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Time Domain Simulation of DP Semi-Submersibles in Numerical Wave-Tank for Large Nonlinear Random Waves

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TIME-DOMAIN SIMULATION OF DP SEMISUBMERSIBLES IN NUMERICAL WAVE-TANK FOR LARGE NONLINEAR RANDOM WAVES

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ABSRACT

In deepwater, Dynamic Positioning (DP) is proved to be cost-effective for the station keeping and controlling of the floating structures. This paper will show that the DP simulation and control of a floating vessel can be achieved in a numerical wave-tank. The complex interaction of the wind, waves and current forces against the vessel is modeled for the required station positioning with the application of controlled propulsion system. The DP simulation and control in a numerical wave tank will be very useful to the offshore industry in terms of DP system design verification and in terms of the vessel design with the maximum DP forces loading condition. In this paper, we discuss a truly dynamic time-domain simulation method for a fully DP assisted semi-submersible. The computational algorithm for the simulation is based on the concept of a numerical wave-tank. For the basic potential flow solver including diffraction and radiation effects, a boundary integral method in conjunction with time-integration of boundary conditions and equation of body motions is used. Nonlinear effects associated with large amplitude waves and other relevant non-linearities that affect the motions of the body are included in the algorithm. Morison elements with braces are represented without any approximation in the sense that these are determined based on nonlinear wave kinematics and the exact wetted part of the elements. The current and winds are based on empirical relations as is the present standard, but can consider spatial (in particular, depth) variations of velocities. Simulated time histories of motions and required DP thrust are shown for two semi-submersible configurations. The results show that the DP simulation and control in a numerical wave tank is a viable alternate to the real life test.

INTRODUCTION

As the offshore industry moves into deeper waters, the design of DP systems for controlling the position of floating production platforms has become increasingly important. These platforms often have to work under severe environmental conditions including effects of currents, wind loads and very severe waves. The DP system controls the vessel's motion in three horizontal degrees of freedom – surge, sway and yaw. The vessel is held in relatively fixed position with respect to the ocean floor, without using anchors by the use of propulsive devices controlled by the inputs for the desired location against wind, wave and current environmental forces on the vessel. In general, the wave induced platform motions can be separated into two major components, the first order high-frequency motions and the second order low frequency motions. The DP systems are usually designed to counter the effects of this low frequency component, in addition to the effects of currents and wind (Barltrop 1998). Efficient and optimal design of a DP system requires that the necessary DP thrust under the combined action of environmental forces be predicted. In a simpler conventional mathematical model where the required DP thrusts are simulated, usually the low-frequency drift force is considered as far as the wave-action is concerned. If the desired position is predetermined, the DP systems can be simulated for automatic positioning and heading control of a vessel. The American Bureau of Shipping (ABS) has developed rules and guides that direct the operators, designers and builders to the DP requirements (ABS 1994).

In this paper, we simulate the required DP thrusts for a semi-submersible. The motion of the semi-submersible under the environmental effects is simulated using a numerical wave-tank approach. The numerical model computes the effect of large and nonlinear waves on floating platforms. All other forces like Morison forces, current forces, wind forces etc are also incorporated. Forces are determined based on the instantaneous location of the platform under the instantaneous wave-profile. In this sense, the model provides a motion simulation of the platform under the combined actions of waves, wind and current including nonlinear and interaction effects between the different environmental forcing components. It is also possible to incorporate any other external forces fairly easily. By using a numerical filter, the high-frequency wave-induced part of the motion can be separated and the required DP thrusts can be modeled by a Proportional-Integral-Differential (PID) based controller algorithm. Therefore, by using the numerical-tank based motion simulation algorithm including the forces produced by the DP thrusters, the motions as controlled by the DP system and the required thrust can be simulated for a situation where all environmental effects and external forces are modeled. From the required DP thrust, the design of the DP system by allocating thrust to individual thrusters, and other details of the DP system are worked out. Figure 1 shows the flow diagram for the numerical wave-tank simulation of the DP system for a floating vessel.

In the following, we discuss briefly the numerical-tank model and the modeling of the DP thrust. Results are shown for some typical semi-submersible configurations in random waves.

THE NUMERICAL-TANK APPROACH

The numerical wave-tank approach for the interaction of waves with a floating platform is based upon potential flow formulation. In this formulation, the velocity potential f , the gradient of which gives the fluid velocity vector $\vec{v} = \nabla f$, needs to be determined from the appropriate boundary value problem. This BV problem is posed by Laplace equation as the governing equation and a set of boundary conditions. The solution of the velocity potential is achieved by a boundary integral method. As is well known, the velocity potential can be represented by a distribution of the sources and dipoles over the boundary of the domain:

$$s(P)f(P) - \int_{\partial\Omega} \left[f(Q) \frac{\partial}{\partial n_Q} \frac{1}{r(P,Q)} - \frac{1}{r(P,Q)} \frac{\partial}{\partial n_Q} f(Q) \right] = 0 \qquad (1)$$

Where *P* is the field point, *Q* is a point on the boundary, σ is the solid angle at *P* subtended by the boundary surface and *1/r* is the potential of a fundamental source.

In the numerical-tank approach, the above relation is used to discretize the body wetted surface and a part of the surrounding free-surface and a hypothetical vertical `control' boundary (i.e., essentially discretize the boundaries of a numerical wave-tank). By using appropriate time integration of the free-surface conditions as well as the equations of body motions, it is then possible to simulate the motion of the body as it evolves through time along with the progression of the wave. In other words, what we achieved is a digital simulation of the physical wave tank where a wave is generated in the tank and the corresponding time-history of the wave and the body as it moves are recorded.

