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EXPERIMENTAL AND NUMERICAL FACILITIES FOR ANALYSIS AND DESIGN OF DYNAMIC POSITIONING SYSTEMS

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Resumo

Sistemas de Posicionamento Dinâmico (SPD) são sistemas complexos de controle utilizados para manter uma embarcação em uma posição ou trajetória definida por meio de propulsão ativa. Um SPD possui diversos algoritmos, tais como controladores, filtros e alocadores ótimos de propulsão. O projeto e análise de um SPD é feito por simuladores dinâmicos e estáticos e por ensaios em tanque de provas. Em seguida, os parâmetros do filtro e controle são ajustados por testes no sistema real durante a fase de comissionamento. Este trabalho descreve instalações construídas na USP para estudar e projetar SPDs. Um simulador dinâmico incluído no Tanque de Provas Numérico (TPN) foi implementado. Este é executado em um cluster com 120 processadores e é dotado de um sistema de visualização estéreo 3D. O simulador possui complexos modelos dinâmicos de embarcações, linhas de amarração e risers, e os algoritmos utilizados em SPDs comerciais, bem como modelos de propulsores. Ele permite a simulação de operações auxiliadas por SPD, tais como posição fixa, controle de trajetória e alívio assistido. Para validar o simulador, construiu-se um experimento em escala reduzida, composto por um aliviador DP dotado de 3 propulsores. Utilizou-se um sistema de medição de posição baseado em visão computacional. O programa de controle utiliza os mesmos algoritmos do simulador, e é executado em um computador externo, que envia os comandos ao modelo por sinais em rádio-frequência. Construíram-se geradores de vento e correnteza simplificados. Diversos experimentos foram realizados, e comparações com resultados de simulação mostraram uma boa aderência. Duas condições de carregamento foram consideradas, com e sem a ação de agentes ambientais.

Abstract

Dynamic Positioning (DP) Systems are used to keep a floating vessel on a specific position or follow pre-defined path through the action of propellers. DPS are feedback control systems, composed of position measurement systems, a set of control algorithms and propellers. Several offshore operations use DP Systems, such as drilling, pipe-laying, offloading and diving support. A DP System requires several algorithms, such as controllers, filters and optimal thrust allocation. The design and analysis of DPS is done by static and dynamic numerical simulations and reduced model tank tests. After that, control and filter parameters are adjusted by a long commissioning time. This paper describes recent facilities developed at USP to deal with DPS, namely a computational dynamic simulator and a model scale test system in laboratory tank. The simulator is an improvement of Numerical Offshore Tank (NOT), a 120 processor cluster with a real time 3D-stereo visualization system. The software can treat 6 degrees of freedom of multiple body systems, risers and mooring line effects. It comprises validated models for environmental forces (current, wind and waves), all DPS algorithms, and a complete dynamic description of propulsion system. It enables the simulation of several DP operations, as station keeping, path following and assisted offloading. In order to validate the simulator, an experiment was set-up, composed by a reduced model of a DP tanker with 3 thrusters. The measurement system is

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based on a computational vision positioning system. Control software contains the same DP algorithms used in the simulator, and is executed in an external computer, which sends commands by a wireless radio communication system. Wind and current generators were constructed. Several experiments were done, and comparison with simulation results showed a good agreement. Two loading conditions were considered, with and without the action of wind and current.

1. Introduction

Dynamic Positioning Systems (DPS) are defined as a set of components used to keep a floating vessel on a specific position or pre-defined path through the action of propellers. DPS include position and heading measurement systems, a set of control algorithms and propellers. Several offshore operations are carried out using DPS, such as drilling, pipe-laying, offloading and diving support. Numerical and experimental tools must be used to design, analyze and predict the performance of a DPS before its commissioning. A DPS is a very complex system that integrates several components, and the overall reliability is a fundamental issue in all offshore operations. Furthermore, the ship is a highly nonlinear dynamic system, excited by random environmental forces with a broad frequency spectrum, which imposes the necessity of including complex control and filtering algorithms into the DPS.

