Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2010
June 6-11, 2010, Shanghai, China

OMAE2010-20827

A NUMERICAL STUDY ON OIL LEAKAGE AND DAMAGED STABILITY OF OIL CARRIER

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ABSTRACT

The objective of the present paper is to carry out a study on coupled transient process of the oil leakage and the damaged stability of a crude oil carrier. For this purpose, numerical simulations based on MPS (Moving particle Semi-Implicit) method are carried out considering a two dimensional small scaled model and the oil-water multiphase flow with free surface. The results are compared with that obtained by the stability analysis software SSTAB, which provides the final list angle in case of the damage, and show good agreement.

Key words: Coupled analysis, particle method, damaged stability, multiphase flow, MPS.

INTRODUCTION

In case of damage of a crude oil carrier, both the stability of the vessel and oil leakage is of great concerns due to the safety and the environmental issues. Depending on the position of the hull damage, draught and filling height of the liquid cargo, the leakage of the oil or water flooding into the tank may occur. As a consequence, the restoring moment, which is affected by the free surface effect of the liquid cargo, may be further changed by the leakage of the oil of water entering and their dynamic effects and leads to dangerous situation. On the other hand, the spillage of the leaked oil may lead to disastrous environmental problems. Within this context, the assessments of the list angle, the volume and the dynamic effects of the oil leakage are relevant topics in the design and operation of the crude oil carriers.

Nowadays, there are several method and computational tools for the calculation of the damaged stability. However, most are based on hydrostatic approach and/or quasi-static assumption, which are unable to take into account the dynamic effects. Even in cases of CFD based approaches, due to the fluid-solid interaction with complex geometry and multiphase flow, the detailed investigation of the phenomena of the oil leakage caused by hull damage, including the coupled transient motions of the fluids and the vessels, still remains as a challenge. Thus, the aim of the present research is to carry out a coupled transient analysis of the oil leakage process and the damaged stability. For this purpose, numerical method based on MPS (Moving particle Semi-Implicit) method [1] is adopted to model both the motion of the vessel and the oil-water multiphase flow with free surface. The effectiveness of the method for the analysis of the damaged stability was shown in a previous study [2] by considering water leakage and entrance in a floating tank. In the present paper, a multiphase flow model is applied to study the complex oil-water flow in case of oil leakage.

For sake of simplicity, a two dimensional (2D) small scaled model is considered. The results were compared with that obtained by the stability analysis software SSTAB, which provides the final list angle in case of the damage, and shows very good agreement. The transient analysis performed by the present 2D approach shows the sway motion of the oil carrier induced by the leakage in the beginning of the process, when a relatively large amount of oil is released suddenly. In addition to this, the volume of leaked oil and the oil spillage soon after the damage are also computed. In the following sections, a brief description of the numerical model, the results of some validations analysis, the study cases, the results and discussions are given.

NUMERICAL METHOD

The governing equations for the incompressible viscous flow that expresses the problem to be solved in this study are:
Continuity equation

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

and the momentum equation

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{u} + \vec{g} + \frac{\vec{\sigma}}{\rho} \quad . \tag{2}$$

Where, ρ is density, v is velocity, p is pressure, υ is kinematic viscosity, σ is surface tension and g the gravity.

The Moving Particle Semi-implicit (MPS) is a Lagrangian meshless method, in which the space domain is descretized in particles, and all the differential operators are derivated from a particle interaction model based on the weight function given by:

$$w(r) = \begin{cases} \frac{r_e}{r} - 1, & (r < r_e) \\ 0, & (r > r_e) \end{cases} \quad . \tag{3}$$

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.

Considering a scalar function ϕ, the gradient vector and the Laplacian of the function at a particle i are determinated by taken into account the values of the neighboring particles j. Within the range r_e, they are given by Eq. (4) and (5), respectively:

$$\langle \phi \rangle_i = \frac{d}{pnd^0} \sum_{i \neq j} \left[\frac{(\phi_j - \phi_i)}{\left|\vec{r}_j - \vec{r}_i\right|^2} (\vec{r}_j - \vec{r}_i) w(\left|\vec{r}_j - \vec{r}_i\right|) \right] \tag{4}$$

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

Where, d is the number of spatial dimensions and pnd is the particle number density. λ is calculated by:

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

and the particle number density (pnd) is proportional to the fluid density and it is given by:

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

and pnd^0 is the initial value of pnd .