The assumption that has been made in the present approach is that nonlinear part of the wave diffraction and radiation in the total interaction of the floating vessel is very small compared to the linear diffraction and radiation hydrodynamic-interaction effects. This assumption greatly reduces the computational burden and makes the method practical for industry applications to realistic offshore-structure configurations.

What is sacrificed here are the nonlinear effects associated with the diffraction and radiation (a small part the nonlinear effects enters the solution through the body-boundary condition in which the full nonlinear incident wave-potential is used). Without this linearization approximation, the solution would have become fully nonlinear. However, at the present time, a fully nonlinear solution algorithm is not available for routine use for practical offshore configurations. And, such full nonlinear schemes would be prohibitively expensive. For most typical floating platforms, the surface-piercing parts are cylindrical with relatively small water-plane area (compared to a ship-shaped body), and therefore the non-linearities associated with the diffraction and radiation potentials are small. It is well documented that the largest part of non-linearities arises from the incident wave-effects. For this component, not only a fully nonlinear numerical wave is considered, the forces are evaluated on the instantaneous location of the body using the exact wetted surface (for simulation of random waves, Wheeler stretching is used, see e.g. Chakrabarti 1987). Thus, the effects of regular incidents waves are fully considered without any approximation.

The equation of motion is given by

$$[\boldsymbol{m}]\{\ddot{\boldsymbol{x}}\} = \{\boldsymbol{f}\} \tag{2}$$

Which can be written as a set of two linear differential equations,

$$[\boldsymbol{m}]\{\dot{\boldsymbol{v}}\} = \{\boldsymbol{f}\} \tag{3}$$

$$\{\dot{\boldsymbol{x}}\} = \{\boldsymbol{v}\} \tag{4}$$

Where $\{\boldsymbol{v}\}$ is the generalized velocity vector, $\{\mathbf{v}\} = \{\vec{U}_G, \vec{w}\}$. The time-history of the motions can be determined by integrating these equations and establishing at every instant the forces and motions. Coupling of the integration of equation of motion along with the solution of the discretized boundary-integral relation is not straightforward as it often leads to numerical instability. Appropriate algorithms have been developed so that the time-simulation scheme is stable. The details of the method, the simplifying approximation and its justifications, and the algorithms used for integrating body-motion equations are available in Srinivasan et. al. (1999) and Sen (2002).

OTHER FORCES

It is straightforward to incorporate effects of other forces in the motion simulation algorithm. The Morison forces at any given instant can be determined using the nonlinear incident wave kinematics, the instantaneous location of the body and its velocity and acceleration as well as by considering the instantaneous wetted part of the Morison member (Chakrabarti 1987). This force (and moment) can be added to the force vector $\{\boldsymbol{f}\}$. Similarly mooring forces, forces arising from riser and any other forces , which can be empirically modeled or determined from other means, can be directly added to the force vector at every instant. It is also straightforward to incorporate nonlinear nature of such forces, e.g. when these forces depend on the variables related to the instantaneous location and kinematics as in the case of nonlinear mooring loads.

In the present algorithm, Morison forces, as mentioned above, are exact without approximation. Current forces on the diffraction-elements of the structure and wind forces are estimated based on the formulation in Faltinsen (1990). Current forces on the Morison elements are determined by modifying the particle velocity by linearly adding the wave-velocity and current velocity and then using an equivalent linearization of the drag force term. Mooring forces presently are modeled as linear spring with appropriate stiffness.

DP THRUST

One of the difficult tasks of this Numerical Wave-Tank DP simulation is to simulate the motions under the combined action of wave, current, wind and the applied DP thrust. Wind, wave and current are user defined based on the environmental design criteria. At first DP is a total unknown. However, the DP must be such that under its application along with all other forcing, the structure maintains a given position with minimum excursion from it. The required DP thrust must be determined from a control system algorithm. The vessel can be controlled in several different modes: Manual, Auto-Heading, Auto-Positioning, Auto-Area, Auto-Track, Auto-Pilot and Follow-Target. Hence the target position could be determined at each time step. Or a PID method could be used for its minimum excursion of the vessel from its mean zero starting reference position.

As it is not usually possible for the thrusters to control the high-frequency cyclic motions induced by first order wave effects, the DP thrusts are determined considering only minimization of the low-frequency wave motions. To obtain low frequency motions, the position reference signals have to be filtered using a low pass filter so as to remove the wave-frequency part of the motions from the motion signal.

There are a number of control systems available, from a simple PID type to more advanced predictor-corrector Kalman filter (Barltrop 1998). In the PID system, the basic principle is to produce thrust which has components Δx proportional to the error in the vessel location, its velocity and the accumulated error, all at time t (se e.g. Nienhuis 1986). Thus the required thrust is:

$$F_{DP} = F_s + c\,\Delta x + b\,\Delta\dot{x} + a\int_t \Delta x\,dt \qquad (5)$$

In which, **a**, **b** and **c** are the proportional, differential and integral constants, respectively. They are used to adjust the rate of response of the system to measure errors and to control unstable or oscillatory behavior. The rate of response is controlled by the proportional and integral terms. Higher rate of response is achieved by increasing the constant terms **c** and **a**. Overshoots, cyclic or unstable motions would occur if the response is too rabid and the damping term **b** is not properly tuned. Excessive damping, however, will make the response sluggish. In fact, Numerical Wave Tank Simulation is very useful to select these parameters for the final tuning on the actual vessel at sea. The primary requirement of this PID system is that it has to be used in conjunction with a low pass filter to remove the high-frequency motions from the position signals. This invariably introduces a phase lag. The design of a filter always involves a compromise between good filtering and good response. Several criteria are available for designing a good filter.