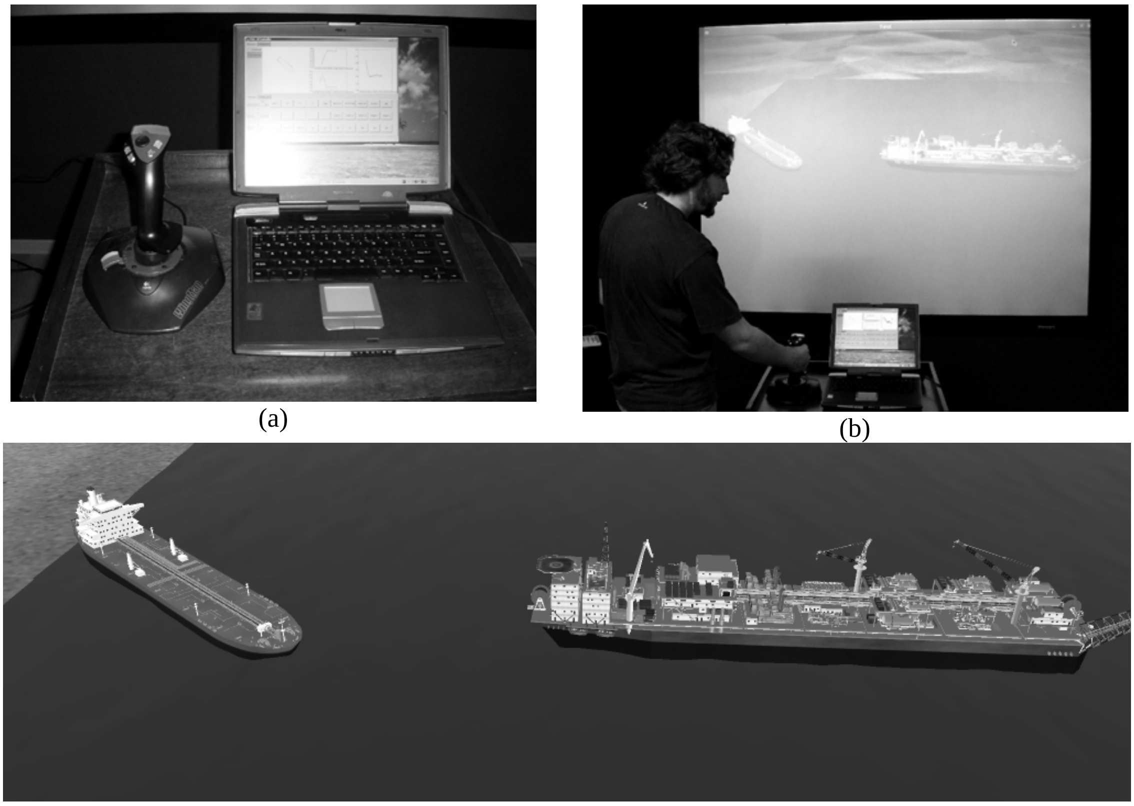
This paper describes recent facilities developed at University of São Paulo to deal with DPS, namely a computational dynamic simulator and a model scale test system in laboratory tank. The simulator can treat 6 degrees of freedom of multiple body systems, risers and mooring line effects. It comprises validated models for environmental forces (current, wind and waves), all DPS algorithms, and a complete dynamic description of propulsion system. It enables the simulation of several DP operations, as station keeping, path following and assisted offloading. In order to pre-validate the simulator, a simplified experiment was set-up, composed by a reduced model of a DP tanker with 3 thrusters. The measurement system is based on a computational vision positioning system. Control software contains the same DP algorithms used in the simulator, and is executed in an external computer, which sends commands to the model by means of a wireless radio communication system. Simplified wind and current generators were also constructed.

