NUMERICAL ANALYSIS OF THE FLOW INSIDE THE MOONPOOL OF A MONOCOLUNM PLATFORM

Alexandre Teixeira de Pinho Alho, alho@peno.coppe.ufrj.br
Sergio Hamilton Sphaier, sphaier@peno.coppe.ufrj.br
Luiz Henrique Barbosa Rocha, lhenrique@peno.coppe.ufrj.br
PENO/COPPE – Universidade Federal do Rio de Janeiro
Centro de Tecnologia, Bloco C, Sala 203
Cidade Universitária, Ilha do Fundão, Rio de Janeiro/RJ
Fernando G. S. Torres, ftorres@petrobras.com.br
CENPES/PDP/MC - PETROBRAS
Cidade Universitária, Ilha do Fundão, Rio de Janeiro/RJ

Abstract. *The monocolumn platform is a newer offshore platform concept that presents some advantages compared to the conventional concepts of semi-submersible and FPSO units. Particularly, the good seakeeping performance and the high storage capacity are the most attractive characteristics. However, monocolumn platforms usually show an undesirable response in heave motion. In recent years, many research projects have been carried out about the problem suggesting that the moonpool geometry has an important effect on damping the amplitude of the heave motion. In order to obtain a better comprehension of the dynamics of the damping process, a numerical analysis of the water motion inside the moonpool was conducted. In this paper, the numerical results obtained for the water motion inside the moonpool of a monocolumn platform were presented and discussed. The numerical model adopted for the simulations was developed in full scale with the experimental model, having both geometric and dynamic similarity. A good agreement between the numerical and the experimental decaying curves was achieved, suggesting that the numerical model is able to reproduce the flow behavior inside the moonpool.*

Keywords*: offshore, monocolumn, moonpool, damping, CFD.*

1. INTRODUCTION

The monocolumn platform is a newer offshore platform concept that presents some advantages compared to the conventional concepts of semi-submersible and FPSO units. Particularly, the good seakeeping performance and the high storage capacity are the most attractive characteristics. However, monocolumn platforms usually show an undesirable response in heave motion. In recent years, many research projects have been carried out about the problem (Aalbers, 1984; Matsuura, 1995), suggesting that the moonpool geometry has an important effect on damping the amplitude of the heave motion. During the last few years, the use of the moonpool as a vertical motion absorption tank in mono-column type platforms is being studied by PETROBRAS as part of the MonoBR Project.

The main goal of the MonoBR project is to develop an efficient design for monocolumn platforms, based on the concept of a unique circular column hull equipped with an open central moonpool (Torres *et al.*, 2004; Barrera *et al.*, 2005, Sphaier *et al.*, 2007). Experimental investigations were carried out at LabOceano ocean basin (COPPE/UFRJ, Rio de Janeiro) for different moonpool geometries in order to study its influence on the platform response in heave motion. The geometry of the moonpool was modified by the installation of bottom skirts with different internal diameters. The results obtained demonstrate that the geometry of the moonpool deeply affects the dynamic behavior of the platform (Torres *et al.*, 2007).

The use of the potential theory is a common practice in the analysis of the dynamic behavior of floating structures in regular waves, coupling wave and viscous effects. This approach works well when the viscous effects have a minor influence on the potential character of the flow around the body. In this case, it is possible to estimate a damping coefficient depending on the wave amplitude to take into account the viscous effect. Basically, the viscous effects affect the response around the natural frequency. In the present case, the experimental results showed that it seems like the viscous effects around a skirt at the bottom of the moonpool may have a stronger contribution in the fluid flow. It seems that the representation of these phenomena can not be well described by a single parameter based on the wave amplitude.

In order to study the viscous effects caused by the bottom skirts a set of free decaying experimental tests was carried out with simplified monocolumn geometry. As in the case of the first experimental tests, skirts with different internal diameters were installed at the bottom of the moonpool. It was observed that the flow inside the moonpool presents a very complex behavior, characterized by the onset of complex vortex structures. Numerical simulations of the water flow inside the moonpool were carried out in order to obtain a better insight into the physics related to the damping process. The numerical model adopted for the simulations was developed in full scale with the experimental model, having both geometric and dynamic similarity. A good agreement between the numerical and the experimental decaying curves was achieved, suggesting that the numerical model is able to reproduce the flow behavior inside the moonpool.

