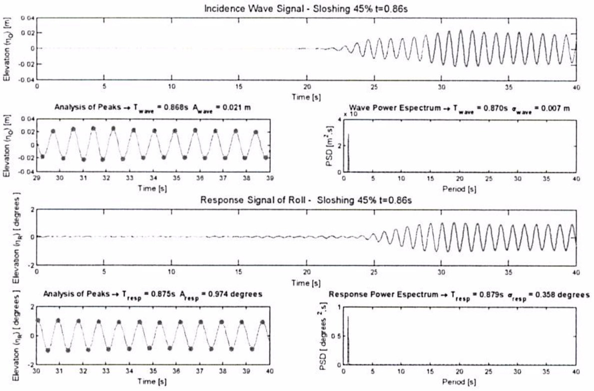

Figure 11 - Experimental results of incident wave and roll response with liquid cargo (T=0.86s)

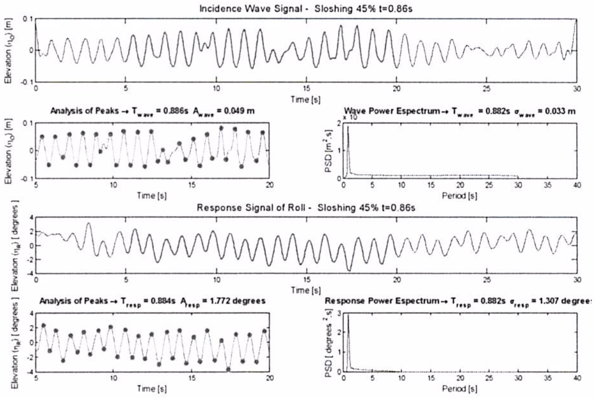

Figure 12 - Numerical results of incident wave and roll response with liquid cargo (T=0.86s)

Figure 13 shows RAO obtained experimentally and numerically. The results show that even in the condition with the liquid cargo, the numerical results fit very well to the experimental ones.

Compared with the response of fixed cargo shown in Figure 10, the roll response in case of liquid cargo is much smaller, mainly in the vicinity of the resonant period of sloshing. This is because, in this conditions, the fluid inside of a floating body works as a passive roll motion absorber.

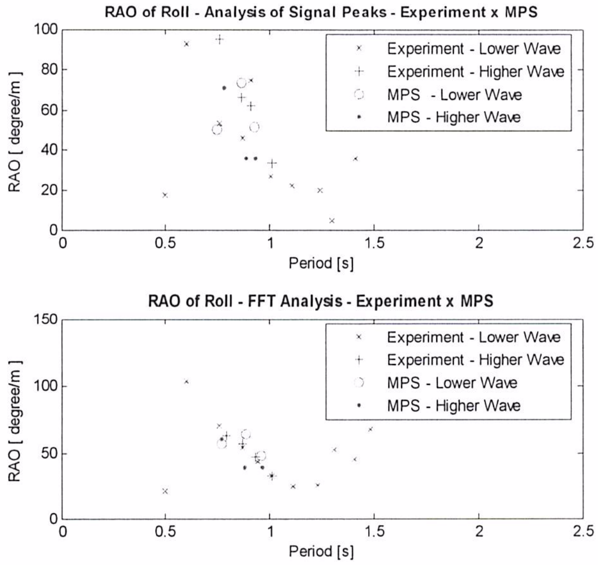

Figure 13 – RAO sloshing – Simulation at MPS and experimental test.

Through the comparison between of RAO obtained experimentally and numerically way, it can be concluded that the results of the MPS agrees with the experimental results in both conditions, especially in case of the RAO calculated through the FFT analysis.

VALIDATION OF SIMULATION OF LIST HEEL OF A DAMAGED VESSEL

To perform the simulation on damaged conditions, a similar model adopted in sloshing simulations was used, but with the internal tank split in two parts. Two cases were analyzed, one with the internal liquid leak after the breakdown and another where water enters into the vessel. The two cases differ in the use of ballast. The first does not use ballast, therefore it has lower draft and the level of the liquid cargo inside the tank is above the waterline. In another condition it was used 15 kg of ballast and the level is below the waterline.

Three different location of damage and three levels of filling the tanks were used. The following table shows the cases that have been simulated.

Table 4 – Simulated Cases - validation of damaged hull.

