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Dynamic simulation of offloading operation considering wave interaction between vessels

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ABSTRACT

Almost all simulators of offshore systems evaluate wave forces using frequency-domain potential analysis. A wave analysis software is previously executed, considering several incidence angles and generating a data base which is used by the simulator. This database contains drift coefficients, RAOs and exciting forces for all incidences. During the simulation, the simulator only performs queries depending on the actual heading of the vessel related to waves.

The simulation of multi-body systems cannot be performed in the same way, since the relative positions of the bodies change during simulation time, altering the influence of each ship on the overall wave field and its effect on the others. So, for each time step a new frequency-domain analysis should be performed, considering the vessel positions at that instant and updating the database used by the simulator. However, the computational effort necessary to perform such simulation turns this approach prohibitive for conventional computers and workstations. The wave forces are evaluated only in a pre-defined configuration of the vessels, or considering the vessels independently. Such approaches neglect all interactions and the complex dynamics behavior that results from it.

The University of São Paulo has been developing since 2001, the Numerical Offshore Tank (NOT), a 120 processor cluster with the ability to perform detailed simulations considering bodies and lines dynamics very efficiently. In order to simulate offloading operations accurately, the commercial wave analysis software WAMIT was integrated to the NOT simulation code, allowing the "update" of wave coefficients data base every time the vessels configuration changes significantly. WAMIT code was adapted to perform parallel processing, greatly reducing the execution time and allowing the simulations to be performed in approximately 7 hours for the analysis of a 3-hour operation. Without WAMIT parallelization, this time would increase by a factor approximately equal to the number of wave frequencies considered in the simulation.

This paper discusses the results obtained by the simulations of offloading operations in the presence of waves, detailing the effects that arise when the bodies interaction is taken into account. Effects are sensed in the equilibrium position, in the first order vertical motions and low-frequency oscillation.

Keywords: offloading operation, multi-body dynamic simulation.

INTRODUCTION

The traditional simulation method to predict motions of multi-body systems simplifies the hydrodynamic (wave and current) interactions between bodies. In the present paper, a simulator that correctly evaluates the wave loads in a multi-body system is presented. Current effects are not considered until the present moment.

Such simulator uses the computational kernel code and the hardware facilities of the NOT (Numerical Offshore Tank), a 120 processor cluster with the ability to perform detailed simulations considering bodies and lines dynamics very efficiently. Such system has been developed at the University of São Paulo since 2001, in cooperation with the oil state company (Petrobras) [1]. Furthermore, the simulator integrates the commercial wave analysis software WAMIT ([2],[3]), which performs a frequency-domain calculation of potential wave effects on the floating bodies.

WAMIT software is able to predict loads on a multi-body system, since it considers the radiation and diffraction of waves due to each body, and the influence of such effects in the overall wave field. The outcomes of the frequency-analysis performed by WAMIT are the drift coefficients, added masses, first order forces and the RAOs (Response Amplitude Operators). This data is used as input by dynamical simulators, including the NOT.

In the traditional simulation method, WAMIT software is executed only once, before the simulation itself begins, in order to evaluate all the coefficients used by the simulator. Of course, the execution of the WAMIT must consider a fixed and pre-defined configuration of the bodies, which generally is chosen as the initial condition of the simulation or an estimated mean-position. However, during the simulation, the relative position of the bodies changes, due to transient behavior or persistent oscillations, altering the wave field incident on each body and the forces on it. Some times, for the sake of simplification, WAMIT software is executed considering each body isolated, disregarding, in this case, all interaction effects that may appear in the real system.

The integration of the NOT kernel and the WAMIT solves such problems. During the simulation, body positions are monitored, and, when a significant alteration is detected, the simulation is interrupted and the WAMIT software is executed, considering this new configuration. All wave coefficients in NOT input data are, then, updated, and the simulation is restarted.

This approach is only feasible in a high-performance computer cluster, due the large time required for WAMIT execution in a single computer. A modified version of WAMIT was specially developed for such integration, with paralleling processing (each wave-frequency is executed in one node of the cluster) and inter-process communication (WAMIT sends/receives messages to/from the NOT).