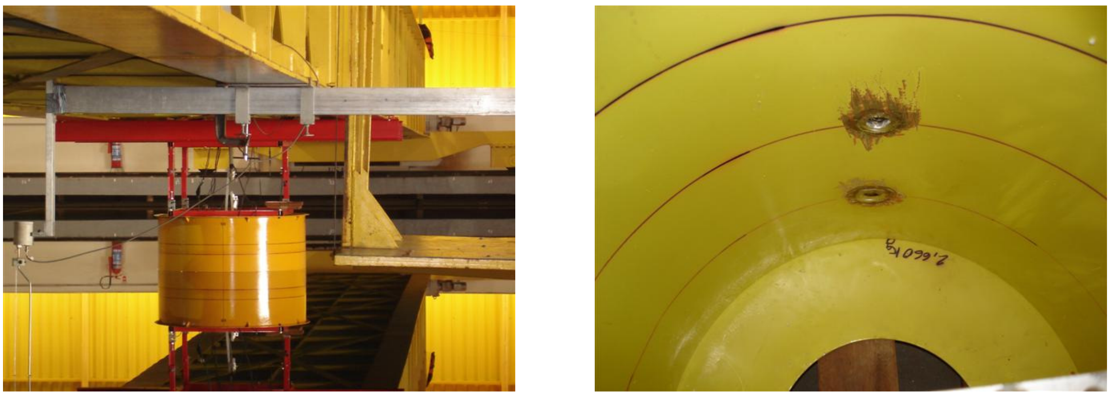
Figure 1. The aluminum monocolumn model – scale 1:100.

2. FREE DECAYING TESTS

The free decaying tests were conducted with a simply monocolumn geometry, consisting of a circular monocolumn model with a central moonpool (Fig.1). The model was built in aluminum in a 1:100 scale to the prototype. The full scale prototype has an external diameter equal to 110 meters with a moonpool diameter of 50 meters. The draft at full scale equals to 30 meters. Skirts with different internal diameters were installed at the bottom of the moonpool in order to obtain different magnitudes for the damping process. Two configurations were used as reference for this study: a) moonpool with no skirt (Model A - 50.0 centimeters opening); b) moonpool with a 4.6 centimeters wide skirt (Model B - 40.8 centimeters opening).

The tests consist of imposing an initial difference between the water level inside the moonpool and the water surface outside the model and then let the water oscillate in a free decaying motion. During the tests the model was maintained at a fixed position with no degrees of freedom. The initial hydrostatic pressure difference was obtained by pumping compressed air inside the moonpool to pull down the water. The tests were started by releasing the compressed air to the atmosphere. A mechanical device installed at the top of the moonpool was used to control the air release. The water motion inside the moonpool was monitored by four cameras positioned in different angles of view. A wave probe installed at the central vertical axis of the moonpool was used to record the water level during the tests. Some pictures of the experimental arrangement are presented in Fig. 2.

Figure 3 shows the decaying curves for the configurations used as reference. As can be seen, the installation of the skirt causes a remarkable influence on the decaying of the water. Not only the amplitude of the motion was influenced but also the period of oscillation was modified by the presence of the skirt. The amplitude of the first oscillation was reduced in 15%. In the case of the natural period, the variation equals to 0.16 seconds, representing a change of 13%. As expected, these results confirm that the viscous effects originated by a skirt play an important role on the dynamic behavior of a monocolumn platform.



a) Model installed at LabOceano basin.

b) Position of internal cameras.

Figure 2. Views of the experimental arrangement of the free decaying tests.