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Kalman filter approach follows from a predictor-corrector type of computer model, where the vessel motion as predicted from a computer model is compared with the measured response. The thrust is then in proportion to the error, which is taken as the difference between the predicted and measured response. In Kalman filter technique, the low and high frequency motions are separated. The computer prediction models are written separately to simulate the vessel motions under low-frequency forces and high frequency forces. This filter is useful during actual operation, as here the measured vessel motions are needed for the corrector part of the algorithm.

In the present example demonstration study, we use the simpler PID control algorithm for the control system in our numerical simulation model. The low pass filtering is performed by a moving average type of filter. In the numerical tank simulation, the motions and all details are available at every time step, typically over 20-40 steps per wave frequency. The high frequency motions are removed by averaging the signals over the past N time steps, where N is chosen such as to span over 3-4 wave-cycles. Although much improvement on the design of the filter can be made, here our primary purpose is to demonstrate the ability of the numerical algorithm in simulating motions along with DP thrusts under the combined action of all environmental and external forces. The response is simulated considering an advanced model for wave action along with other possibly interacting effects.

RESULTS AND DISCUSSION

The first set of simulation results are for a twin-pontoon four-cylinder semi-submersible. The pontoons are 90m*15m*6.5m and cylinders are 9 m dia. There are 13 Morison members of average dia. of 1m. Figure 2 shows the semi-submersible in the numerical wave tank with random wave environment. Figure 3 shows the simulation results for the case of an irregular head wave with 0 deg. heading (i.e. along x-direction) and significant wave height of *Hs*=4m. for the cases of no mooring or DP, soft and hard mooring, and with DP working. As can be seen, without any mooring or DP, the body drifts along surge direction. The performance of the mooring and DP system is comparable. (The mooring is a spread-mooring system with four lines.). Although no current and winds are considered for this result, with current and wind, the results are of similar nature except that the drift is far greater when no position controller is used, as would be expected.

In Figure 4, we show the simulation result with DP working in presence of a 1 m/s current along x-direction for the same wave condition. The offset in the surge position is a consequence of the fact that no mean thrust to compensate for the mean steady current load has been applied (i.e. the term F_s in equation 5 is zero).

Figure 5 shows the results with a mean load (of 1000 kN). In all results, the initial transient obtained from numerical tank program is retained to demonstrate that the displacement and thrust values eventually reach the desired value (i.e. a value with small changes). The initial transient in the thrust value 1000kn seen in figure 5 was due to the thrust of 1000 kN that was applied using a ramp function. This is done to avoid any numerical instability problem that could have arisen during the numerical time-integration process. Note that in both figure 4 and figure 5, thrust value reached is of the same order. Figure 5 shows that surge is within 1 m.

Figure 6 shows that result for a wave heading of 45 deg. and a current heading of about 30 deg. (current headings are taken such that the estimated mean current loads are 1000kN and 500kN in surge and sway directions respectively). As can be seen, the DP is again able to keep the vessel position within 1 m. with minimal variation in thrust.

In figure 7, the wave is a nonlinear very steep steady wave of period 10 sec. and height 10m, progressing along x-direction. Here although the surge is retained within about 1 m., there appears to be a slow oscillation. This is possibly due to the choice of the controller constants (***c,b,a***) in eqn. 5, which has not been optimized for performance, as well as for the filtering technique used which invariably introduces a phase shift. The appearance of high frequency oscillations in the thrust is also due to the filtering process: the average-based filter used is unable to filter all high frequency signals. In reality, the applied thrust will not contain this high frequency component.

Finally, we show the simulation results for a triangular semi submersible. The discretization of the platform is illustrated in figure 8. No Morison members are considered for this body. Results shown in figure 9 are for random waves of significant wave height 6 m. making a heading angle of 30 deg. Note that the x-axis for this body is taken parallel to one of the sides and thus the body is not symmetric about surge axis. Current of 1 m/s comes from a direction with a heading of 45 deg. Results are shown for surge, sway and yaw. Note that the yaw angle is extremely small

The above simulations show that the required thrust for a DP system can be studied using the numerical wave tank computations in which environmental and external forces can be modeled considerably more accurately compared to most of the existing the mathematical simulation models for DP systems. Once the thrusts are determined, these can be allocated to different thrusters.

ADVANTAGES OF NUMERICAL WAVE TANK DP SYSTEM SIMULAION

The use of Dynamic Positioning system is likely to increase with deepwater applications in the future. Even the permanently placed floating production-platforms in deepwater may use DP system, in assistance to their cost-effective polyester moorings because of the elastic nature of the polyester moorings. A combination of DP system with polyester mooring could be ideal for a production semi-submersible in 10,000-ft water depth.

The safety and operation of the DP system should be given top priority in deepwater applications. The random external forces have catastrophic peaks in the service of the vessel in the ocean environments. Designing the DP system for the maintaining of the vessel in position involves several risks in such conditions. Real time testing during the sea trail is not a sufficient safety and test proven criteria. DP control and monitoring system is to be designed for these catastrophic peaks with different combinations of wind, wave and current peak forces in different direction combinations. On the other hand model tests are not accurate either because of the high viscous effect due to the scale down dimensions.

Under these situations, a numerical tank DP simulation and control is a very valuable tool. Numerical wave tank could be used not only to find the required DP forces for the positioning of the vessel but could also be used to test the control system for different environmental and operational conditions. The failure modes and effect analyses could be performed in the numerical wave tank DP simulation and control. The effects from human / operator mis-operation can be studied and could be auto piloted by over ride system if significant consequences are foreseen. The accuracy of the control system could be verified with the numerical wave tank DP simulation. The new concepts could be tested well with the numerical wave tank DP simulation. Constraints in thruster and power systems could be verified in the design stage itself.

