Numerical Offshore Tank: New Design Paradigm for Offshore Production Systems

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ABSTRACT

There are several developments concerned to simulate the behavior of floating bodies under waves in the restricted boundary conditions so called numerical wave tank. The main feature of these tanks is to calculate full Navier-Stokes equations taking account the viscosity and free surface conditions. However, the dynamic behavior of oil floating exploitation units in actual ocean environmental condition, in waves, wind and current, is more complex and very difficult to simulate using full non-linear Navier Stokes equations. In addition, in the ultra-deep water, it is the primer importance to consider the more precise mooring line and riser's dynamics in the analysis.

The present numerical simulator laboratory called Numerical Offshore Tank is a development that takes account almost all physical phenomena acting on the floating bodies and mooring and risers lines. Since full non-linear solution is not available, the several numerical, empirical and analytical models are being considered and integrated to numerical simulator

The time domain potential problem is solved to wave forces acting on the bodies and empirical models are used to simulate current and wind forces. To represent mooring & riser lines, the finite element model with more realistic hydrodynamic force models is used.

Even the simulator is using the full hydrodynamic equation, the calculation time of the simulation for floating bodies with several risers & mooring lines is very high. Therefore, special cluster with 120 PC based computer was built running the code in the parallel processing.

Since the preparation of all data set for numerical experiment is very tedious work, the special pre-processor PREA3D was developed for this purpose. This pre-processor allows the fast change of the environmental and system conditions to run several test conditions.

Another important feature is the visualization of the results of the simulation tests. The entire 3D view of the system is presented in the Virtual Reality room with stereoscopic projection of the Numerical Tank Laboratory.

INTRODUCTION

The Brazilian oil company, Petrobras, was pioneer in deepwater oil production systems breaking several world wide records in deep water oil exploration. It is well known that there are several oil & gas fields in more deep water at offshore Brazil and Petrobras is preparing to produce oil in ultra deep water (more than 3000m).

PROCAP 3000 is a Petrobras research program to develop several new technologies to reach the oil production in the ultra deep water. Besides ultra deep water sub sea facilities developments, there are several challenges in the Naval & Ocean Engineering fields like mooring & positioning systems, riser technology, installation & conceptions of the floating production systems.

Traditionally, verification & validation of those systems are performed using reduced models in the Ocean Basin tests with wave, current & wind to observe dynamic behaviors of the full system. The special facilities for wave, current & wind generators are equipped in the Basin to reproduce several ocean environmental conditions

However, even for deepest Ocean Basin in the world, there are some physical restrictions to perform some validation model tests. For 3000m water depth, for example, the model scale could be smaller than admissible level of precision and scale effects. Some ocean basins are provided with pit tank for deep vertical risers or positioning systems, but for floating production systems that use SRC, flexible risers and taut synthetic mooring system these pit tanks can not used for simulate these lines.

Especially in the Brazil, there is some tendency to install floating units with several risers in the deep waters. Some units are provided with almost 100 risers and mooring lines. It is not possible to imagine dynamics of floating body without the effects of dynamics of these lines.

The effect of the current velocity profile on the lines also is becoming very important to know how current velocity profile affects the dynamics of the all system.

Another important hydrodynamic effect that should be considered is the effect of the presence of two or more floating bodies near by the main production unit. The interference effects on the wave, current and wind should necessary incorporated in the simulation process.

Several Computer Fluid Dynamic –CFD codes, solving the full Navier Stokes equation, are being developed for the analysis of the floating structures, but still are not useful for high Reynolds number and even so, computer time is excessively high.

Therefore, the oil & gas industry was searching the alternative solution for validation of the new ultra-deep water production units and fill the empty space left between model tests and full scale design process.

The Numerical Offshore Tank is a laboratory that the Center of the Excellence of Naval & Ocean Engineering & Petrobras joined several research groups of different institutions related with the development of the deep water production units of Petrobras.

The main purpose of the laboratory is to develop numerical simulator enable to simulate dynamics of the floating units coupled with pipelines or risers and all production risers and mooring lines in several combination of the ocean environmental conditions.

Therefore, this paper is presenting the contents of the development and main results that obtained using this challenging development and innovating technology.

SIMULATION CODE

The heart of the numerical simulator is equation of the motion given by traditional Newton law developed for floating bodies' dynamics representation.

In order to study the ship motions, it is useful to adopt two different coordinate systems as shown in Figure 1.