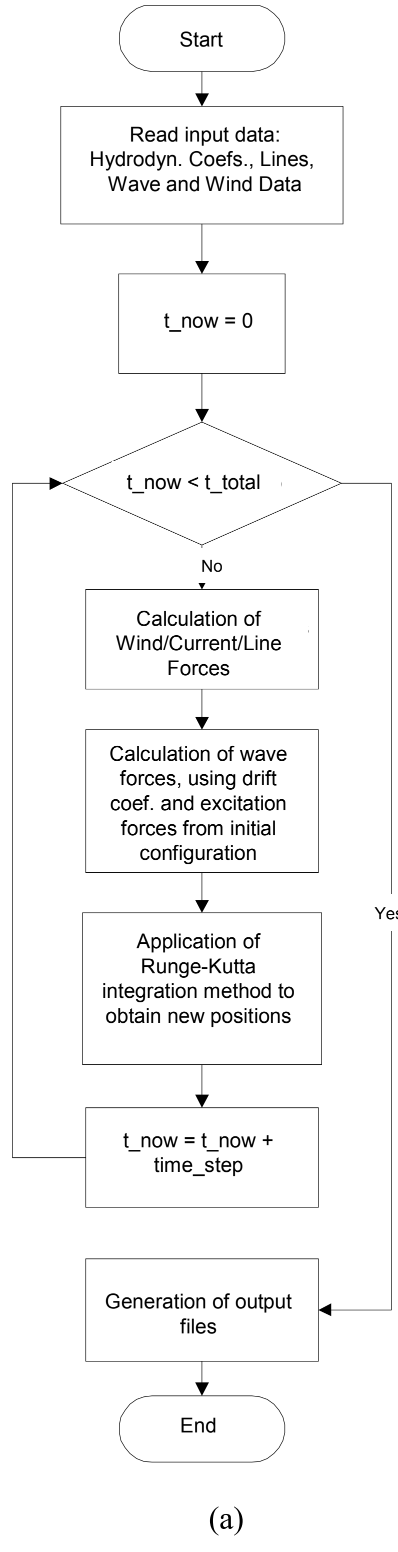
Next section presents a technical description of the simulator, emphasizing the differences of a conventional offshore system simulator and the main features of the parallel processing. After that, a real offloading operation is simulated and analyzed, detailing the effects of the interaction between bodies.

TECHNICAL DESCRIPTION OF THE SIMULATOR

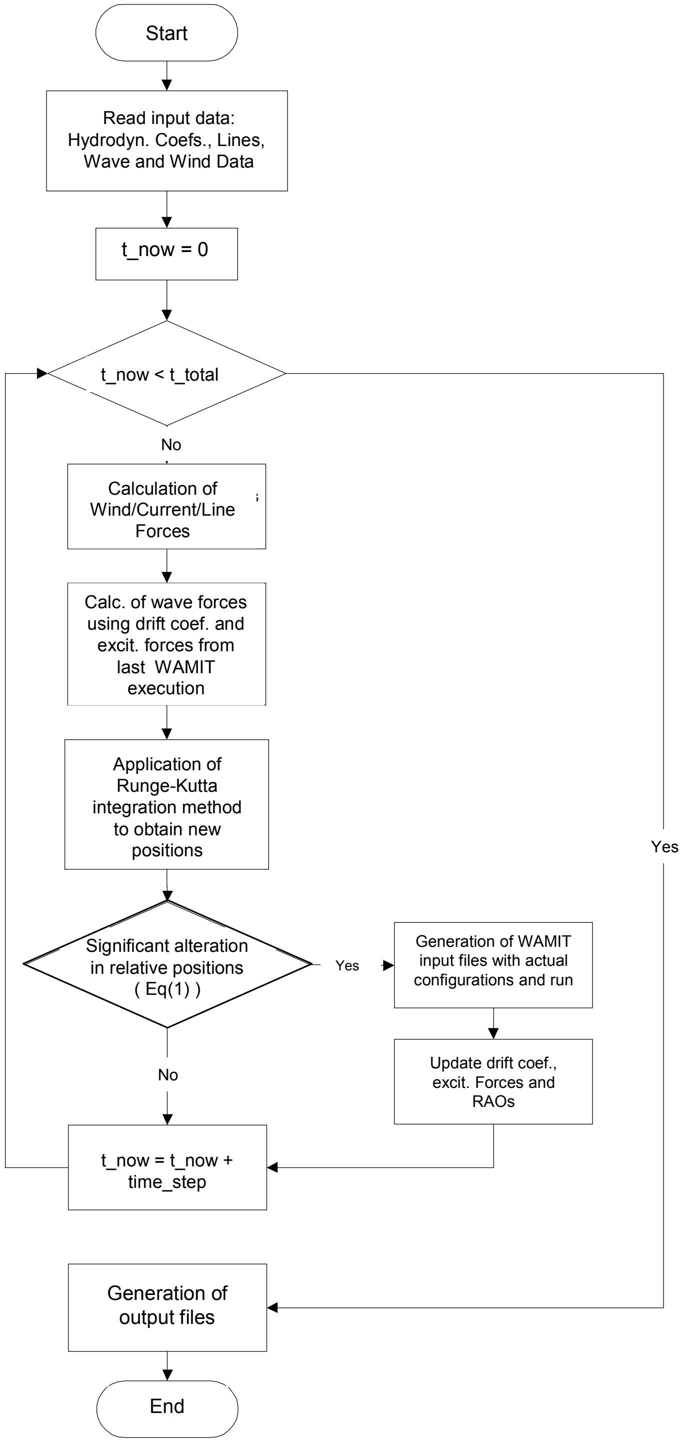
Figure 1 contains the flowcharts for the NOT Simulator in both cases, with and without the integration with WAMIT software.