For the design of the DP vessel, Numerical Wave-Tank DP simulation is a very helpful tool. Numerical wave-tank simulation also gives the panel pressure of the vessel model for further structural integrity analyses. Non-linear regular or random waves could be considered and the instantaneous location and orientation of the vessels are used. Random wind and spatial current forces could be applied. DP forces are applied at the location and direction of the thrusters for the desired control system. With the user defined design environmental forces solution is obtained at each time step of the motion simulation. The load cases pertinent to DP critical thruster forces can also be studied for the structural integrity of the floating vessel. The total panel pressure and the wave slamming, deck run-up could be studied. The air gap spatial time history could be obtained. The worst panel pressure loads could be used for further FEM-structural analysis for yield and buckling checks.

SUMMARIZING REMARKS

One important component in the design of the DP system for floating production platforms is to carry out a simulation using a mathematical model. In general, the mathematical model considers the vessel response to environmental excitations, together with DP thrust. Most existing algorithms use a simplified mathematical model for environmental forces, and therefore may not adequately represent some of the effects of these external forces. Examples are severe nonlinear response that may arise from a very steep wave, incorporation of some components of wave-forces such as Morison forces (which may be significant), any possible nonlinear interaction and coupling effects between the difference forces and responses, etc.

In our approach, current and wind forces can also be determined from improved models by considering their spatial and temporal variations, for example the variation of current along depth, and considering the exact wetted part of the hull. From this point, our numerical wave-tank DP simulation represents a significant improvement for simulating the motions of a DP controlled vessel. Once the DP thrusts are determined, the thrust allocation logic can be carried out, and then simulations can be carried out for different environmental scenarios. As mooring, riser etc all can be considered in the simulation program, control of the position using a combination of mooring and DP can also be studied through appropriate simulation.

ACKNOWLEDGEMENT

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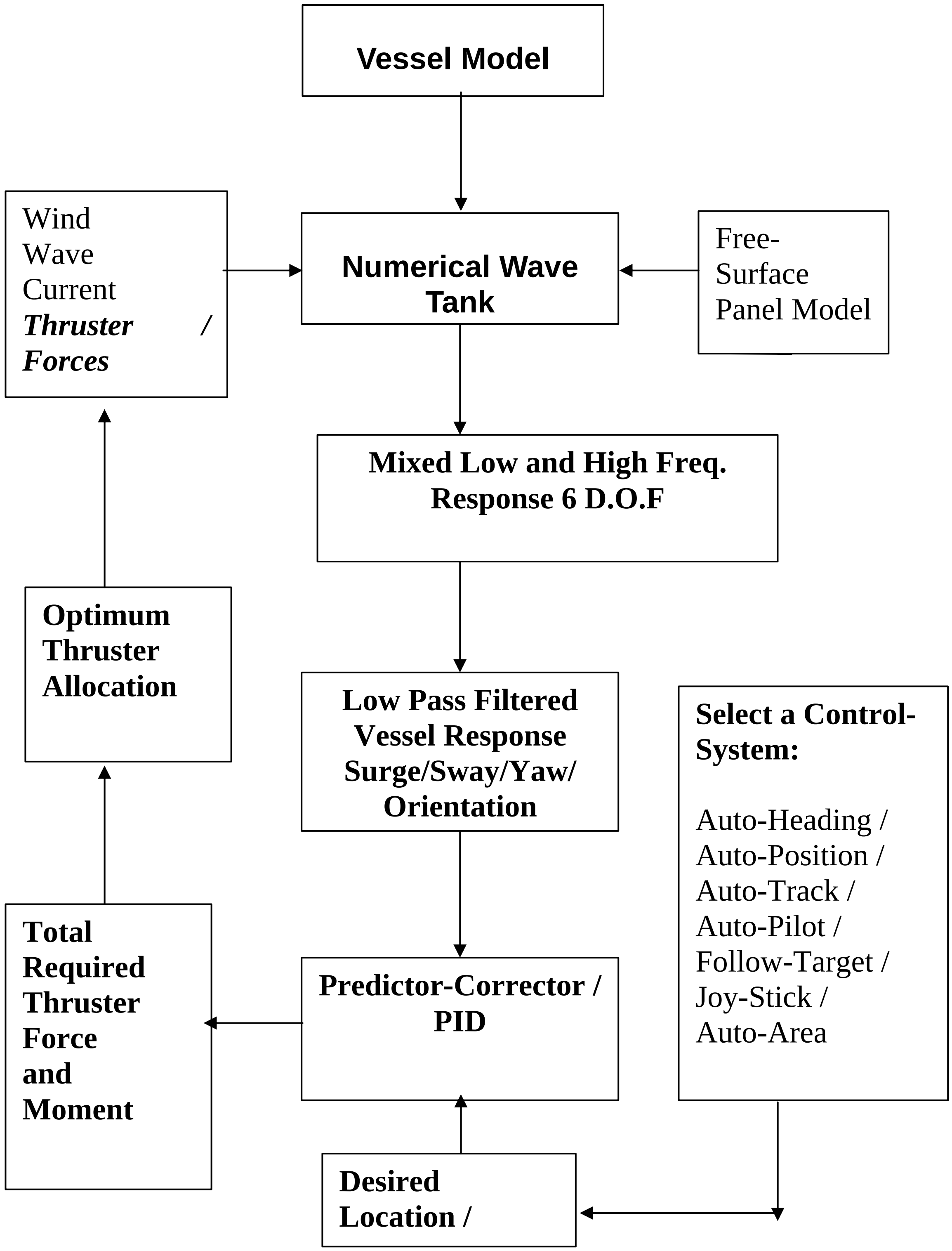