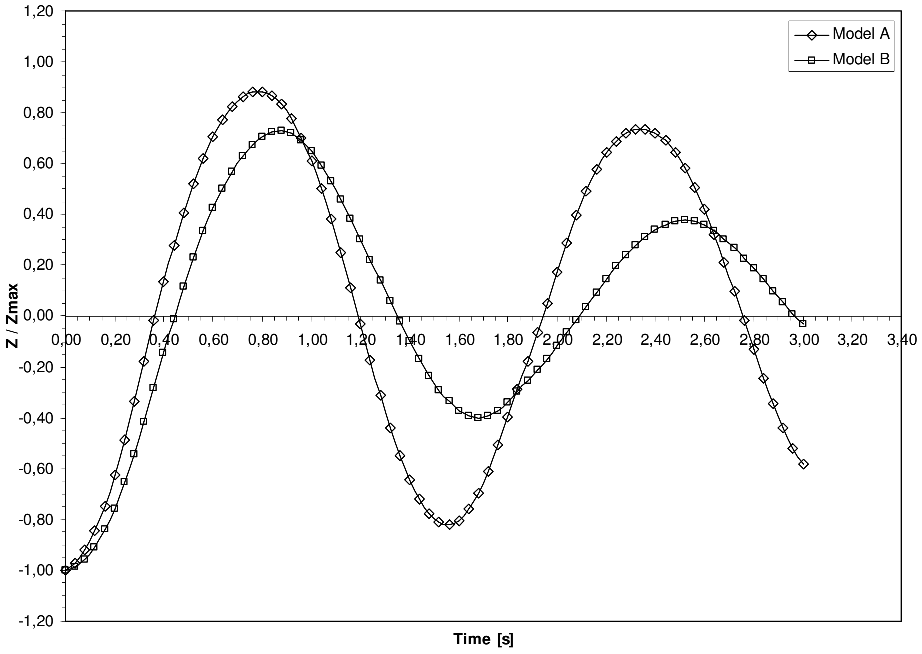
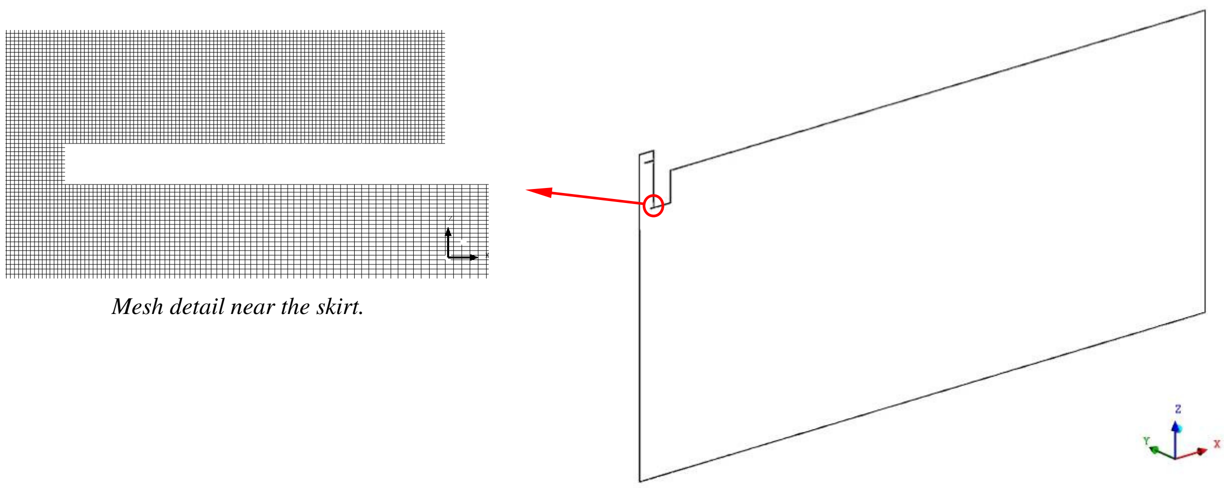


Figure 3. Decaying curves of the water motion inside the moonpool.

3. NUMERICAL SIMULATIONS

As mentioned before, numerical simulations of the water flow inside the moonpool were carried out in order to obtain a better insight into the physics related to the damping process. The numerical model was developed in full scale, having both geometric and dynamic similarity with the experimental model.

Computations were conducted on a 2D domain taking the advantage of the radial symmetry of the monocolumn structure. A slice type geometry was developed for the domain with an angle of rotation about the moonpool vertical axis of 0.5 degrees. A cartesian (x, y, z) coordinate system was used, with the Z coordinate as the vertical direction vertical and the bottom of the domain representing the x = 0 cm coordinate (Fig. 4).



Mesh detail near the skirt.

Figure 4. 2D numerical domain, slice type geometry.

The domain was discretized by a structured mesh consisting of hexahedrons. An extensive domain and grid-independence tests were performed resulting in a final non-uniform, body-fitted mesh with 1200k hexahedral elements. The mesh was particularly refined in the near wall region so as to completely resolve the inner turbulent and viscous sub-layers. As a result of the grid-independence test, a fine grid with y^+ varying from 0.5 to 2 was obtained. The cell-aspect ratios in the region near the internal skirt/bottom of the hull were 1.0/1.0. At the bottom and the outer regions of the domain, a relatively coarse mesh was used, with cell-aspect ratio of 50/1. The boundary conditions at the hull and the symmetry planes are immediately defined. The dynamics of the air and the water flows, respectively, at the top and the outer edge of the domain were modeled adopting an opening type boundary condition.