The MPS method adopts a semi-implicit algorithm. Except the pressure gradient term, the right side of the Navier-Stokes equation are calculated explicitly to estimate velocity and position. After that, the Poisson's equation of pressure is solved implicitly at ($t + \Delta t$). The Poisson's equation is given by:

$$\langle \nabla^2 P \rangle_i^{t+\Delta t} = -\frac{\rho}{\Delta t^2} \frac{pnd_i^* - pnd^0}{pnd^0} \tag{8}$$

Where, pnd^* is the particle number density calculated using the estimated position of the particles. pnd^* is kept as pnd^0 to ensure the condition of incompressibility. The term of the left hand side of equation (8) can be discretized using the Laplacian model, leading to a system of linear equations.

For the present two-dimensional analysis, r_e was set to $2.1\, l_0$, where l_0 is the initial distance between particles, to calculate pressure gradient and the particle number density. r_e is set to be 4.0 l_0 for cases involving the Laplacian operator.

When the particle number density of a particle is smaller than $\beta \cdot pnd$, it is considered to be on the free surface. The pressure of all free surface particles is set to zero. According to Koshizuka and Oka [1], β may vary between 0.80 and 0.99.

For the calculation of the surface tension $\vec{\sigma}$ in the free surface and in the water-oil interface, the interparticle potential force model proposed by Kondo et al [3] is used.

In MPS, rows of different type of particles are used to describe the geometry of the rigid walls. Pressure is calculated in the first row that is in contact with fluids. The rows of particles that have no contact with fluids are formed by dummy particles used to guarantee the correct calculation of the particle number density, but in which the calculation of pressure is not necessary.

In case of the floating body with inner tank analyzed in the present study, as the calculation of the liquid pressure on the outside of the hull must not affect the calculation of the pressure inside the hull, and vice-versa, for r_e equals to $2.1\, l_0$, it is necessary put at least two rows of dummy particles between the rows of pressure particles that define the geometry of the hull and the inner tank, as shown in Fig. 1 and Fig. 2.

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. Fig. 3 shows an example of hull particles, their elementary areas and normal vectors.

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

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

$$M = \sum_i P_i \cdot (S_{i1} \cdot \vec{n}_{i1} + S_{i2} \cdot \vec{n}_{i2}) \times (\vec{r}_i - \vec{r}_{CG}) \,. \quad (9)$$

Where, S_{i1} and S_{i2} are the dimension of the two elementary 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.

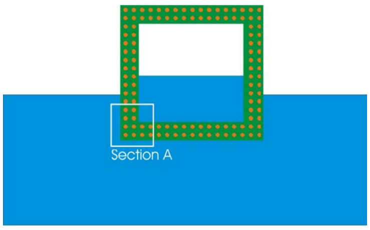


Figure 1. Modeling of a hull with internal tank.

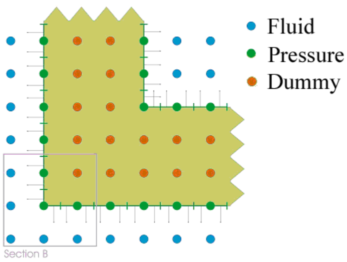


Figure 2. Section A – Rows of pressure and dummy particles that define a hull with internal liquid tank.

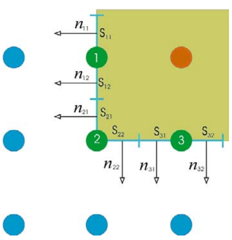


Figure 3. Section B – Elementary area and normal vector.