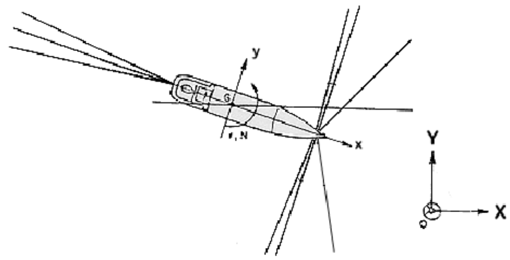

Figure 1 – Coordinate system

The axis system, OXYZ is fixed on the earth (inertial system) and the axis system, Gxyz is fixed on the ship with the origin at the ship center of gravity.

Applying Newton's law of the motion, the following differential equations describing the relationships between the motion variables, referred to the Gxyz system, and the external loads are obtained:

$$\mathbf{M} \cdot \mathbf{a} = \mathbf{F}_{\mathbf{ext}} \qquad (1)$$

where **M** is the mass matrix (6x6) and $\mathbf{F}_{ext}$ (6x1) is a vector of the external load acting on the center of gravity in each of six dimension of the problem. In this way **a** is the acceleration of the unit in each dimension.

The external loads and moment may be expressed in terms of different factors, as, for instance for $\mathbf{F}_{ext}$:

$$\mathbf{F}_{ext} = \mathbf{F}_{\mathbf{i}} + \mathbf{F}_{\mathbf{h}} + \mathbf{F}_{\mathbf{wav}} + \mathbf{F}_{\mathbf{c}} + \mathbf{F}_{\mathbf{w}} + \mathbf{F}_{\mathbf{wd}} + \mathbf{F}_{\mathbf{m}} \qquad (2)$$

where $\mathbf{F}_{\mathbf{i}}$ represents the hull inertia force, $\mathbf{F}_{\mathbf{h}}$ the hull damping force, $\mathbf{F}_{\mathbf{wav}}$, $\mathbf{F}_{\mathbf{c}}$ and $\mathbf{F}_{\mathbf{w}}$ represent the wave, current and wind, respectively, $\mathbf{F}_{\mathbf{wd}}$ represents the current and wave interaction and $\mathbf{F}_{\mathbf{m}}$ the mooring loads.

In Brazil, several simulators for semi-submersible & Ship form platforms were developed in past 10 years to attend Petrobras deepwater challenges.

The DYNASIM (2001) & PROSIM (2000) have been used for several mooring & riser design projects for FPSO & SS production platform.

Both programs have been calibrated using several model tests carried from MARIN & MARINTEK and full-scale measurement.

Since the coupled dynamics with floating bodies & risers-mooring lines are very important for ultra deep water production units validation and verification, more adequate and precise hydrodynamic models and lines Structure Finite Element model are desired.

To consider this coupled dynamics and more adequate hydrodynamic model, computer process time increases.

Differently from CFD based Numerical Wave Tank, the Numerical Offshore Tank main propose is to obtain more realistic real scale dynamics behavior in total environmental forces in the sea.

For hydrodynamic force estimation, the NOT uses WAMIT (2000) for first and second order wave forces with or without interaction between two or more floating bodies, the current and wind forces extrapolate from semi-empirical formulation based on the towing and yaw rotating tests and interaction between current and wave and Wave Drift Damping also are considered in the numerical model.

To estimate the dynamic effect of the lines an algebraic expression and a nonlinear time domain method, using finite element method, were implemented to estimate the dynamic tension in the time domain.

For FEM lines model, two types of elements are implemented, truss and beam elements can be chosen for adequate analysis of the lines.

Aranha et. al. (2001) presents some results obtained with the algebraic expression and Silveira et. al. (2000), some results obtained wit the FEM.

There are, at least, two part of the simulator that is time-consuming process, one is the FEM of the lines and another part is the calculation of hydrodynamic forces when two or more bodies are present.

Looking for a analyses of the production system with *n*-bodies (platforms, vessels etc.), the inclusion of six degrees of freedom effects, static configuration calculus in each moment and the possibility of the analyses of the lines in Finite Element Method it has become fundamental the code parallelization for its execution on several processes that would be parallel and independent in different processors.

The parallelization code

Four initial decisions should be taken when it is decided to parallelize a program: the hardware and the software to be adopted and how and how much the code should be parallelized.

In the hardware scene, the choice was between a supercomputer with several CPUs or a cluster, which is a group of PC-like microcomputers that intercommunicate by a net and uses as little as possible room.

The second option was chosen due to the following advantages:

- More facility of expansion and maintenance.
- Lower costs.

In the hardware scene, the question was what kind of process manager should be chosen. The options, PVM (Parallel Virtual Machine) and MPI (Multiprocessing Parallel Interface), are quite similar, and the later was chosen because it was developed by companies and universities groups to be a standard in the market, besides it has more advanced implementations in a comparison to the PVM.