The equations governing the problem were solved using the well known code ANSYS CFX, release 11. The code solves the Reynolds averaged Navier-Stokes equations (RANS) through a finite volume approach. The solution procedure is based on a fully implicit discretization of the governing equations. In the present work, the well-known eddy viscosity model SST (Shear Stress transport) κ–ω Based Model was adopted for the computation of the turbulent properties. The Volume of Fluid (VOF) method was adopted for the simulation of free surface flow.

The κ–ω model considers that the turbulent viscosity, ν_τ, is related to the turbulent kinetic energy, κ, and the turbulent frequency, ω, through the expression

$$\nu_\tau = \kappa/\omega \tag{1}$$

The κ–ω based model formulation has become very popular over the last few years for its apparent superior performance for the treatment of near wall conditions. The κ–ω model does not require the introduction of the typical non-linear dumping functions present in the κ–ε model and, for this reason, should be more accurate and robust. As a matter of fact, the κ–ω model can be resolved with a near wall resolution of $y^+ < 2$.

The two transport equations for the κ–ω model can be written as

$$\frac{\partial \kappa}{\partial t} + \overline{u_i}\frac{\partial \kappa}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\upsilon + \left(\frac{\upsilon_t}{\sigma_\kappa}\right)\right)\frac{\partial \kappa}{\partial x_i}\right] + P_k - \beta' \kappa\omega \tag{2}$$

$$\frac{\partial \omega}{\partial t} + \overline{u_i}\frac{\partial \omega}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\upsilon + \left(\frac{\upsilon_t}{\sigma_\omega}\right)\right)\frac{\partial \omega}{\partial x_i}\right] + \alpha\frac{\omega}{k}P_k - \beta\omega^2 \tag{3}$$

where $\overline{u}$ represents the mean flow velocity.

The κ–ω model constants are given by

$$\alpha = 5/9$$
$$\beta = 0.075\ ;\ \beta' = 0.09$$
$$\sigma_\kappa = 2\ ;\ \sigma_\omega = 2$$

The Shear Stress Transport (SST) κ–ω Model accounts for turbulent shear stress transport by considering

$$\upsilon_\tau = \frac{\alpha\kappa}{max(\alpha\omega, SF_2)} \tag{4}$$

where F_2 is a blending function and S is an invariant measure of the strain rate.

The blending function F_2 is given by

$$F_2 = \tanh(\arg_2^2) \tag{5}$$

with

$$\arg_2 = \max\left(\frac{2\sqrt{k}}{\beta'\omega y}, \frac{500\upsilon}{y^2\omega}\right) \tag{6}$$

Numerical computations of the flow inside the moonpool were carried out for two configurations. The first model, named Model A (50.0 centimeters opening), does not have any restriction at bottom of the moonpool. The other model selected for the numerical investigations was Model B (40.8 centimeters opening), which has a skirt installed at the bottom of the moonpool.

The numerical simulations covered the first 3 seconds of the experimental tests. In Fig. 5 and Fig. 6, the numerical results obtained for the variation of the water level inside the moonpool are compared to the experimental data for each model. As can be seen, a good agreement between the numerical and the experimental decaying curves was achieved, suggesting that the numerical model is able to reproduce the flow behavior. Considering that, the numerical results can be used to obtain a better understanding of the physics of the flow inside the moonpool.

A sequence of vector plots showing the velocity field inside the moonpool of Model A is presented in appendix (Fig. A1..A7). As the flow enters the moonpool a vortex structure is formed near the bottom edge. The vortex structure grows until the water level reaches its maximum level. As it leaves the moonpool, a counter vortex is formed. This vortex actually acts as a buffer of energy. When the second cycle begins, a higher amount of energy is transferred to the vortex that is formed at the bottom edge, resulting in a larger structure. It is important to notice that the original vortex did not vanish.