With the force and the moment calculated by equations (9), the dynamics of the floating body can be obtained by:

$$m \frac{d^2 \vec{r}_{CG}}{dt^2} = F$$

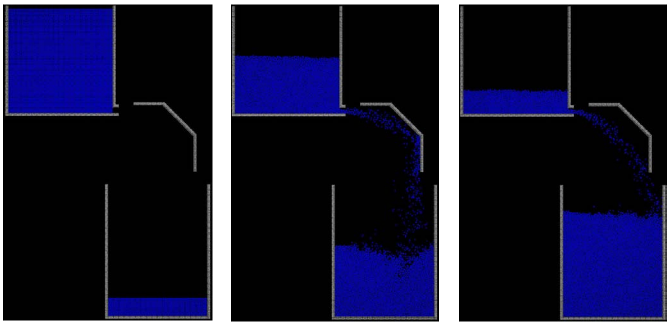
$$I \frac{d^2 \vec{\theta}}{dt^2} = M \quad . \quad (10)$$

Where, m and I are mass and inertia of rigid body respectively; θ is the roll angle.

VALIDATION

Aiming to verify the effectiveness of the numerical approach in the fluid leakage problem, a simple case of jet with no velocity of approach is presented herein. The leakage and flooding in a water tank were tested by the authors of the present paper [2], as well as the dynamics of a floating body in waves and coupled motion of sloshing and vessel in wave. Further basic tests on fluid-solid interaction such as free heavy and roll motions of a floating body with and without elastic connection were also carried out by the authors [4].

In the case of jet with no velocity of approach, a 2D tank of 0.99 m wide and initial water levels of 0.99 m are considered. The opening located in the right low corner has 0.05 m height. The simulation were carried out by using distance between particles of 0.01 m. Fig. 4 shows the snapshots of the simulation from the initial condition (Fig. 4(a)) to 8 s (Fig. 4(c)).



(a) t=0.0 s (b) t=4.0 s (c) t=8.0 s

Figure 4. Snapshots of the case of the jet with no velocity of approach.

For the quantitative check, the mean velocity of the particles passing through a imaginary square of 0.05x0.05 m just beneath and out side of the opening was computed and compared with the theoretical value. Fig. 5 presents the comparison between the computed and analytical values for the velocity of the jet. The presence of air is neglected in both computational and analytical calculations. The computed velocity shows the typical fluctuation of the time series obtained by lagrangian particle based methods. However, the mean value and the integral of the computed time series agree well with the analytical results.

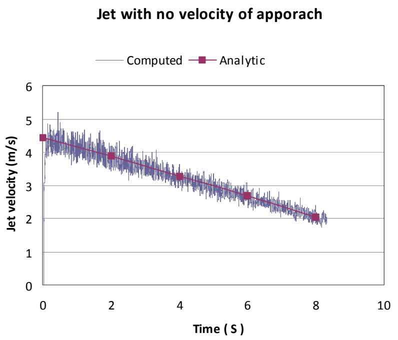


Figure 5. Comparison between the computed and analytical velocity of the jet with no velocity of approach.

CASES OF STUDY

To perform the simulation on damaged conditions with oil leakage after the breakdown, a 2D numerical model whose main characteristics are described in Table 1 was used.

Table 1. The main properties of the hull.

Beam (m)	0.415
Depth (m)	0.325
Mass (kg/m)	20.30
Inertia (Kgm^2/m)	0.657
TCG (m)	0.0
VCG (m)	0.1097

As shown is Fig. 6, the scaled model has two internal tanks. The thickness of the walls is 0.02 m except in center, where the thickness is 0.025 m, and in the bottom, where the thickness of 0.055 m is used to model the double bottom. The opening for the oil leakage is 0.05 m. In the case shown in Fig. 6, the opening height is 0.10 m from the keel, and the filling ratio of the internal tank is 75%.

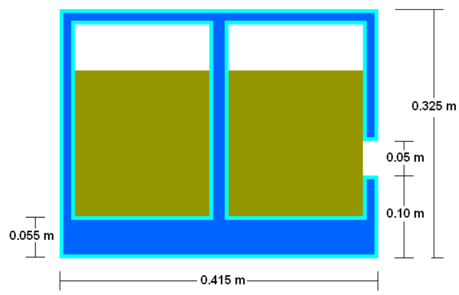


Figure 6. Cross-section of the model.