The adopted way to parallelize was the static one, which means using no dynamic management of processes. It means that each process occurs in a unique CPU during the simulation. Besides the simpler implementation, the static processes distribution is adequate to the frequent interprocessual communication type that happens in NOT in relation to its performance.

Parallel processes

The object-oriented programming adopted in the NOT code allows distinguishing clearly three possible levels of implementation to parallelize:

the case level (environmental condition combination), the bodies level (floating units) and the lines level (mooring lines, risers and linking cables among the several floating units). Each case is characterized by the calculus of the position, the velocity and the acceleration of units (bodies) for a determinate group of environmental conditions. Each body must consider the environmental, inertial, hydrodynamic, mooring lines, risers and linking cables with other bodies' forces. Since the computational time of the lines forces, using the Finite Element Method as a model, is much higher than the time required to compute all the others forces, a parallelization level only to the line calculus was created. In this way, there are three types of processes:

- Case process: position, velocity, acceleration and linking line tensions are obtained and the output files are generated
- Body process: all forces in the unit are calculated except the lines ones
- Line process: the line tension belonging to a determinate body is calculated

Due to this structure, two synchronization processes occur during the simulation:

- Synchronization inside the cases processes, because it is only possible to initiate the next "time step" calculus when every bodies processes have finished their calculus
- Synchronization inside the bodies processes, once it is necessary that every line processes finish their tensions calculus of in order to sum all loads above each body process.

The distribution of process is linear among processors. First the cases processes are processed and in sequence the bodies and lines processes.

The communication among the processes occurs as the following manner:

Before initializing the simulation, main-process import the data file and distributes it among other processes.

In each time step of simulation, the body process receives the force that each line process computes, sums the other loads and computes the acceleration, velocity and position of body, sending this data to the case process that it belongs. The case process replenishes its body's processes whit this data and the line forces that attach the bodies (linking lines) for the calculus of next time step. Simultaneously, it gives directly to the lines processes the position of corresponding body, since the calculation of force acting in the line depends only upon its upper ending coordinates.

The figures down illustrate, respectively, the distribution of processes in the computers and the exchange of information among processes during simulation.

It must be emphasized that when the number of processes is superior to processors, the manager of MPI distributes automatically the extra load homogeneously among CPUs.

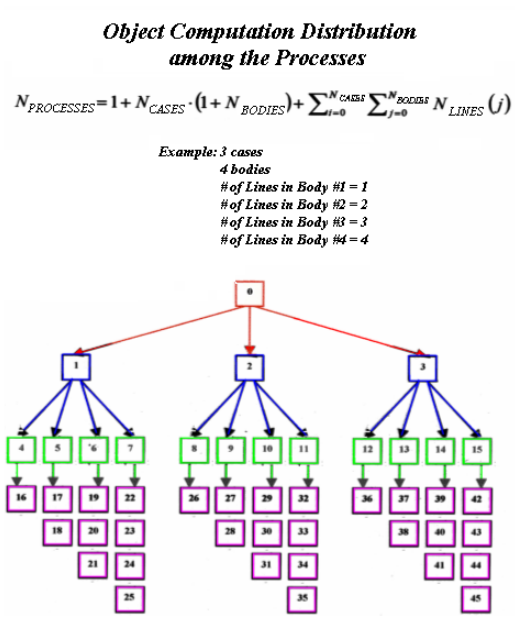

Figure 2 – Processes Distribution

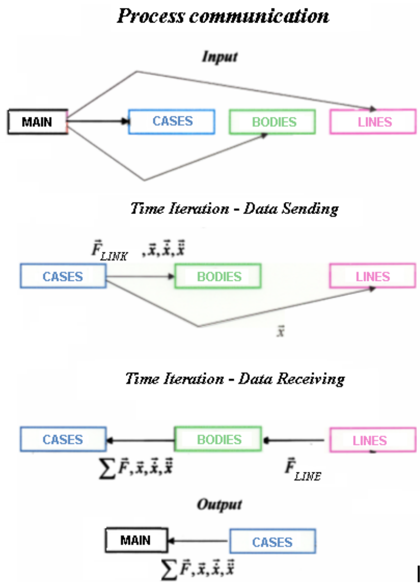

Figure 3 – Exchanged information between processes

Computer Cluster

The concept of parallel processing *Beowulf* came up from Goddard Space Flight Center, USA, at 1994 by Thomas Sterling and Donald Becker.

The *Beowulf* machine is a cluster of the PC computer connected by network that works as a parallel super computer system.

The use of this machine is not just replacing the conventional super computer workstations, but also changing the computer *culture* when the simulation software is developed.