Figure 1 Numerical Wave Tank Simulation of DP Svstem

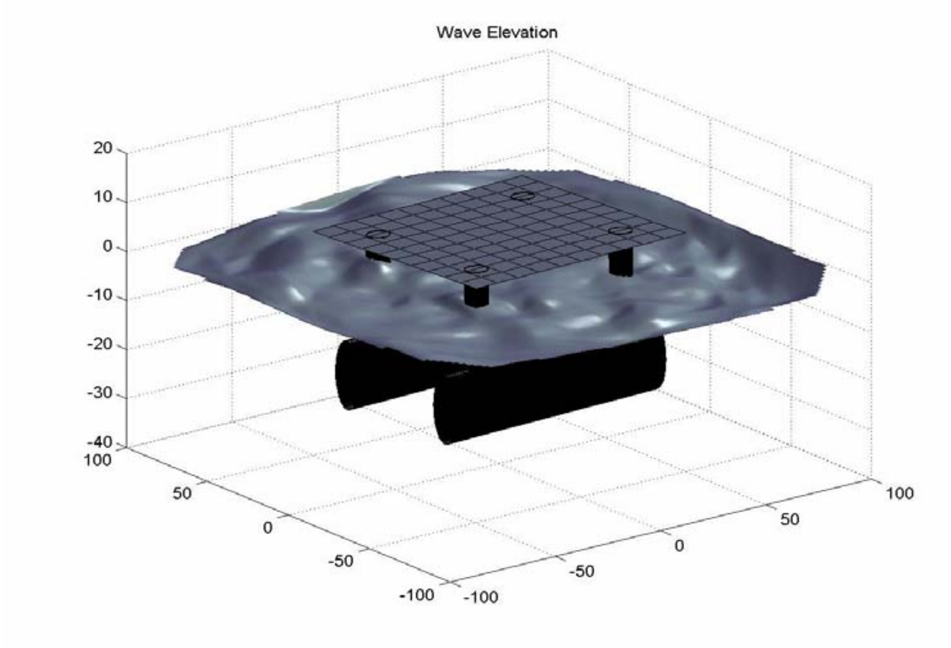

Figure 2. A 3D View of the Semi-submersible in Numerical Wave Tank Simulation for Random Waves

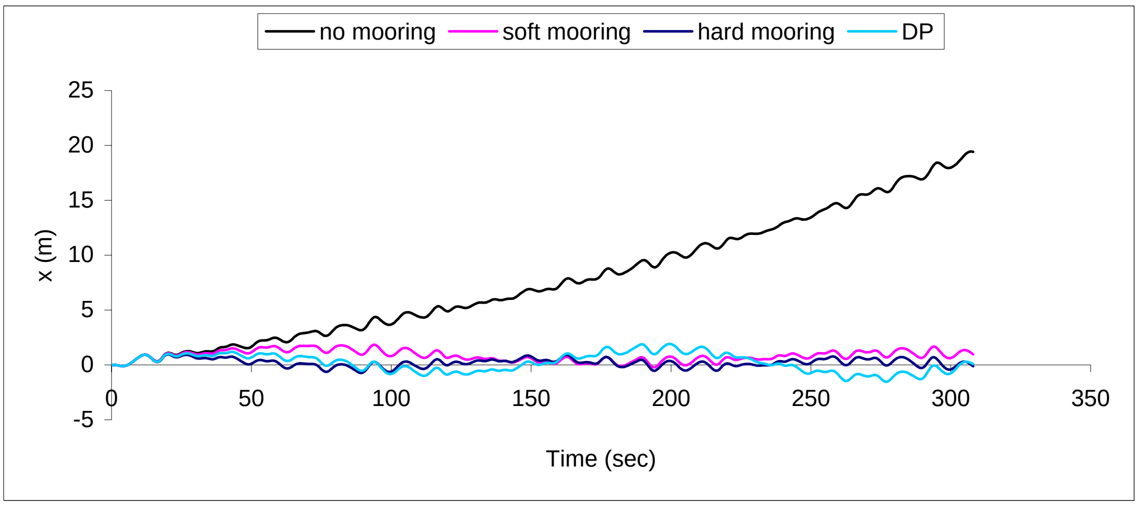

Figure 3. Surge displacements for different mooring and DP; *Hs* = 4m., heading=0 deg.

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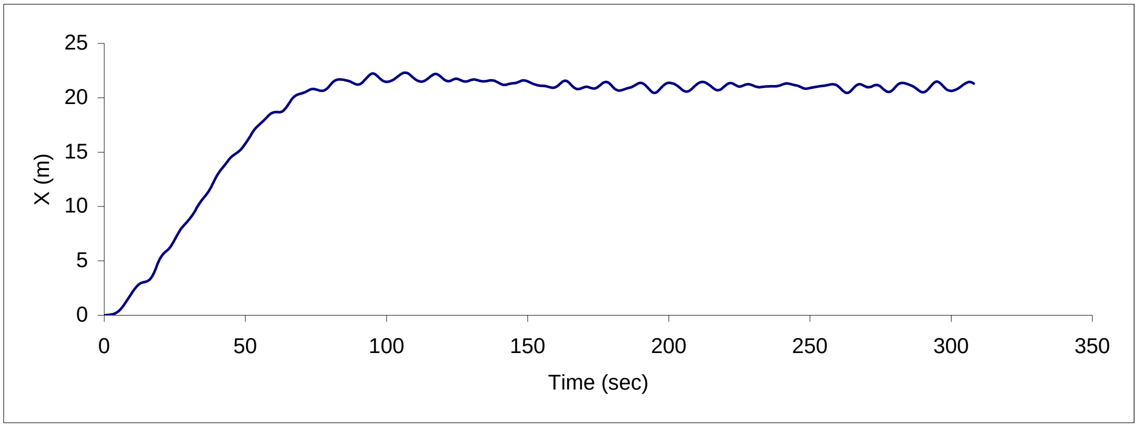