The DP algorithms used in the simulator and in the experimental set-up try to emulate the commercial DP systems. It is then applied an Extended Kalman Filter, cascaded with a Proportional-Derivative controller and an optimal thrust allocation algorithm. The early Dynamic Positioning Systems was based on three term PID control with notch filter in order to avoid thruster to counteract high frequency motion due to wave. However the controller based on classical control theory exhibits phase lag that causes performance loss. In order to try to solve this problem in the 70´s and 80´s DPS with Kalman Filter was proposed (Balchen, 1980) and nowadays it is the standard of all commercial DPS. Several reasons explain the wide application of KF in DP systems. The KF reduces the phase lag introduced by the filtering process, compared to conventional low-pass or notch filters (Tannuri et al., 2005), since it incorporates a model of the system, and is able to make predictions about the motions. The reduction of phase lag results a better performance and smaller control power. Furthermore, the KF allows the utilization of several redundant sensors, and performs the optimal estimation of the position and heading based on the information of them. This feature is important for DPS, since reliability and security are key issues for such systems. Finally, the KF also predicts the environmental forces acting on the vessel, what is an important information for the operators and may be used in the controller instead of an integral action (Bray, 1998).The control algorithm itself calculates thrust forces and moment based on low-frequency motion estimates. Modern commercial systems still employ simple PD algorithms. The integral action is given by the direct compensation of environmental forces, which are also estimated by the Kalman filter, as will be shown in the next section.

In the present paper, the numerical simulator and all DP algorithms are described in section 2. The experimental set-up is described in section 3, being the comparisons between simulation and experimental results presented in section 4. Finally, section 5 presents the conclusions. A more detailed description of all DP algorithms may be found in Tannuri et al. (2006).

2. Numerical Simulator

As already mentioned, the Numerical Offshore Tank (NOT) is an advanced offshore system simulator. Furthermore, it is equipped with a console that emulates a real DP system, including a joystick for the full-manual and semi-automatic control modes (Figure 1). Propellers can be disabled or enabled during the simulation, and one can evaluate the consequences of simple or multiple failures.



(a) (b)

(c)

Figure 1. NOT – (a) DP Console emulator with joystick; (b) simulation being conducted; (c) 3D visualization.

Several experimental and numerical validations have been conducted with NOT and its desktop version (called Dynasim). These are considered important tools for design and analysis in the Brazilian oil industry (Nishimoto et al, 2001; Nishimoto et al., 2003; Tannuri et al., 2003).

A low-pass wave filter is employed to separate high-frequency components (excited by waves) from measurement signals. Such decomposition must be performed because the DPS must only control low-frequency motion, since high-frequency motion would require enormous power to be attenuated and could cause extra tear and wear on propellers. Furthermore, an optimization algorithm, called thrust allocation, must be used to distribute control forces among thrusters. It guarantees minimum power consumption to generate the required total forces and moment, positioning the vessel. Finally, a control algorithm uses the filtered motion measurements to calculate such required forces and moment. Normally a wind feedforward control is also included, enabling estimation of wind load action on the vessel (based on wind sensor measurements) and compensation by means of propellers.

In order to address the performance of commercial DPS, a conventional control algorithm was implemented in the simulator, namely a 3-axis uncoupled PD controller, coupled to a feedforward wind compensator. Furthermore, an Extended Kalman Filter (EKF) was used as the wave filter. Such a filter also predicts the non-measured environmental forces, which can be used by the controller. The EKF estimator is widely used in commercial systems. Finally, a thrust allocation algorithm, based on a pseudo-inverse matrix technique, was implemented, with extra features that are normally employed in real DPS.

Three DP operation modes were considered in the simulator. The first mode is the conventional station-keeping mode, in which the desired position and heading (set point) are fixed. It is extensively used in drilling operations. Furthermore, a path-following mode was also considered, with a time-varying set point, as commonly used in pipe-laying operations. Finally, offloading operations require special control strategies, which were also implemented in NOT. Such operations may present a quite interesting dynamic behavior and equilibrium maps, as shown in Morishita and Bolognani (2005).

The simulator also includes models for commonly used propellers, taking into account their characteristic curves, being able to estimate real power consumption and delivered thrust. It also evaluates the time delay between command and propeller response, caused by inertia.

3. Experimental Set-up

In order to make preliminary validations of simulation results, a DPS experiment was implemented in the towing tank of the Naval Architecture and Ocean Engineering Department.

The tank size is 1.5m depth, 5m width and 21m length. A reduced scale model of a shuttle tanker was built, with a scale factor . Main dimensions and mass properties of the vessel, in two loading conditions, are given in Table 1.