NOT laboratory provided by a cluster room with the capacity of the more than 300 CPUs of class of Pentium IV.

The actual configuration of the NOT is 60 CPUs with following specifications:

- Main Processor**;** Intel Pentium III of 866 MHz;
- RAM with 256 Mbytes;
- Hard Disk of 20 Gbytes - IDE;
- Ethernet network system with 100 Mbits/s;
- Flexible disk Drive;
- Video board;
- Cabinet.

For end of this year, more 60 or 90 CPUs will be installed in this room increasing the capacity of the NOT.

Since the cost effectiveness is very high and cluster is inexpensive compared with conventional workstations, the actualization of the hardware will be easier than traditional super computing.

Figure 4 – Cluster view from rear side.

HYDRODYNAMIC COEFICIENTS & LOADS

The dynamic of the floating bodies depends of accurate estimation of the hydrodynamic forces acting on the bodies.

The strong point of the NOT simulator is the real time calculation of the hydrodynamic wave diffraction and radiation potentials.

When the floating body is alone without connection of another body, the process is conventional. However, when there are more than two bodies connected by lines, the problem becomes more complex, especially because the position of each body changes with time.

Wave

The first and second order wave radiation and diffraction forces are calculated by potential theory using panel method. For a case, the TPN used WAMIT code and extracted added mass, potential damping, wave first and second order exciting forces to generate memory function and impulse response function to be used in the equations (1) and (2).

The Investigation brought to us the new form to calculate interaction between two or more floating bodies.

Since parallel processing is very fast and the relative attitude between the bodies is given by simulation, if the calculation of the memory and impulse functions from frequency domain will be very fast, the calculation of hydrodynamic iteration between bodies can be done from this way.

Current

The current loads are given by three different models developed along of the time:

- Cross Flow based model
- Low speed manoeuvring model
- Short Wing based model

The details of all these models are described in Fujino et. al. (1984), Obokata (1987) and Obokata et. al. (1988), Takashina (1986) and Takashina et. al. (1990) and Leite et. al. (1998). Difference between the models is not so small.

Wind

The wind forces also can be obtained from empirical formula, since the numerical direct calculation still expensive and inaccurate.

Interaction between Wave & Current

It had been shown that there is an influence of drift velocity of an ocean vehicle on the exciting forces that cause it. This effect is called wave drift damping and may be the dominant damping mechanism. Description of the phenomenon and derivation of computing methods were presented by different authors: Wichers (1982) and (1988), Grue et. al. (1997) and Aranha (1994).

In the present paper we use the procedure proposed by Aranha (1994) and Martins et. al. (1999) to compute the wave drift damping matrix and the interaction between wave and current.

Mooring & Riser Lines Damping

There are some procedures proposed to estimate this source of damping, like those proposed by Huse et. al. (1989) and recently Le Boullec et. al. (1994). A methodology proposed by Nishimoto et al. (1997) is used other than direct calculation from Finite Element method in coupled analysis.

Coupled analysis – lines &floating bodies

The most accurate design methodology for floating offshore systems comprises the use of analysis programs based on coupled formulations, such as those included in the Numerical Offshore Tank project. Such programs incorporate, in a single code and data structure, a hydrodynamic model for the representation of the vessel, coupled to a 3D finite-element model for the representation of the hydrodynamic and nonlinear structural dynamic behavior of the mooring lines and risers.

Programs with these characteristics have been developed since 1997 by the R&D center of Petrobras, with the cooperation of researchers from COPPE/UFRJ and DENO/USP: the Prosim (2000) and Dynasim-A (2001) programs.

The development of the Prosim program began in 1997. It is oriented towards the coupled analysis of floating production systems based on TLP, semi-submersible or Spar platforms, characterized by large-diameter cylindrical members or framed members in general. The hydrodynamic model that represents the hull is based in an extended Morison formulation, similar to the employed in the TDSIM6 program, TDSIM (1992). The extended Morison formulation allows the representation of diffraction and radiation effects that occur in large-diameter members. Mean and slow drift forces, and frequency-dependent radiation damping, are incorporated and calculated from coefficients previously calculated by a diffraction program such as Wamit (2000). The Prosim program incorporates also 3D frame elements to adequately represent the bending behaviour of risers, and solves the line dynamics with an extension of the implicit Newmark algorithm, Newmark (1959), presenting numerical dissipation properties to eliminate spurious high-frequency components of the response. See Daniel (1997) and Wood et. al. (1981).

The Dynasim program, on the other hand, incorporates the hydrodynamic model for ships based on potential theory. Therefore, it is oriented to the analysis of floating production units based on ships, such as FPSO units. The initial version of the coupled Dynasim-A program incorporated the finite-element formulation, including 3D nonlinear truss elements, and the time integration of the line dynamics is performed using an extension of the explicit Central Difference algorithm.