The energy dissipation inside the moonpool is governed by the vortex formation process. The higher the vortex structure the higher dissipation of energy. The maximum size that a vortex can attain inside the moonpool is a function of the magnitude of the flow velocity near the bottom edge. Since the flow inside the moonpool is mainly governed by the hydrostatic pressure gradient, the scale of the vortexes structures is directly influenced by the local draft at the moonpool. It can be clearly observed in the results obtained for the Model B (see vector plots in appendix: Fig. B1..B7). The initial displacement of the free surface adopted for the experimental test of Model B was higher compared to Model A. Tests with Model A were conducted with an initial displacement of the free surface of 6.0 centimeters, while an initial displacement of the free surface of 10.3centimeters was used for the experimental tests with Model B. These initial displacements conditions are comparable to full scale conditions.

As predictable, the initial vortex structure that appears in Model B is larger than that observed in Model A. This is a direct effect of the higher flow velocity at the bottom edge caused by the higher initial draft step. The existence of the skirt results in a more complex vortex pattern. Counter vortexes appear near the skirt edge during the entire test. An important behavior that was observed in the test of Model B is that the vortex initially formed did not leave the moonpool. Even when the flow is coming downward the vortex did not come out of the moonpool. It can be noticed that the vortex scale almost reach the moonpool radius. When the flow comes upward at the beginning of the next cycle this huge vortex structure goes up towards the free surface. As it comes upward with the flow another vortex structure is formed at the end of the skirt. The presence of this new vortex structure will result in an interesting effect. The first vortex that goes upward with the flow remains confined near the free surface by the new vortex. As the flow goes upward and downward the first vortex grows until it reaches the free surface. At this moment, a spurt occurs at the free surface, dissipating the vortex energy.

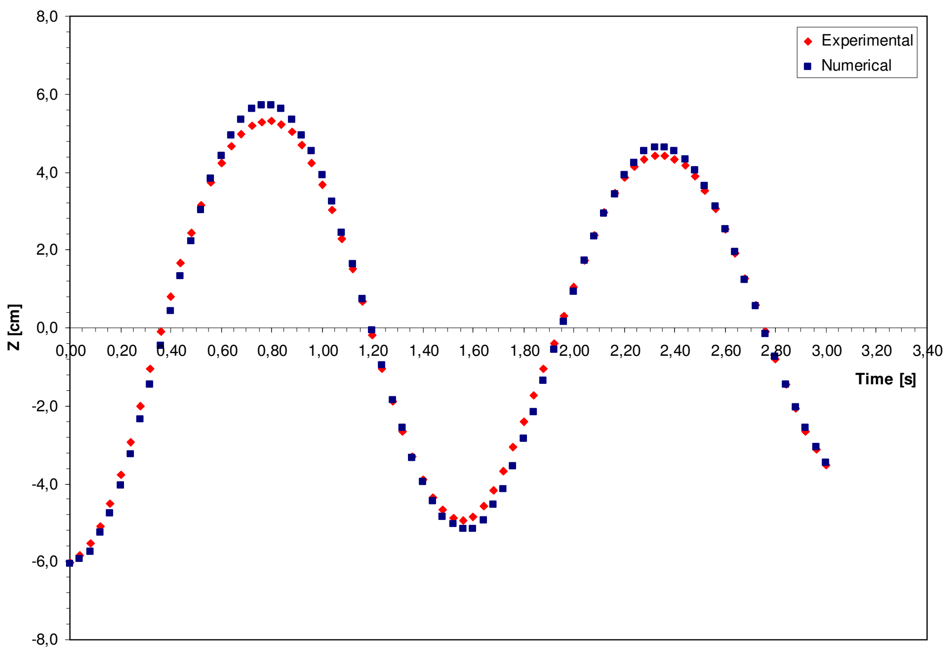


Figure 5. Experimental and numerical decaying curves - Model A.