Table 1. Tanker model properties

	Fully loaded	**Ballasted condition**
Mass (kg)	52.5	30.5
Mom. Inertia (kg.m^2)	4.63	5.18
Length (cm)	178	
Beam (cm)	29	
Draft (cm)	12	8

The tanker is equipped with 2 tunnel thrusters (a bow and a stern thruster) and with the main propeller (Figure 2).

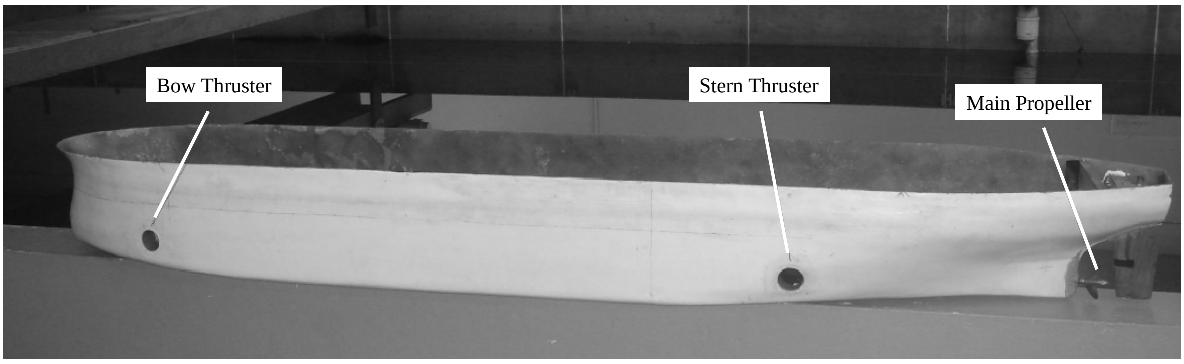


Figure 2 Tanker reduced model

The maximum thrust delivered by the main propeller is approximately 500gf, and by the tunnel thrusters is about 40gf. Converting the maximum thrusts to real scale, on obtains 1885tonf and 151tonf respectively. Such values are higher than those obtained in a typical DP shuttle tanker, in which the main propeller delivers up to 200tonf, and each tunnel thruster delivers up to 30tonf. However, since the objective of the present experiment is to make comparisons with simulator results, such differences between the model and the real ship properties are acceptable since the simulations will be done with the same conditions of the model.

The position and heading measurement is done by an artificial vision system, comprising a camera and an image acquisition board. The total resolution of the system is 320×280 pixels, and the monitoring area dimension is approximately 6m×5m. The resulting resolution of the system is approximately 1.7cm. A simplified method to correct the distortion introduced by the lens is also implemented (Gribbon et al., 2003). Two LEDs installed close to the bow and close to the stern are tracked and their positions evaluated. With such information the software is able to evaluate the midsection position and heading of the vessel. The maximum measurement error due to the resolution is 0.85cm for the midsection position and 1o for the heading angle.

All numerical calculations are done by a Pentium-III 800MHz computer, with a time-step of 0.1s. The commands to the motors are sent to the ship by a radio communication module. The control, filter and allocation algorithm is implemented using Matlab/Simulink, including a special block that imposes the simulation to be executed in real-time (Daga, 2006). A diagram of the experimental set-up is shown in Figure 3.