Ballast (kg)	% Tank Fill	Damage high above keel (m)	Case Denomination
0.0	25%	0.10	B0_25%_0.1
0.0	45%	0.10	B0_45%_0.1
0.0	45%	0.14	B0_45%_0.14
0.0	75%	0.10	B0_75%_0.1
0.0	75%	0.14	B0_75%_0.14
0.0	75%	0.20	B0_75%_0.2
15.0	25%	0.10	B15_25%_0.1
15.0	45%	0.10	B15_45%_0.1
15.0	45%	0.14	B15_45%_0.14
15.0	75%	0.14	B15_75%_0.14
15.0	75%	0.20	B15_75%_0.2

The validation of final equilibrium angle of list has been carried out by using the SSTAB [5] . SSTAB is the official stability analysis code adopted by PETROBRAS, and uses the hydrostatic theory to calculate the stability of floating bodies with and without free surface effects.

Figure 14 shows the animation obtained from the simulation with 75% tank filled no ballast and damage at 0.10 m above the keel.

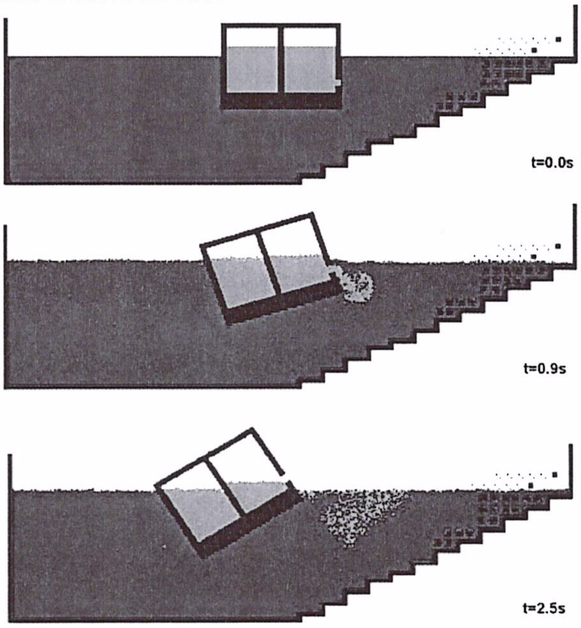

Figure 14 –Damage Simulation snapshots - case B0_75%_0.1

Figure 15 to Figure 18 show the transient motions obtained from MPS simulation and the final heel angle obtained by SSTAB. The results obtained by MPS and SSTAB of the list heel angle agree very well

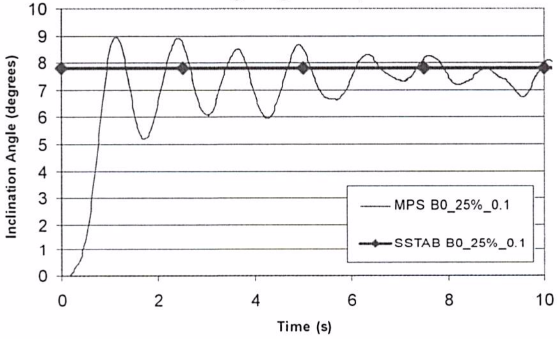

Figure 15 – Simulation x SSTAB– Model without ballast – internal tank with 25% of loading

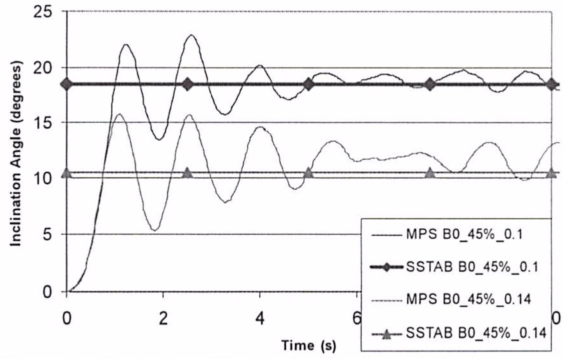

Figure 16 – Simulation x SSTAB – Model without ballast – internal tank with 45% of loading