As already mentioned, in the traditional simulator (Fig. 1a), WAMIT is previously executed, in order to calculate drift coefficients, excitation forces, added masses and RAOs for the initial configuration of the multi-body system. All coefficients are used as input by NOT. In such case, the simulator uses the same wave coefficients along all simulation, even when the relative position of the bodies changes significantly. Some times, for the sake of simplicity, WAMIT is executed considering each body isolated, disregarding all wave interaction effects.

The new approach is represented in Fig.1b. In each time step, bodies positions are evaluated and the relative positions between bodies and wave headings are verified. If the variation in such values is superior to a pre-defined value, NOT simulation is interrupted, all WAMIT input files are generated considering the new configuration of the bodies and WAMIT is started. After the execution, WAMIT output files are read by NOT, in order to update the wave coefficients used in the simulation, which is then restarted.



(a)



(b)

Fig. 1 Flowcharts: (a) NOT (conventional), (b) NOT and WAMIT integrated

Figure 2 shows a general configuration of a two-body system. The interaction between bodies are determined by the relative positions are ΔX and ΔY and the vessel headings ψ_1 and ψ_2.

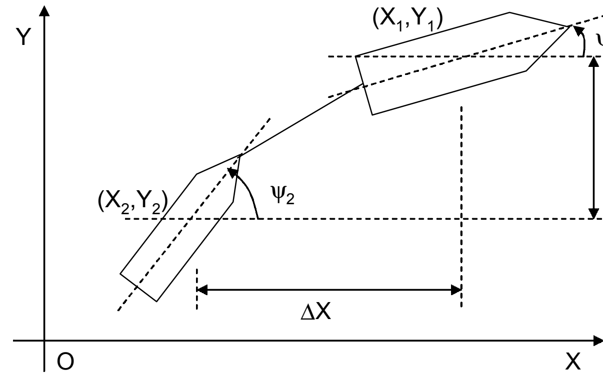


Fig. 2 Configuration of a two-body system

Being *l* the index for the last time step in which WAMIT was executed, and *i* the actual time step, the following condition is used to determine if a new WAMIT execution must be carried on:

$$if \begin{cases} |\Delta X_i - \Delta X_l| > \Delta X_{max} \\ or \\ |\Delta Y_i - \Delta Y_l| > \Delta Y_{max} \\ or \\ \max(|\psi_{1,i} - \psi_{1,l}|, |\psi_{2,i} - \psi_{2,l}|) > \Delta\psi_{max} \end{cases} \quad (1)$$

Obviously, the utilization of small values for the pre-defined variations ΔX_{max}, ΔY_{max} and $\Delta\psi_{max}$ causes a large number of WAMIT executions, and the simulator will use more accurate wave coefficients for each configuration, with a better prediction of interaction effects. However, it increases the simulation time. On the other hand, large values decrease the number of WAMIT executions and the simulation time. The interaction effects are, in this case, less accurately predicted. Such trade-off is illustrated in the next section, by means of the case study.