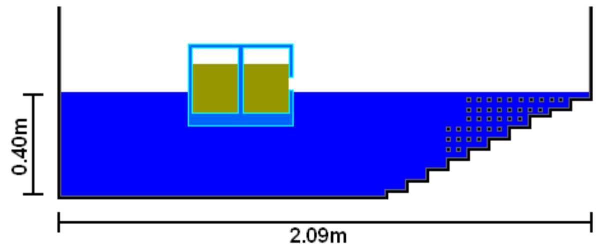


Figure 7. Cross-section of the towing tank.

The length of the towing tank used in the numerical simulations is 2.09 m. The slope of the beach is approximately 30 degrees. Squares of 3x3 particles are fixed close to the beach. The depth of the towing tank used in the simulation is 0.40 m, as shown in Fig. 7.

Table 2 shows the cases analyzed in the present study. Three different location of damage and two levels of filling inside the tanks were considered. The properties of the water and the oil are given in Table 3.

Table 2. The cases of study.

Case denomination	Filling ratio (%)	Damage height above the keel (m)
BO_75%_020	75	0.20
BO_75%_014	75	0.14
BO_75%_010	75	0.10
BO_45%_014	45	0.14
BO_45%_010	45	0.10

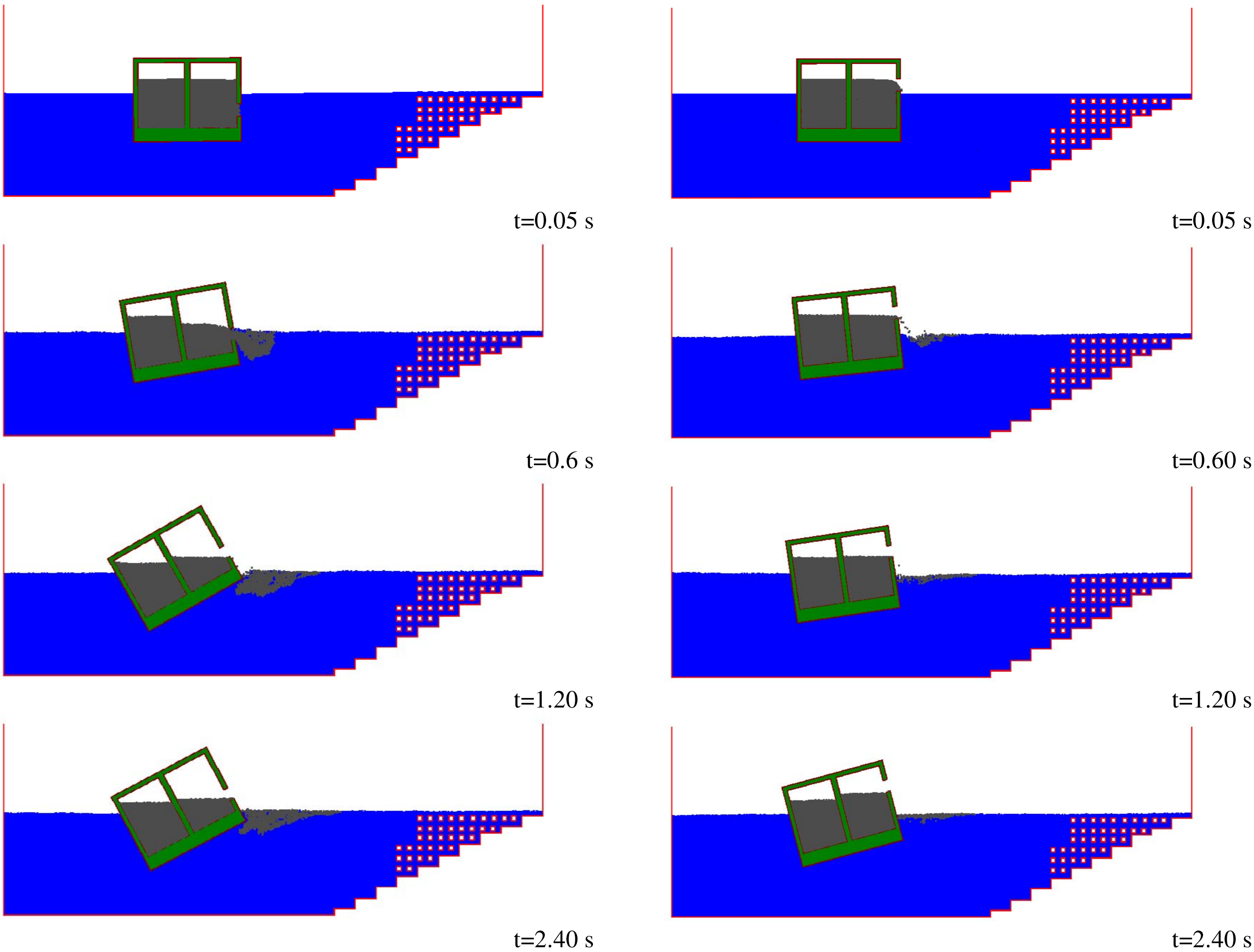
Table 3. The properties of the water and oil.