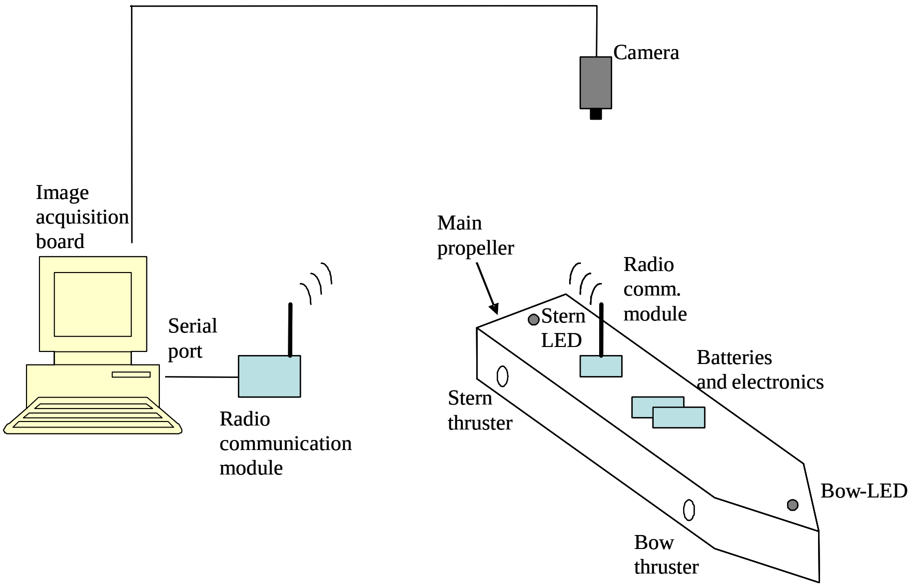


Figure 3. Set-up of the DP experiment

4. Results and Comparisons

The experiments were carried out for two loading conditions (full and ballasted). Figure 4 shows the ballasted model during an experiment.