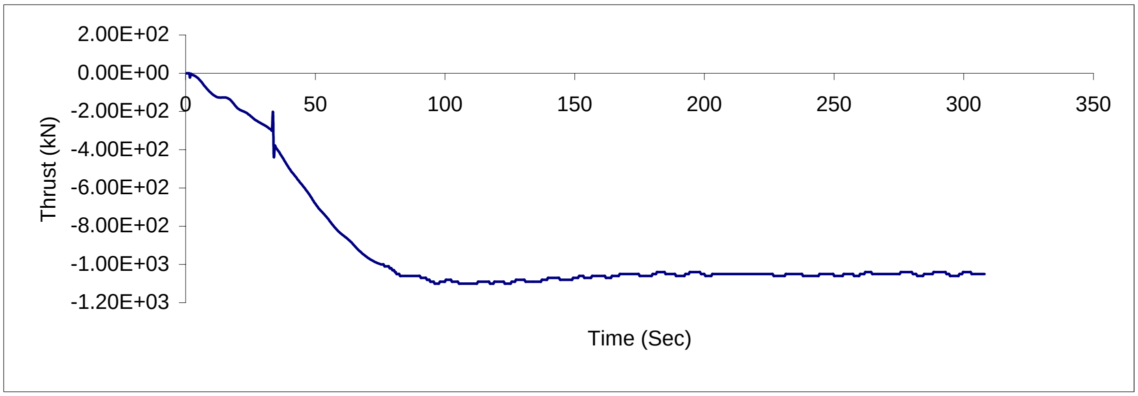
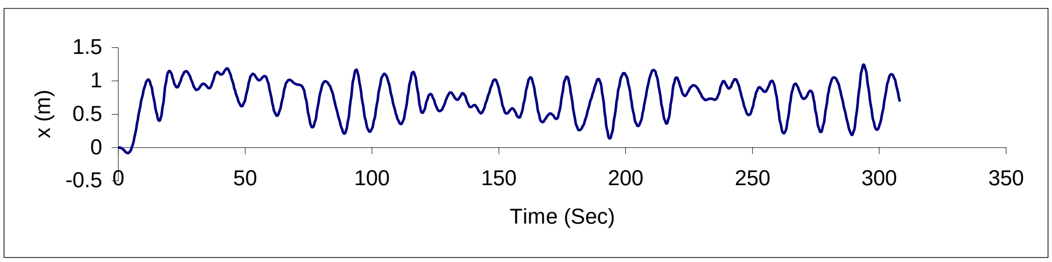


Figure 4. Surge displacement and DP thrust; *Hs* = 4m, heading = 0deg., current = 1m/s, no initial steady mean thrust .



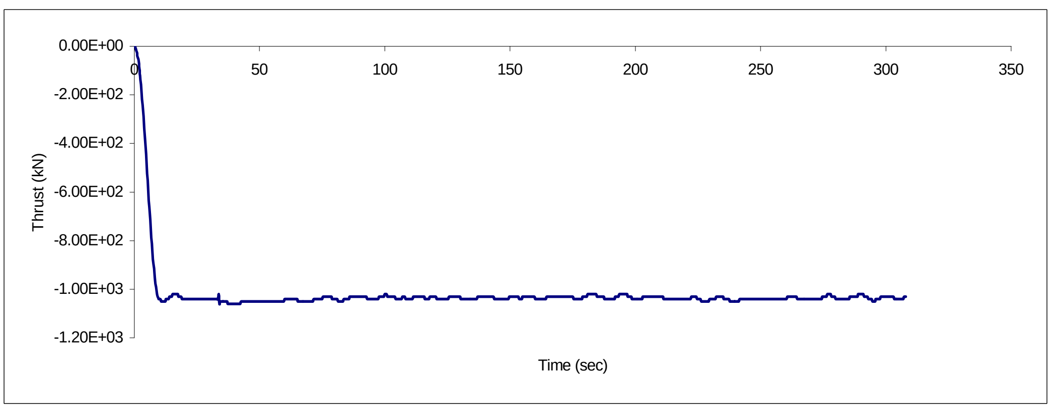


Figure 5. Surge displacement and DP thrust; *Hs* = 4m, heading = 0deg., current = 1m/s, initial steady mean thrust of 1000 kN.