Property	Water	Oil
Density (kg/m^3)	1000.0	900.0
Surface Tension Coefficient (N/m)	0.072	0.026

The simulations were carried out by using distance between particles of 0.005 m. The time step was 0.0005 s and simulation times up to 10.0 s were used. In a typical case there are about 30000 particles.

RESULTS AND DISCUSSIONS

Fig. 8(a) gives the snapshots of the animation obtained from the MPS simulation with 75% filling and damage at 0.10 m above the keel. The transient analysis performed by the present simulation shows that, beside the roll motion of the hull, sway motion induced by the leakage occurs in the beginning of the process when a relatively large volume of the oil is released suddenly.



(a) BO_75%_0.10 (b) BO_75%_020

Figure 8. Snapshots of the simulation of the cases BO_75%_0.10 (a) and BO_75%_020 (b).

Fig. 8(a) shows that a list angle of about 30^{o} degrees is reached in about 2 seconds after the release of the oil. This short time is expected considering the characteristics of the model adopted herein: the reduced dimensions of the model with a relatively large opening. Also, the 2D analysis means unlimited longitudinal extension of the opening. This is a hypothetical condition that leads a relatively large volume of oil being released at once in the beginning, which is very different from the actual situation. Thus, it should be emphasized that all the results presented herein should be interpreted with these differences in mind. A complete 3D analysis should be done instead of extrapolating straightforwardly the 2D results to the actual situations.

Fig. 8(b) provides the snapshots case BO_75%_020, i.e., with 75% filling and damage at 0.20 m above the keel. As the opening height is close to the free surface of the oil inside the tank, the volume of the leaked oil is relatively small, as well as the motion of the hull. Due to smaller hydrodynamic motion, the leaked oil seems to spread easily and forms a thin film on the water surface. Also, the sway motion observed in Fig. 8(a) is almost negligible in Fig. 8(b).

The validation of final equilibrium angle of list has been carried out by using 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, and free to pitch and heavy. In order to model the 2D problem, a 3D model of B/L=1/100 with constant cross section and without trim is used in the SSTAB calculations.