The formulations involved on these programs have been enhanced and incorporated into the Numerical Offshore Tank project. The advantages of the coupled formulation implemented in these programs methodology are many:

- The interaction between all effects that dictate the nonlinear dynamic behavior of the system (vessel + lines) is considered – implicitly/automatically, and precisely:
    - **Implicitly** because there is no need of additional, explicit procedures to take into account the contribution of the lines in terms of stiffness, damping, mass and hydrodynamic loadings (such as the procedures presented in the previous section that calibrate scalar coefficients); everything is already incorporated in the algorithm.
    - **Precisely** because the dynamic equilibrium between vessel and lines is assured at every time step of the time integration process; the nonlinear effects due to the variation of stiffness, damping, added mass and hydrodynamic loads with respect to time and position are taken into account.
- The combination of these characteristics leads to results that are not only more accurate, but also more robust and reliable, since they do not depend on the know-how of the engineer, needed in the process of evaluating and calibrating the different scalar coefficients that represent the contribution of the lines in the uncoupled methodology.

One single analysis can generate simultaneously the motion response of the vessel, and all parameters of the structural response of the lines and risers (e.g. tension in mooring lines, tensions/bending moments/curvatures in all sections of the risers).

However, this latter advantage will only be fulfilled if all risers can be modeled by a finite-element mesh as refined as the ones employed in the structural analysis of a single riser (with the Anflex program, Anflex (1996), for instance), that are performed on the second stage of the uncoupled methodology.

This reflects the only disadvantage of this coupled methodology, which is its excessive computer cost (at least for the current level of PC computing power). Fully coupled time-domain analyses are therefore currently unfeasible for the current design practice, which requires, for instance, hundreds of analysis for the assessment of fatigue behaviour on lines. This disadvantage will eventually be circumvented by the development of optimized algorithms for the solution of the nonlinear dynamic problems, including equation solvers, time-integration algorithms, and sub cycling techniques, also associated with the implementation on computers with parallel architecture. Efforts in this direction are being performed in the context of the Numerical Offshore Tank project

Nevertheless, although not currently suitable for design practice on daily-basis, the use of fully coupled models are already being employed for the verification of special designs and critical cases, and in situations where the development of an experimental model is not feasible because of scale limitations due to the maximum depth in the available wave tanks. In fact, this is exactly the main objective of the Numerical Offshore Tank project.

Post processors virtual reality scientific visualization

Usually, the results of the simulation program like NOT are visualized in the conventional scientific visualization program. Some times, those programs bring us several graphs and statistics, but physics meaning of the graphs and time histories are not explained clearly and for person from different field of study difference between good and poor results is not clear.

In the Numerical Offshore Tank project, there are two type of post processor. One is PosTPN that can run in the personal computer and on the Visualization room, but it is more traditional post process.

Another one is TPNView, which tried to bring the Virtual Reality World into Scientific Visualization.

The Virtual Realty World is introduced in several field of application like medicine, home architecture, etc.. However, because of the computational time, the 3D model presented in this World is always static.

If the VR models move dynamically, you can visualize simulation results and see and feel the real displacement, velocity and acceleration of the bodies.

The TPNView is a code that makes this happen without much computational time.

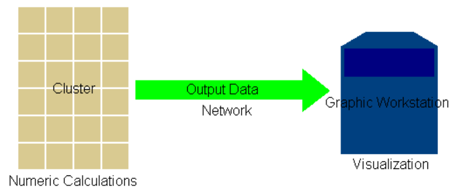

Figure 5 – Architecture of NOT

Since the output data produced from cluster is very large, the data should be stored before or visualized on real time.

To store the data, the common data base is structured and all the data necessary to visualize each time is provided in fast way.

The Figure shows the relation between NOT simulation code and TPNView through database. The TPNView is divided in two modules; one for Graphic representation of results by CG (Computer Graphics) and another is to interface GUI (Graphical User Interface) to help the users.

The TPNView is completely written in C++, object oriented, on an API (Application Program Interface) OpenGL PERFORMER and X/Motif.

The CG engine of the TPNView is composed by following independent component that represents the total scenario of simulation:

Floating Unit – In the present stage of development, the floating unit is represented as the rigid body and created by Multigen Creator running on the SGI platform.