NOT and WAMIT codes are adapted for a parallel computing cluster, utilizing the LAM/MPI[1] parallel computing library [4]. NOT parallelization creates individual processes for the finite element method calculation of each mooring line, hawser line and hose, besides the main process that is responsible for dynamical simulations of each vessel and evaluation of environmental forces. The processes are then distributed among the nodes (computers) by the LAM/MPI internal procedures. A detailed description of NOT parallelization is given in [1]. WAMIT parallelization creates processes for each wave frequency, with a reduction in processing time (relative to a single computer processing) approximately equal to 1/n, being n the number of frequencies. For typical analysis of offshore bodies, n varies between 20 and 50. The parallel version of WAMIT code was developed by Petrobras.

Specific commands of LAM/MPI library are used to create two groups of processes and an intercommunicator between them. The first group is used by NOT, and the second one by

[1] Local Area Multicomputer (LAM) ; Message Passing Interface (MPI)

WAMIT. It allows the starting of WAMIT directly by NOT, as well as message transfer between them. All data communication are still done by WAMIT output and input files, since it does not reduce performance and keeps the original implementation scheme of WAMIT.

CASE STUDY

In this section, a case study is presented, aiming to emphasize the effects of wave-interaction in a two-body system. A typical offloading configuration is adopted, with a SMS (Spread Mooring System) moored FPSO (Floating Production, Storage and Offloading system) connected to a shuttle vessel by a hawser (Fig. 3).

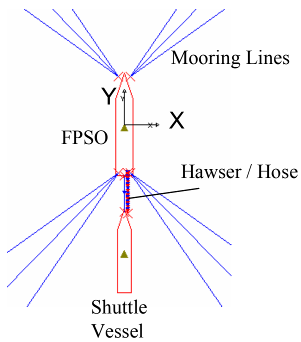


Fig. 3 System configuration

In this analysis environmental loads refer exclusive to wave action, with direction of incidence OX, modeled by a Pierson Moskowitz spectrum with 4m significant wave height and 8s peak period.

Main characteristics of each vessel are presented in Tables 1 and 2. FPSO is considered a VLCC in ballast draft condition and the shuttle tanker is fully loaded.

Table 1 VLCC characteristics (ballasted condition)

Properties	Values
Mass (M)	126100 ton
Moment of inertia (I_Z)	8.0×10^8 ton.m^2
Length (L)	320 m
Draft (T)	9.0 m
Breadth (B)	54.5 m
Wetted Surface(S)	27342 m^2
Block Coefficient(C_B)	0.85

Table 2 Shuttle vessel characteristics (full loaded condition)

Properties	Values
Mass (M)	154860 ton
Moment of inertia (I_Z)	6.9×10^8 ton.m^2
Length (L)	260 m
Draft (T)	16.2 m
Breadth (B)	44.5 m
Wetted Surface(S)	17645 m^2
Block Coefficient(C_B)	0.82

Case 1 - Without interaction

In the fist test, the traditional approach was used to simulate the system response. Wave coefficients were obtained considering both vessels in the initial positions, as shown in Figure 4.