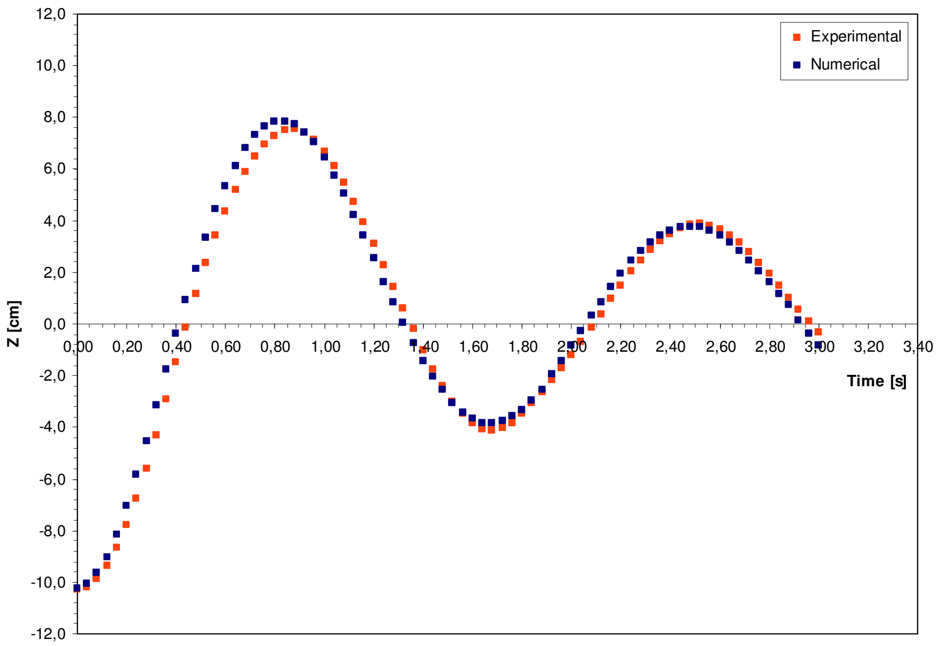


Figure 6. Experimental and numerical decaying curves - Model B.

4. CONCLUSIONS

Experimental results showed that the viscous effects caused by a skirt installed at the bottom of the moonpool may have a stronger influence on the dynamic behavior of a monocolumn platform. Although the use of the potential theory is a common practice in the analysis of the dynamic behavior of floating structures in regular waves, coupling wave and viscous effects, it seems that the representation of the complex flow around the skirt can not be well described by a single parameters.

In order to obtain a better insight into the flow characteristics around the skirt numerical simulations of the water flow inside the moonpool were carried out using as reference a set of free decaying experimental tests. It was observed that the flow inside the moonpool presents a very complex behavior, characterized by the onset of complex vortex structures. A good agreement between the numerical and the experimental decaying curves was achieved, suggesting that the numerical model is able to reproduce the flow behavior inside the moonpool.

5. REFERENCES

Aalbers, A. B., 1984, “The Water Motions in a Moonpool”, Ocean Engineering, Vol. 11, No. 6, pp. 557-579.

Barreira, R. A., Sphaier, S. H., Masetti, I. Q., Costa, A. P. and Levi, C., 2005, “Behavior of a Mono-Column Structure (MONOBR) in Waves”, 24th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Halkidiki, Greece.

Matsuura, M., Isozaki, Y., Ishibashi, Y., 1995, “Development of Monocolumn Type Hull Form with Passive Type Motion Damping Devices for Floating Production System”, 14th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), V. I-A.

Nishimoto, K. *et al.*, 2001, “A Study of Motion Minimization Devices of FPSO”, 20th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Rio de Janeiro, Brazil.

Sphaier, S. H., Torres, F. G. S., Masetti, I. Q., Costa, A. P. and Levi, C., 2007, “Mono-Column Behavior in Waves: Experimental Analysis”, *Ocean Engineering*, OE 1319.

Torres, F. G. S. *et al.*, 2004, "Study of Numerical Modeling of a Moonpool as a Minimization Device for a Monocolumn Hull", 23th International Conference on Offshore Mechanics and Arctic Engineering (OMAE), Vancouver, Canada.

Torres, F. G. S. *et al.*, 2004, "Projeto Hidrodinâmico de uma Plataforma do Tipo Mono-Coluna – MONOBR", Sociedade Brasileira de Engenharia Naval (SOBENA), R122, Rio de Janeiro, Brazil.

Torres, F.G.S; Nishimoto, K.; Sphaier, S. H., 2007, "Brief Discussion of the Behavior of a Mono-column coupled with a Moonpool", 3rd International Workshop on Applied Offshore Hydrodynamics (IWAOH), Rio de Janeiro, Brazil.

Torres, F.G.S. et al., 2007, "Hydrodynamic Design of a Monocolumn Platform Avoiding Excessive Heave and Pitch Motions", 11th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS), Houston, EUA.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.