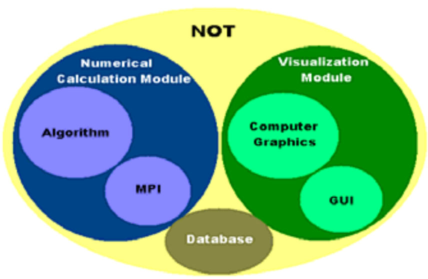

Figure 6 – Modular Diagram

ILLUSTRATIVE EXAMPLES

The results presented in this section try to show the relationship between vessel motions and line tensions. A unit in a DICAS (*Differentiate Compliance Anchoring System*) configuration is used to illustrate the results obtained with the simulator of the TPN.

Data and Assumptions

Unit

The unit used as illustrative example has the following main characteristics:

draft (T): 21.62 m;
beam (B): 25.6 m.
total length (L): 175.8 m;
total dead weight 20000 tons;
maximum displacement: 35000 tons;

In the analyses, the unit used a DICAS mooring system configuration operating in a water depth equal to 152 meters.

Environmental data

The unit will be analyzed when submitted to real environmental conditions corresponding to its probable operation site. Table 1 presents the values considered to each environmental agent.

A triangular profile of current with velocity equal to zero at bottom was considered in these analyses.

Table 1 – Environmental data

Current Velocity (m/s)	1.15
Wind Velocity (m/s)	30.7
Significant Wave Height (m)	8.7
Up-zero crossing period T_Z (s)	12.6

Mooring System

The analyzed mooring system was composed by 10 lines. All lines were identical and two segments composed them. Figure 7 illustrate the system and Table 2 presents the mechanical properties of each segment.

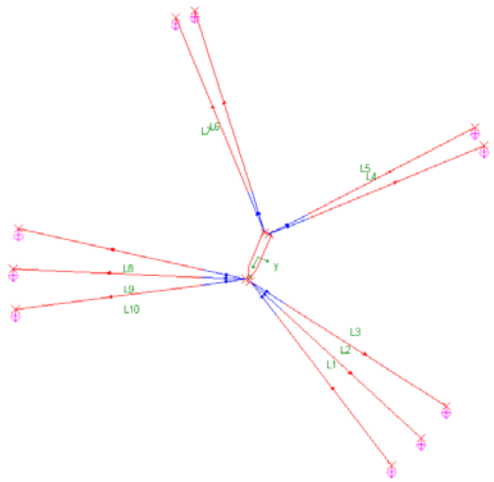

Figure 7 – Analyzed System

All the lines had 2 segments with the following composition:

Table 2 – Line Composition

	Top	Bottom
Length (m)	150	650
Diameter (m)	0.076	0.105
Weight in Water (kg/m)	1.2	2.1
EA (kN)	546000	904000
Material	R4 Studless Chain	R3 Stud Chain

Results

Figure 8 and Figure 9 show, respectively, the linear and angular motions and the Figure 10 represents de vessel motion and line top tension of line #1 between 300 seconds and 400 seconds of simulation. Theses signals are not perfectly phased due to the dynamic influence of the line portions near the top, which are not necessarily moving in phase with the vessel.