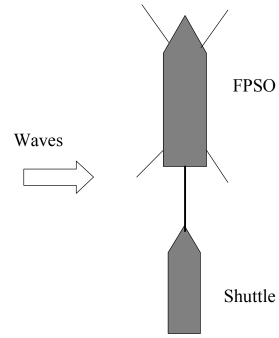


Fig. 4 Initial configuration

This approach disregard the fact that the wave field is altered by the presence of the FPSO and shuttle behavior will be approximately equal to the one if the hawser was connected to a fixed point, since the FPSO presents a small oscillation due to the large SMS rigidity. Shuttle presents a "fishtailing-like" oscillation around the wave direction, as shown by simulation results (Fig. 5). As expected, the mean yaw position is close to

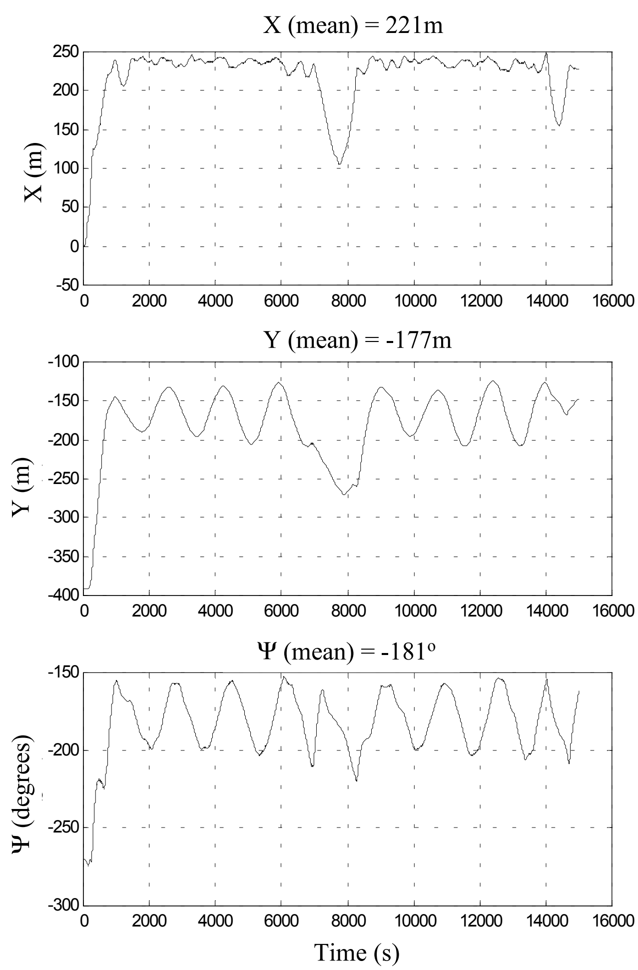


Fig. 5 Shuttle vessel position and heading (without interaction)

Figure 6 shows a trace plot of the system after 10000s, illustrating the oscillatory motion around wave direction.

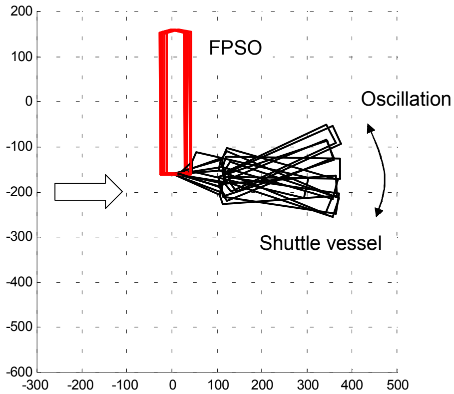


Fig. 6 Trace plot after 10000s (without interaction)

Case 2 - Considering the interaction

Wave field is affected by the presence of the FPSO, as is shown in Fig. 7, for a uniform wave pattern. A shadow zone is well identified behind the VLCC vessel, inside which the wave height is reduced. This result, obtained by WAMIT, shows that the shuttle tanker will be attracted to that region, what was not predicted by the traditional simulation approach (without interaction).