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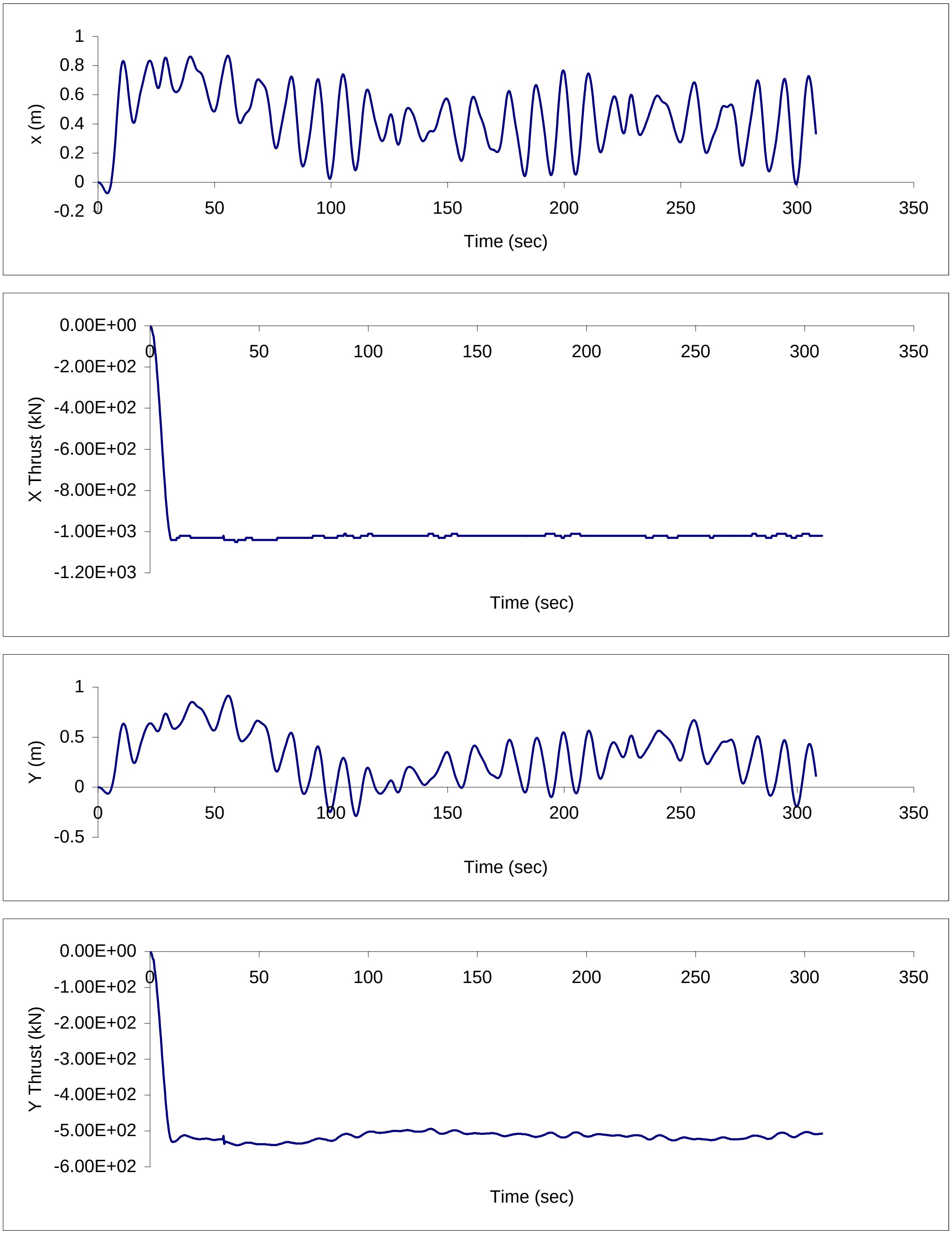

Figure 6. Surge and sway displacements and thrust, *Hs*=4m, wave heading 45 deg., current of 1m/s with an (approximate) heading of 30 deg.

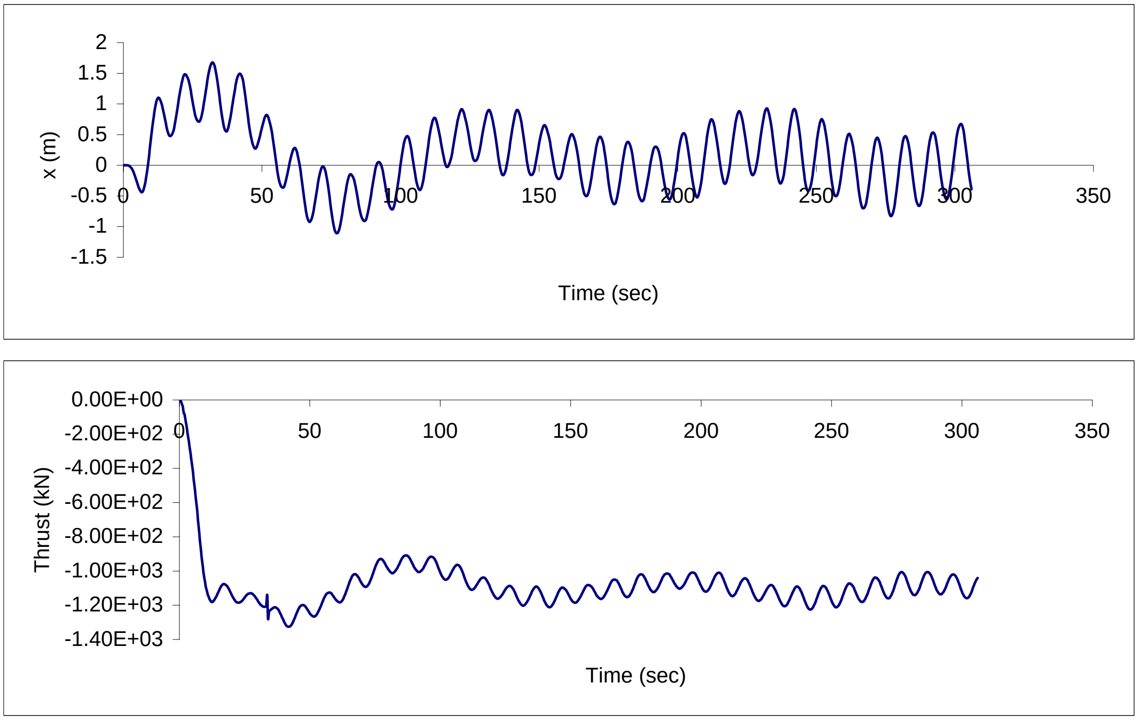

Figure 7: Surge displacement and thrust for a very steep nonlinear regular wave of period 10 sec. And height 10 m, wave heading 0 deg., current 1m/s.