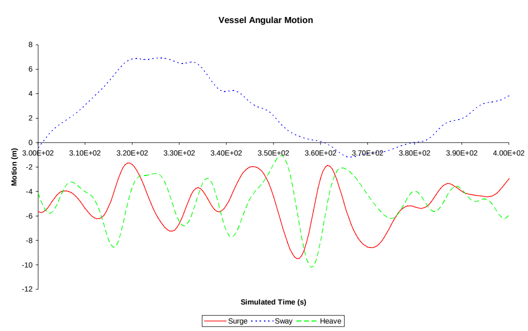

Figure 8 – Vessel Linear Motion

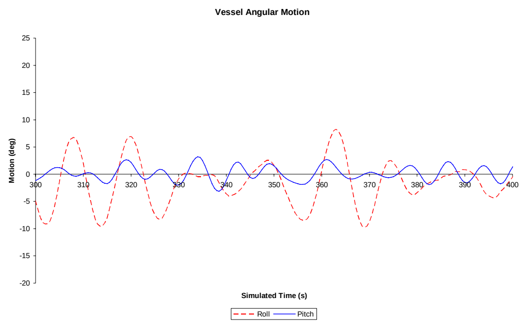

Figure 9 – Vessel Angular Motion

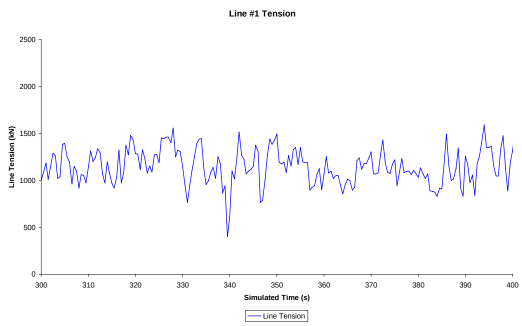

Figure 10 – Line #1 Tension

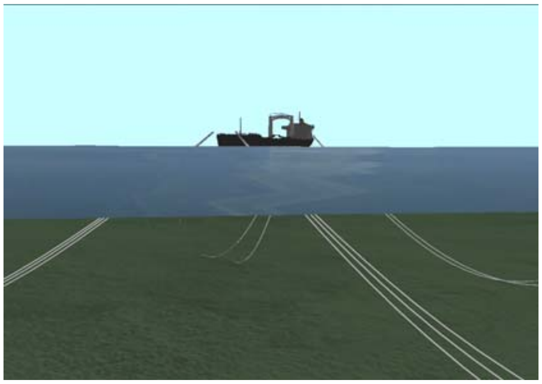

Figure 11 – 3D visualization of results

These results can be manipulated by the NOT's pos-processor, TPNView, both in graphical mode, for a statistical analysis, or in 3D view mode, for a overall system quality analysis.

CONCLUSIONS & REMARKS

NOT, due to its fully compared models with ocean basin and full scale tests, can be used in complementation to the ocean basin tests when the later has some limitation in representing the full scale system.

Even the cases that can be carried out using reduced scale models, the availability of a simulator is interesting in the matter of defining basic system characteristics and estimative analyses, thus reducing these tests costs.

In the simulations executed using NOT, the offshore floating systems analyzed computationally and the full scale operating systems had similar dynamic behavior.

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REFERENCES

ANFLEX (1996). *Análise Não-Linear de Risers e Linhas de Ancoragem (Versão 3.0).* Reference Manual, DIPREX/SEDEM/CENPES/PETROBRAS, 1996.

Aranha, J. A. P.; Pinto M. O. (2001). *Dynamic tension of cable in a random sea: analytic approximation for the envelope probability density function*, Applied Ocean Research, vol. 23/2, pp. 93-101, 2001.

Aranha, J. A. P.; Pinto M. O. (2001). *Dynamic tension in risers and mooring lines: an algebraic approximation for harmonic excitation*, Applied Ocean Research, vol. 23/2, pp. 63-81, 2001.

Aranha, J.A.P. (1994)*. A formula for "wave damping" in the drift of a floating body,* Journal of Fluid Mechanics, vol. 275, pp. 147-155, 1994.

Astrup, O.C., Nestegard, A., Ronoess, M., Sodahl, N. – *Coupled Analysis Strategies for Deepwater Spar Platform*" – ISOPE June/2001.

Chaudhury, G. - *A New Method for Coupled Dynamic Analysis of Platforms* – ISOPE June/2001.

Daniel, W. J. T. (1997). *The Subcycled Newmark Algorithm,* Computational Mechanics, vol. 20, pp. 272-281, 1997.

Dynasim (2001). *Dynamic Simulation – version 2.06*, Reference Manual, Department of Naval Architecture & Ocean Engineering, University of São Paulo.

Finn, L., Datta, I., Gupta, H. *Coupled Dynamics of Spars in Deep Water* – DOT 2000.

Fujino, M.; Ishiguro, T. (1984). *Study of the mathematical model describing maneuvering motion in shallow waters*, Journal of the Society of Naval Architects of Japan, vol. 154, nov. 1984.

Grue, J. & Palm, E.(1997). *Wave drift damping of floating bodies in slow yaw motion*, Journal of Fluid Mechanics, 1997.

Heurtier, J.M., Buhan, P.Le, Fontaine, E., Cunff, C.Le, Biolley, F., Berhault, C. – *Coupled Dynamic Response of Moored FPSO with Risers* – ISOPE June/2001.

Huse, E.; Matsumoto, K. (1989). *Practical Estimation of Mooring Line Damping,* Offshore Technology Conference, Houston, 1989, Proceedings paper 6137, pp.135-148.

Jacob, B.P., Ebecken, N.F.F. - *An Optimized Implementation of the Newmark/Newton-Raphson Algorithm for the Time Integration of Nonlinear Problems* – Communications in Numerical Methods in Engineering, vol. 10 pp. 983-992, John Wiley & Sons, UK/USA, 1994.

Jacob, B.P., Masetti, I.Q., *PROSIM – Coupled Numerical Simulation of the Behavior Of Moored Semisubmersible Units* – COPPETEC-Petrobras Internal Report, Rio de Janeiro, 1997.

Kim, M.H., Ward, E.G., Haring, R. *Comparison of Numerical Models for the Capability of Hull/Mooring/Riser Coupled Dynamic Analysis for Spars and TLPs in Deep and Ultra-Deep Water*" – ISOPE June/2001.