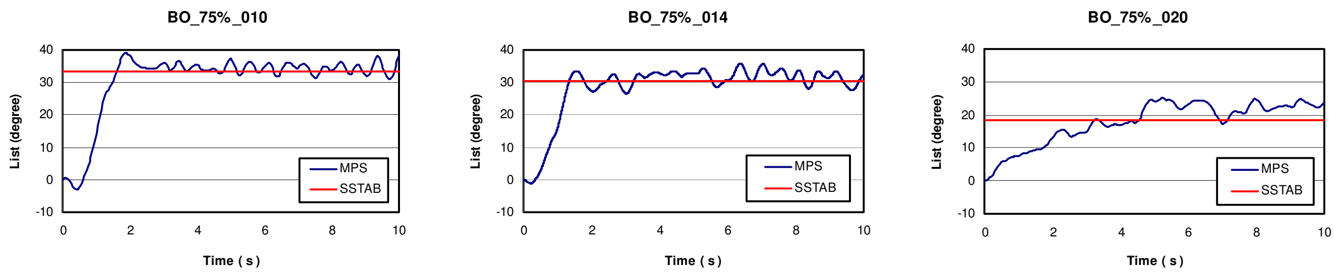
Although SSTAB is able to provide an estimate the final list angle through a quasi-static approach, it is unable to take into account the dynamic effects in assessment of the volume of the leakaged oil, specially in the cases where the water enter into the damaged tank, as reported by Silva et al [2]. In this way, the final list angle provided by SSTAB is determined by using the volume obtained by MPS simulation.

Fig. 9(a), 9(b) and 9(c) present the time series of the roll motions obtained by MPS simulation and the final list angle obtained by SSTAB for the cases BO_75%_010, BO_75%_014 and BO_75%_020, respectively. The transient motions calculated by MPS show residual oscillations after quick inclination from the initial position. These oscillations are caused by the reflection of waves from the left wall of the numerical towing tank and its beach, which did not absorbed the wave entirely. Nevertheless, the mean values of the oscillations agree very well with the final list angle obtained by SSTAB in case of opening height of 0.10 m and 0.14 m. When the opening height is 0.20 m, the mean value from MPS is about 4 degrees higher than that obtained by SSTAB. In the last case, the transient motion is relatively longer than the former two cases.

Fig. 9(a) and 9(b) show that the roll angle of the cases BO_75%_010 and BO_75%_014 shortly decreases to negative values soon after the start of the process. The reason of this negative heeling is the modeling of the opening. As shown in Fig. 6, the opening that represents the damage is relatively large and it is a void space not occupied by oil or by the water. Soon after the start of the process, as shown by the snapshot of t=0.05 s in Fig. 8(a), not only the oil, the water outside the damaged tank also invade this space. Thus, in both cases BO_75%_010 and BO_75%_014, where the opening is under the waterline, small negative roll angle occurs. In the case BO_75%_020, as the opening is above the waterline (see snapshot of t=0.05s of Fig. 8(b)), no negative value occurs in time series of the list angle (see Fig. 9(c)).

A comparison of the snapshot of the list angle obtained by MPS at 7.55 s and the graphic output of SSTAB in case of BO_75%_014 are illustrated in Fig. 10(a) and 10(b), respectively. The images show that in this case both the list angle and the volume of the oil inside the internal tanks are in agreement. However, due to the residual oscillation of the hull, the draught obtained by MPS is slightly different from that calculated by SSTAB. From the estimates obtained by using the snapshots, the mean error of the volume of displaced water is about 5 to 10%.

Fig. 11 gives the comparisons of the list angle obtained by MPS and by SSTAB for 45% and 75% filling and damage height of 0.10 m, 0.14 m and 0.20 m. No leakage occurs in the case of 45% filling and 0.20 m height, so that it was not considered. Here, as the SSTAB results shown before, the leaked volume determinated by MPS simulation is used in



(a) (b) (c)

Figure 9. Time history of the list angle obtained by transient analysis of MPS and list angle obtained by the hydrostatic analysis of SSTAB for internal tank with 75% filling and damage height of: 0.10 m (a), 0.14 m (b) and 0.20 m (c).

(a) (b)

Figure 10. Comparison between the final list angle obtained by MPS (a) and by SSTAB (b) for BO_75%_014(75% filling and damage height of 0.14 m).

SSTAB calculation. The comparison shows that, comparing to SSTAB results, the discrepancy of final list angle obtained by MPS increases when the height of the opening increases. On the other hand, the discrepancy also increases when the filling ratio decreases. This behavior seems to be related to the discretization adopted by the simulation: the discrepancies increases when the quantity of the 'oil particles' released from the internal tank is reduced drastically.