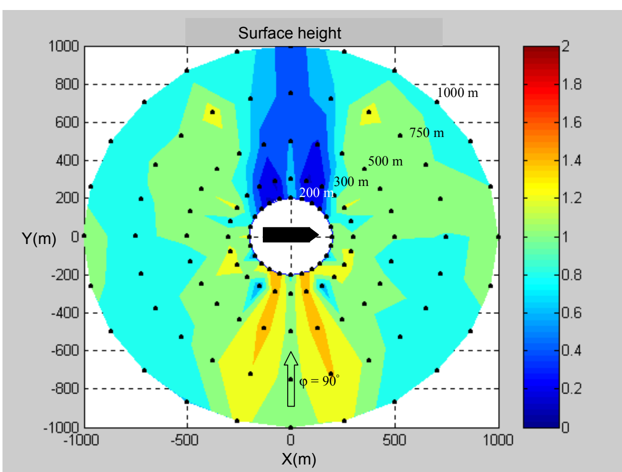


Fig. 7 Wave field in presence of a FPSO (uniform wave, 1m height and 8s period)

Such effect was confirmed by the dynamical simulation, as is shown in Figure 8. It was used $\Delta X_{max} = \Delta Y_{max} = 10$m and $\Delta\psi_{max} = 5^o$. The mean value of shuttle vessel heading is now -161^o, confirming the tendency of attraction to the shadow zone. This effect is well illustrated by the trace plot of Figure 9. Furthermore, it can be seen that the fishtailing-like oscillation presented in the first case does not appear here, indicating that such phenomenon shall not occur in the real case.

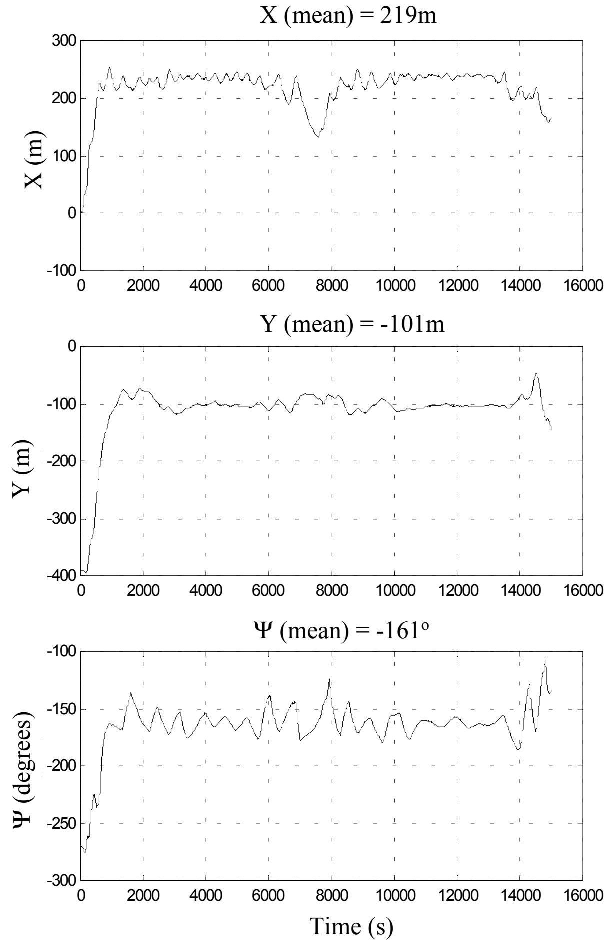


Fig. 8 Shuttle vessel position and heading (with interaction)

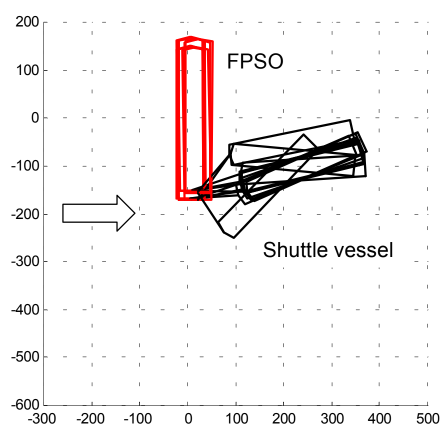


Fig. 9 Trace plot after 10000s (with interaction)

Another interesting effect is related to first order vertical motions. Though the shuttle vessel is attracted to the shadow zone with smaller wave heights, the incidence direction of the waves is altered. In the first case (without interaction), wave incidence angle oscillates around 180^o (longitudinal direction). In the last simulation, wave pattern around the vessel is completely altered due to the FPSO, what may induce non-longitudinal incidence and larger first order vertical motions.