Le Boulluec, M.; Le Buhan, P.; Chen, X.B.; Deleuil, G. Foulhoux, L.; Molin, B.; Villeger, F. (1994). *Recent Advances on the Slow Drift Damping of Offshore Structures,* International Conference on the Behaviour of Offshore Structures, BOSS'94. Oxford: Perganon Press, 1994, vol.1, pp.9-30.

Lee, C.H. *WAMIT – Wave Analysis MIT Program, User Manual* Dept. of Ocean Engineering, MIT, USA, 1998.

Leite A.J.P. & Aranha J.A.P. & Umeda C. & Conti M.B. (1998). *Current forces in tankers and bifurcation of equilibrium of turret systems: hydrodynamic model and experiments*, Journal of Applied Ocean Research, vol. 331 1998.

Martins M.R. & Brinati H.L. & Aranha J.A.P. & Leite A.J.P. (1997). *Influence of the Wave-Current Interaction on Drift Loads in FPSO*, 9th International Offshore & Polar Eng. Conference, Brest, France, may.30-june 04, 1999.

Mourelle, M.M., Gonzalez, E.C., Jacob, B.P. *ANFLEX – Computacional System for Flexible and Rigid Riser Analysis*, in: CARNEIRO, F. L. L. B. et alii (eds), International Offshore Engineering, pp 441-458, John Wiley & Sons, Chichester/New York, 1995.

Newmark, N. M. (1959) *A Method of Computation for Structural Dynamics*, ASCE Journal of Engineering Mechanics Division, Vol. 85, pp. 67-94, 1959.

Nishimoto, K. & Kaster, F. & Masetti, I.Q. & Matsura, J. & Aranha, J.A.P. (1997). *Full scale decay test of a tanker: field data and theoretical analysis*, Journal of Ocean Engineering.

Nishimoto, K., Masetti, I.Q., *DYNASIM – Numerical Simulation of the Behavior Of Moored Ships* – USP-Petrobras Internal Report, 1998.

Obokata, J. (1987). *On the Basic Design of Single Point Mooring Systems (1st report),* Journal of the Society of Naval Architects of Japan, vol. 161, june 1987.

Ormberg, H., Fylling I. J., Larsen K., Sodahl N. *Coupled Analysis of Vessel Motions and Mooring and Riser System Dynamics* – OMAE 1997, Volume I-A, Offshore Technology.

Ormberg, H., Sodahl, N., Steinkjer, O. *Efficient Analysis of Mooring Systems Using De-Coupled and Coupled Analysis* – OMAE98-0351.

Pauling, J.R., *TDSIM6 – Tune Domain Platform Motion Simulation with Six Degrees of Freedom*, 1992.

Prosim (2000), *Programa PROSIM:Simulação Numérica do Comportamento de Unidades Flutuantes Ancoradas*, Reference Manual, Civil Engineering Program, COPPE/UFRJ, Rio de Janeiro, 2001.

Silveira, E.S.S., Jacob, B.P., Masetti, I.Q., *Dynasim-A Program: Coupled Analysis of Floating Production Systems*, COPPETEC-Petrobras Internal Report, Rio de Janeiro, 2000.

Silveira, E. S. S.; Menezes, I. F. M.; Masetti, I. Q.; Martha, L. F. R (2000). *Um Sistema Computacional Integrado para Análise Não-Linear Geométrica de Linhas de Ancoragem*. Proceedings of XVI Congresso Ibero Latino Americano sobre Métodos Computacionais para Engenharia, UFPR/AMC, Curitiba, Brazil, Nov.-Dez. 1995.

TDSIM (1992). *Time Domain Platform Motion Simulation with Six Degees of Freedom,* Theory and User Guide, Third Edition, march 1992.

Silveira, E.S.S., Tese de D.Sc., PUC/RJ, 2001.

Connaire, A., Kavanagh, K., Ahilan, R.V., Goodwin, P. *Integrated Mooring and Riser Design: Analysis Methodology* – OTC 10810, May/1999.

WAMIT (2000). *Wave Analysis Program – Reference Manual*, WAMIT, Inc.

Wichers, J.E.W. (1988). *A simulation model for a single point moored tanker*, Publication N.797, Maritime Research Institute Netherlands, Wageningen, 1988.

Wichers, J.E.W. (1982). *On the low-frequency surge motion of vessels moored in high seas,* 14th Annual OTC, Houston, Texas, 1982.

Wood, W. L., Bossak M., Zienkiewicz (1981), *An alpha modification of Newmark's method*, International Journal For Numerical Methods in Engineering, vol. 15, pp. 1562-1566, 1981.