Fig. 12 gives the volume of the oil leakage calculated by MPS, together with the leakage estimate by using SSTAB through quasi-static approach. The vertical axis of Fig. 12 is the volume of the leaked oil in relation to the total volume of an internal tank. The comparison of MPS and SSTAB results shows that the discrepancy increases in both 75% and 45% filling when the height of opening decreases. The cause of the discrepancy seems to be the dynamic effects: for lower openings, the leakage is larger as well as the dynamic motion caused by the leakage. On the other hand, as the leakage reduces when opening becomes higher, the motion becomes near to the quasi-static assumption of the SSTAB calculations. As mentioned above, the 2D reduced model associated with a large opening leads to a relatively high heeling moment and motions, so that large discrepancies from the quasi-static approach may be expected. It is also important to point out that the results of the simulations show that the computed leakage volumes present some variations when different simulation parameters are adopted due to numerical instability, and the results shown in Fig. 12 are that obtained by the most stable cases. The numerical instability is a shortcoming of the lagragean particle based methods. It was reported by several authors, and several numerical techniques to improve the stability of the computation were proposed [6], [7], [8].

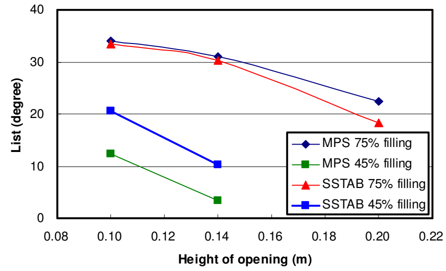


Figure 11. Comparison of the list angle obtained by MPS and by SSTAB for 45% and 75% filling and damage height of 0.10 m, 0.14 m and 0.20 m.

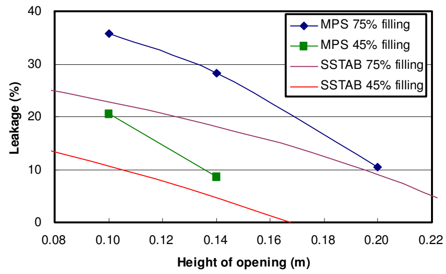


Figure 12. Oil leakage obtained by MPS and by quasi-static calculation using SSTAB for 45% and 75% filling and damage height of 0.10 m, 0.14 m and 0.20 m.

CONCLUDING REMARKS

In the present paper the dynamics of the oil leakage and the damaged stability of a crude oil carrier is investigated. Numerical simulations based on MPS (Moving particle Semi-Implicit) method is carried out to take into account the coupling between the damaged hull and the multiphase flow.

The numerical simulations of the transient motion show that the sway motion induced by the leakage may occur in the beginning of the process when a relatively large volume of oil is the released. From the comparison of the final list angles with that ones obtained by SSTAB, which is a static stability code, it is clear that the numerical approach is very effective in cases where the filling ratio is large and the height of the damage is low.

For the cases with filling ratio of 45%, the discrepancy of final list angle from the SSTAB calculation is quite large and the effect of the resolution on the accuracy of the results should be investigated.

Also, despite the complete simulation of the oil spillage was not realized because the formation of a thin film of oil will demand a very large number of particles that is beyond the scope of the present study, the leakage was computed. The comparison of the computed oil volume with that obtained by quasi-static approach shows the effects dynamic motion.

In the cases analyzed herein, no water entering the damaged tank was detected. Further studies on different loading conditions, such as ballasted ones, are required.

Finally, for sake of simplicity, 2D modeling was carried out to investigate the complex fluid-solid interaction phenomena. This is a hypothetical situation in which the dimension of the opening is much larger than the actual cases. In this way, instead of extrapolating straightforwardly the 2D results to the actual situations, further complete 3D analysis should be done.

ACKNOWLEDGMENTS

The author would like to express their gratitude to PETROBRAS for the financial support to the research.

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