7. APPENDIX

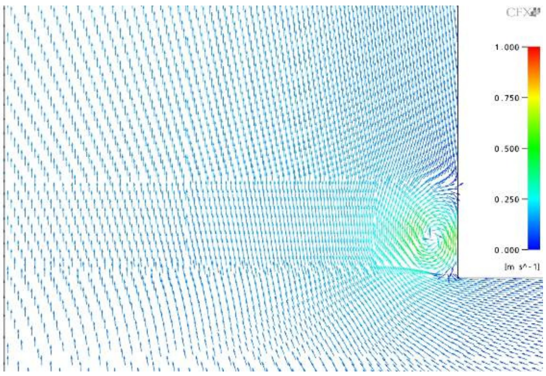


Figure A1. Model A – t = 0.6s.

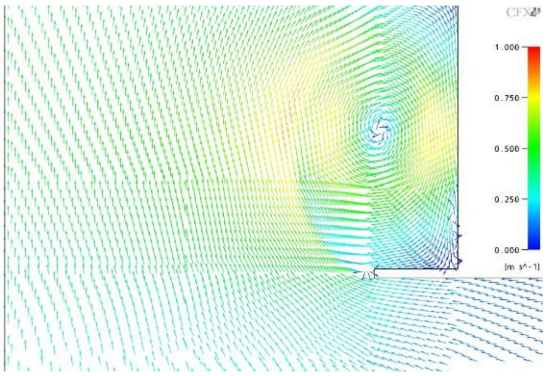


Figure B1. Model B – t = 0.6s.

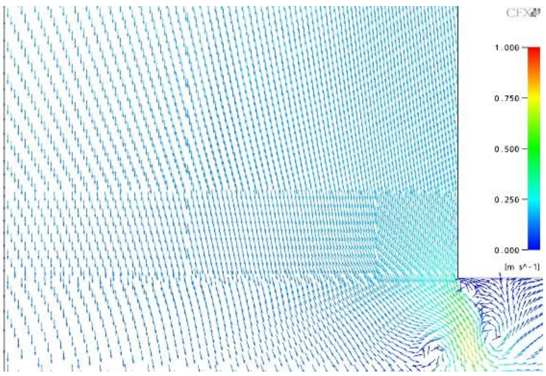


Figure A2. Model A – t = 1.0s.

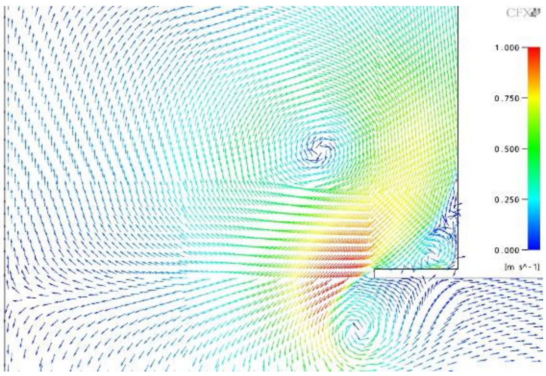


Figure B2. Model B – t = 1.0s.

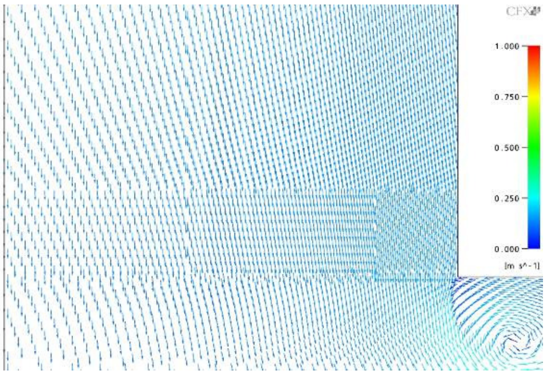


Figure A3. Model A – t = 1.4s.

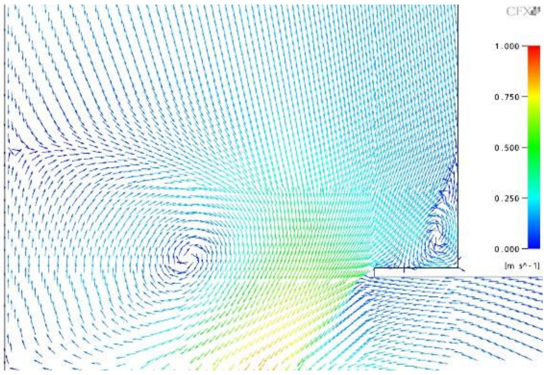


Figure B3. Model A – t = 1.4s.