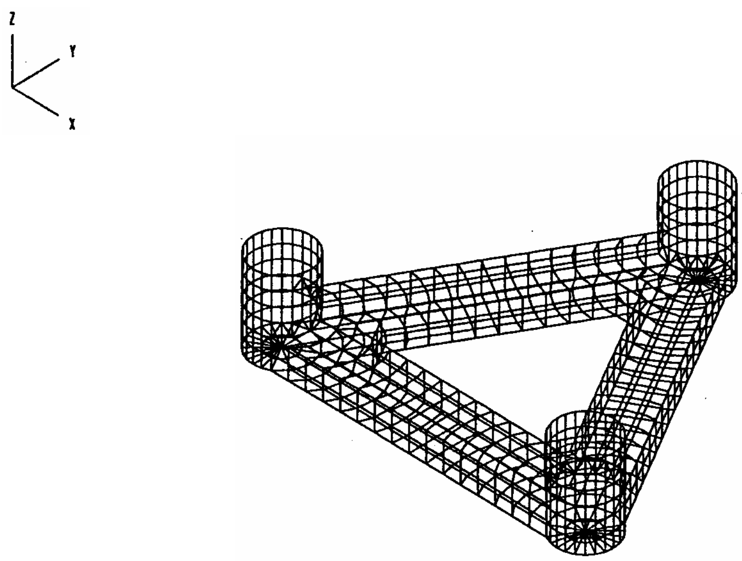

Figure 8. The triangular semi-submersible : discretization

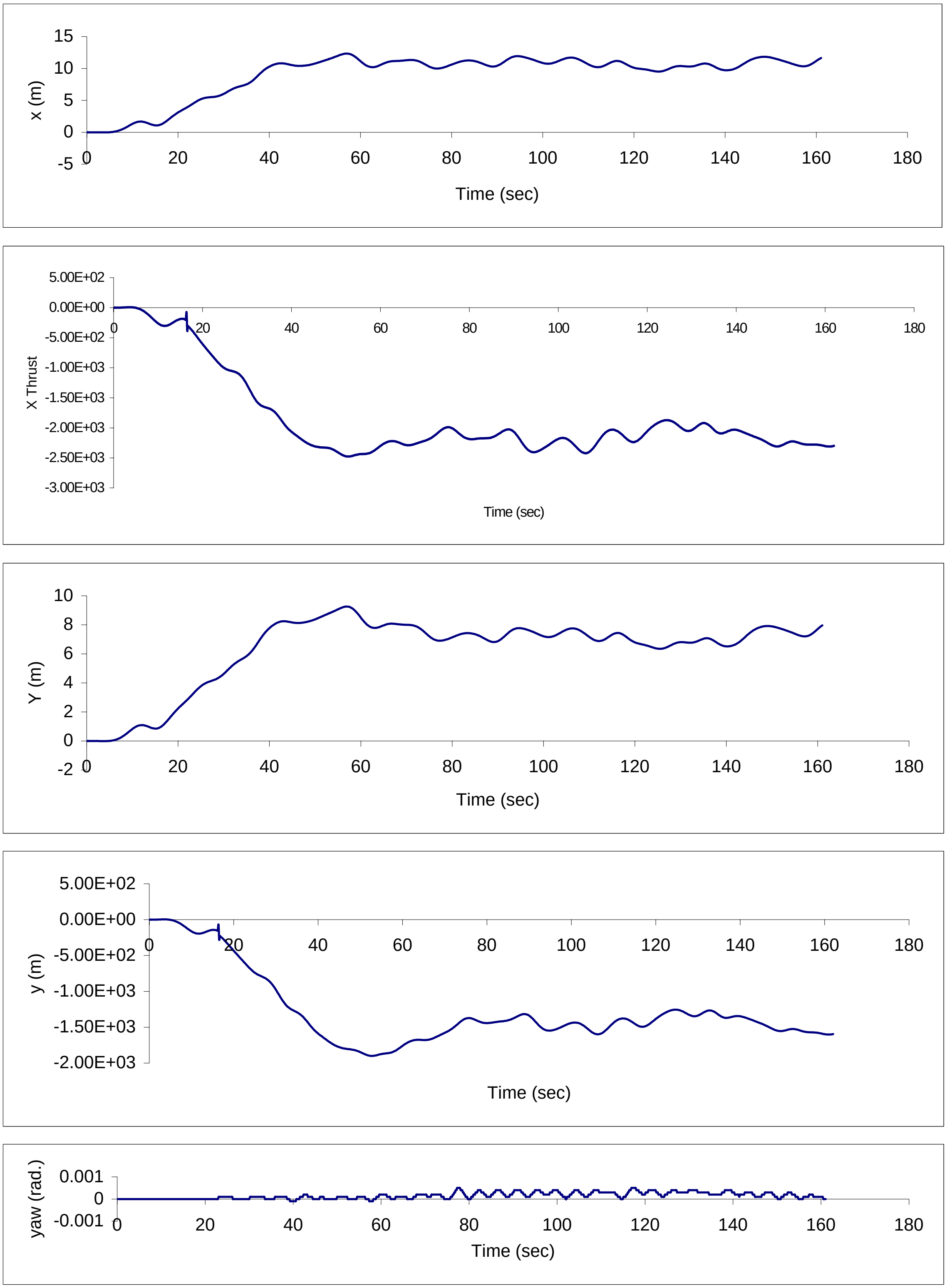

Figure 9. Surge, sway and yaw displacements and D thrust for the triangular semi submersible; *Hs*=6m, heading = 45 deg., current 1m/s with heading 30 deg.