Indeed, Table 3 shows that the standard deviation of first order oscillations may increase almost 70% when the interaction is considered.

Table 3. First order vertical motions: standard deviation

	Heave	Pitch	Roll
Without Interference	0.38m	0.58m	0.82 ^{o}
With Interference	0.62m	0.64m	1.4^{o}

Case 3 - Sensitivity Analysis

A sensitivity analysis concerning values for minimum variations ΔX_{max}, ΔY_{max} and $\Delta\psi_{max}$ was performed, in order to evaluate the already mentioned trade-off between simulation time and accuracy.

The time required for the simulation previously presented, in which (ΔX_{max}, ΔY_{max}, $\Delta\psi_{max}$) = (10m, 10m, 5^{o}) was 12h. The same case was executed considering (ΔX_{max}, ΔY_{max}, $\Delta\psi_{max}$) = (30m, 30m, 15^{o}), reducing the processing time to 7h. Finally, the set (ΔX_{max}, ΔY_{max}, $\Delta\psi_{max}$) = (5m, 5m, 2.5^{o}) was tested, taking 58h to be executed.

Shuttle vessel heading is presented in Fig. 10 for all cases. A convergence of statistical properties (mean and oscillation amplitude) of time series can be verified when the maximum differences Δ are reduced. This fact can also be verified in Table 4.

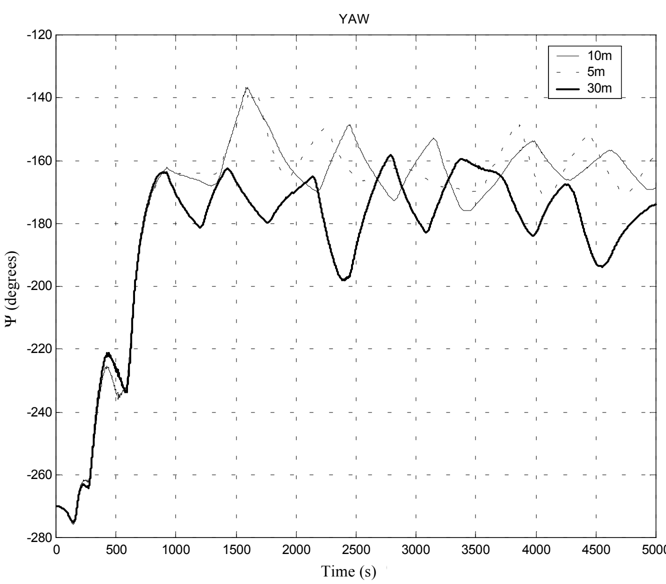


Fig. 10 Shuttle vessel heading for all cases – sensitivity analysis

Table 4. Shuttle vessel mean position and heading for all cases

	(30m,30m,15º)	**(10m,10m,5º)**	**(5m,5m,2,5º)**
X	225,6m	219,1m	220,7m
Y	-137,7m	-105,1m	-111,3m
Ψ	-172,7º	-160,9º	-161,4º

The reduction of the differences from (10m, 10m, 5^{o}) to (5m, 5m, 2.5^{o}) increases the simulation time by a factor 5 and results a variation smaller than 5% in mean values. So, the differences (10m, 10m, 5^{o}) were chosen for future analysis of the present system.

Obviously, a new sensitivity analysis must be performed for different systems (vessels).

CONCLUSIONS

The present paper describes a new offshore system simulator, developed at the University of São Paulo with cooperation of Petrobras. The simulator considers the wave interaction between multiple bodies, since it incorporates the commercial software WAMIT in the simulation loop.

With the hardware facilities of Numerical Offshore Tank, composed by a high-performance computer cluster, the time-demanding simulations could be executed in 12h, what is reasonable in some stages of the design and analysis of offshore systems.

After a brief technical description of the simulator, a case study was presented. The simulated system represents an offloading operation composed by a shuttle vessel linked to a moored FPSO. It was showed that the overall dynamic behavior of shuttle vessel is extremely affected by the presence of the FPSO, since it alters the wave field close to the shuttle position. Both low-frequency motions and high-frequency oscillations are affected.

ACKNOWLEDGMENTS

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