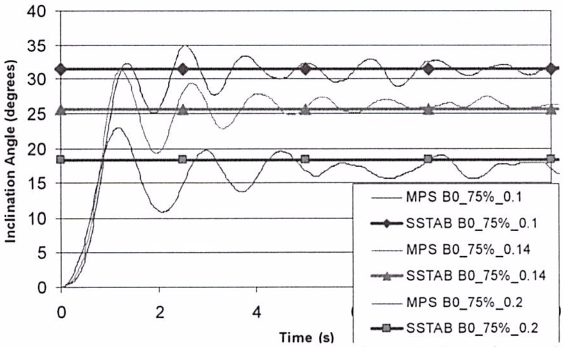

Figure 17 – Simulation x SSTAB– Model without ballast – internal tank 75% of loading

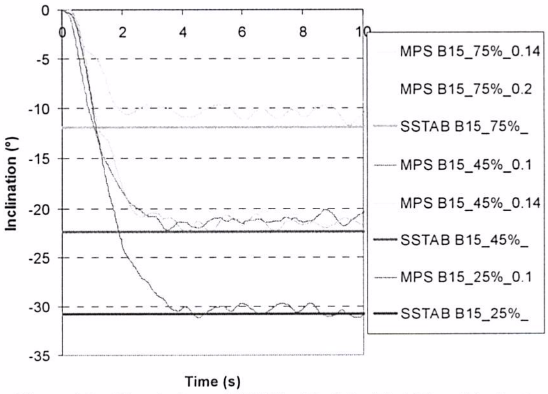

Figure 18 – Simulation x SSTAB– Model with 15 kg of ballast

CONCLUSIONS

In the case of sloshing in waves, the comparison between the RAO obtained experimentally and the RAO obtained by the MPS shows good agreement between the two results, despite the difficulties encountered in both tests. The agreement between the RAO's of experimental test with the MPS occurred in both cases with fixed cargo and with liquid sloshing, especially when calculated using the amplitude calculated by the analysis of the power spectrum. However, while the power spectrum of sloshing simulation presents a broadband behavior, the power spectrum obtained from experimental results is a narrow band one. This may be caused by the phenomena of wave reflection that occurred in the MPS simulations. This phenomenon was observed in all the simulations with greater intensity in the sloshing, because there is less roll motion and greater reflection. One of the measures to mitigate the problem is the increase the size of the tank, but improvements of computational performance should be made to reduce the time for simulation

The simulations of damage hulls gave inclination angle close to the ones calculated by the static stability method, both in the cases of oil spill as well as in the case of shipment of water. Tests will be done to validate the dynamics of the body during the damage and also the behavior of damage hull in waves.

ACKNOWLEDGEMENTS

The authors wish to thank PETROBRAS for the financial support of the present research project, and all the colleagues of TNP/University of São Paulo and Petrobras who helped with ideas, technical knowledge and practical experience in the development of this work.

REFERENCES

[1] Koshizuka, S. and Oka,Y. Moving-particle semi-implicit method for fragmentation of incompressible fluid. Nuclear Science and Engineering, 123:421–434, 1996

[2] Naito, S. and Sueyoshi, M.. A numerical analysis of violent free surface by particle method. In The Proceedings of TheFifth (2002) ISOPE Pacific/Asia Offshore Mechanics Symposium, page 219, Daejeon, Korea. International Society of Offshore and Polar Engineers (ISOPE), 2002

[3] Sueyoshi, M. and Naito, S.. A numerical study of very large motion of floating body by particle method. In Asia Pacific Maritime Congress, pages 146–150, Kobe, Japan. Asia Pacific Workshop on Marine Hydrodynamics., 2002

[4] Nishimoto, K., Martins, M. R., Ferreira, M. D., Masseti, I. Q., Martins, C. A., Jacobi, B., Goulard, R., Russo, A., Caldo, J. R., Silveira, E.E.S., Numerical Offshore Tank: Development of Numerical Offshore Tank for Ultra Deep Water Oil Production Systems, 22rd International Conference on Offshore Mechanics and Arctic Engineering, 2003

[5] Coelho, L.C.G., Nascimento, A.A. – SSTAB User's Manual, PUC, Tecgraf, 2003

[6] Tsukamoto, M. M., Nishimoto, K., Asanuma, T., Development of particle method representing floating bodies with highly non linear waves, 18th International Congress of Mechanical Engineering, COBEM, 2005

[7] Maeda H., Nishimoto K., Masuda K., Asanuma T., Tsukamoto M. M., Ikoma T., Numerical Analysis for hydrodynamics motions of floating structures using MPS method, 23rd International Conference on Offshore Mechanics and Arctic Engineering, 2004