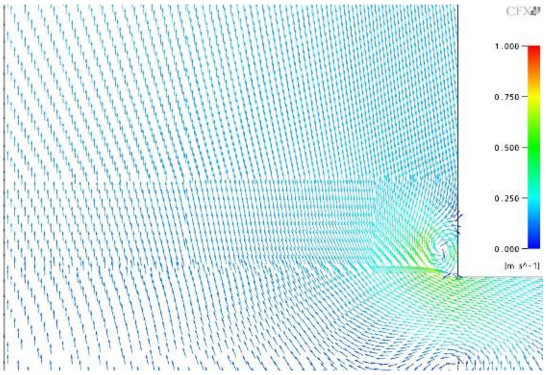


Figure A4. Model A – t = 1.8s.

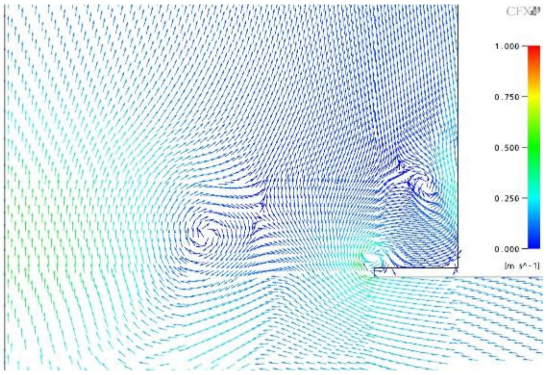


Figure B4. Model A – t = 1.8s.

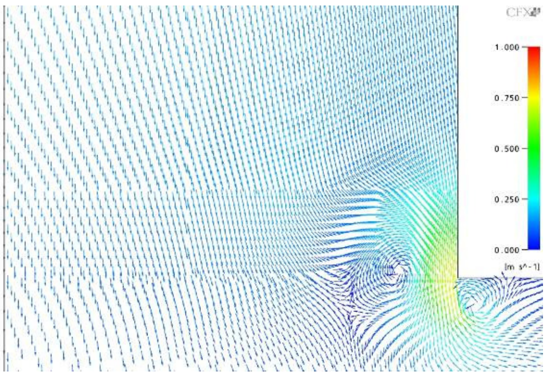


Figure A5. Model A – t = 2.6.

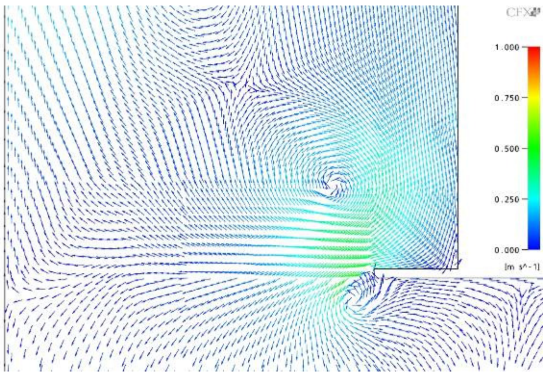


Figure B5. Model A – t = 2.6.

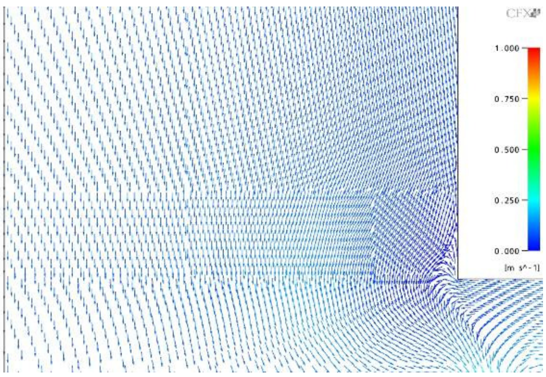


Figure A6. Model A – t = 3.0s.

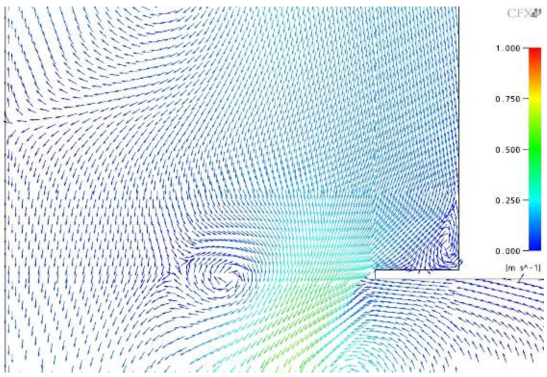


Figure B6. Model A – t = 3.0s.