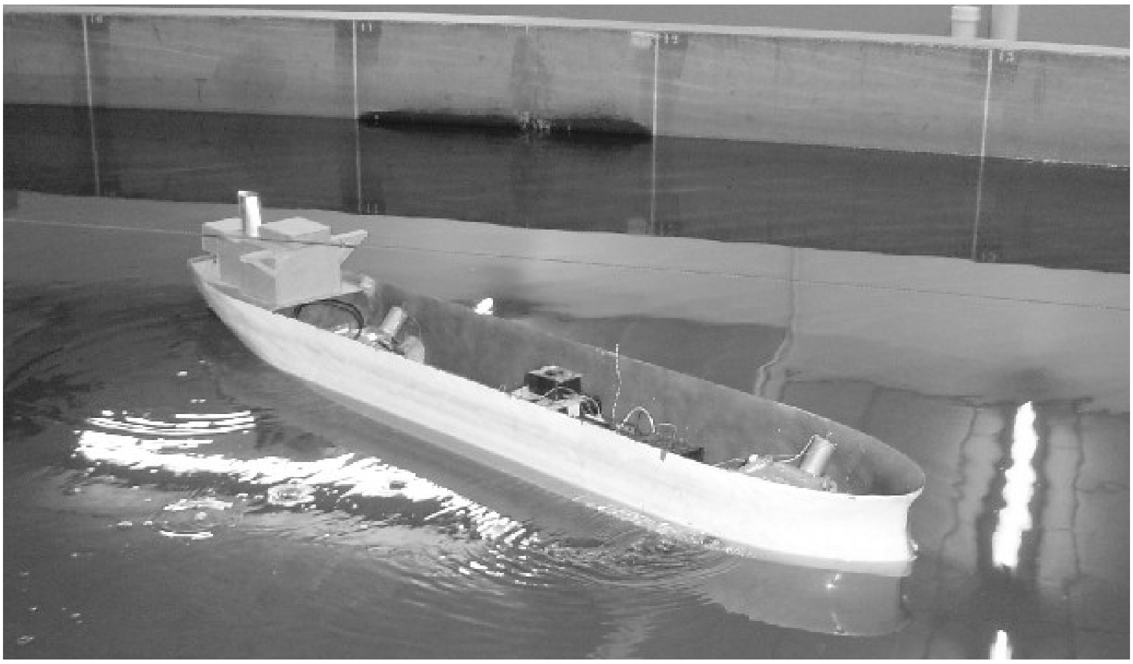


Figure 4. Experiment in ballasted condition

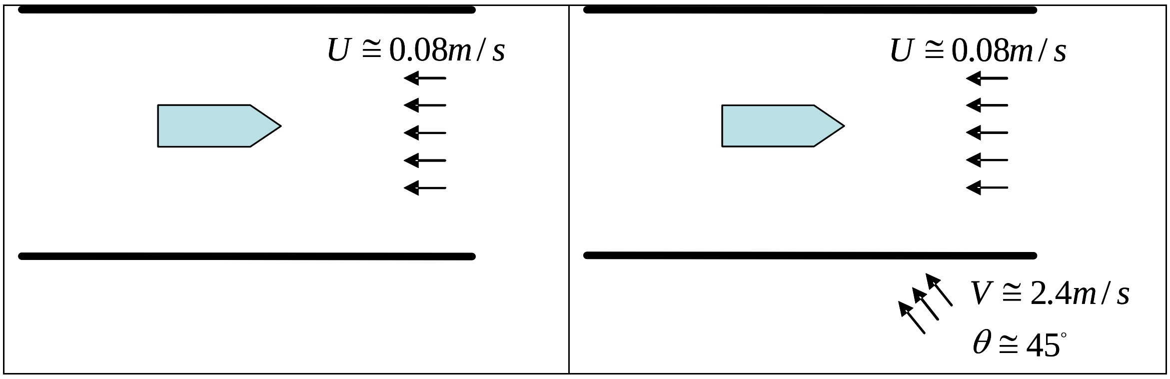


Figure 5. Condition: (left) only current; (rigth) current + wind

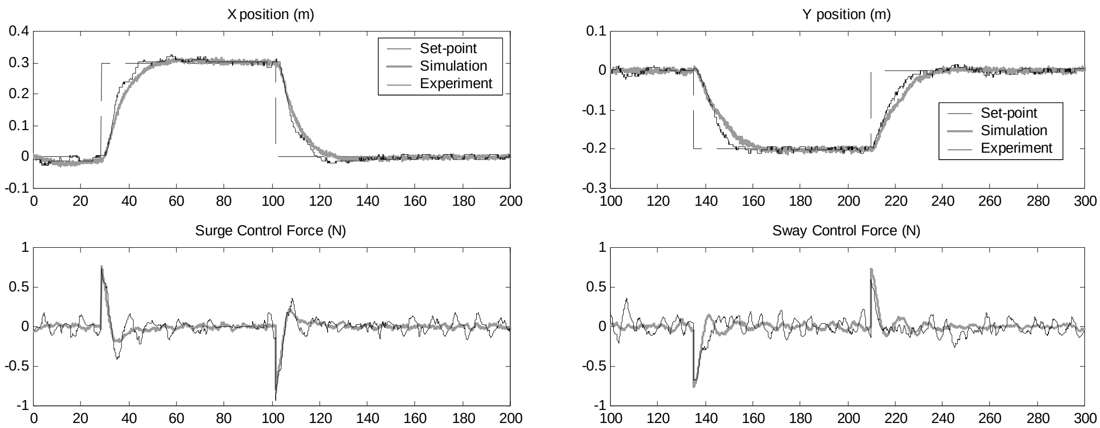
Three environmental conditions were considered. In the first condition, no environmental agents were active over the ship. In the second condition, a 0.08m/s current was imposed to the ship (equivalent to 1m/s current in real scale), and in the third condition, a wind of approximately 2.4m/s was simultaneously imposed (Figure 5).

The current is generated by a tube, mounted transversely in the tank, with several orifices along its length. The wind is generated by a conventional fan. Although such simple apparatus does not guarantee a constant velocity of the environmental actions, the purpose here is only to perform a qualitative evaluation of their effects.

Since in the experiments there was no anemometer available, the wind-feedforward control was not enabled, in either the simulation or the experiment. White-noise was imposed in the simulation in order to represent the measurement noise of the experiment.

Figure 6 shows the comparison of experiment and simulation results, for the fully loaded condition under no environmental action. In all experiments, a 0.3m step was imposed to the surge set-point, and was retuned after the stabilization. The same kind of motion was imposed in the sway direction (with a step of 0.2m) and in yaw (with a step angle of 20^{o}).

Taking into account the simplicity of the experimental set-up, the results show quite a good overall agreement between the experimental and simulation results. In fact, horizontal motions are very well predicted by the simulation. A slightly higher overshoot in the experimental yaw motion may be explained by differences in the proper and added yaw inertia considered in the simulation, as well as in the damping coefficient.



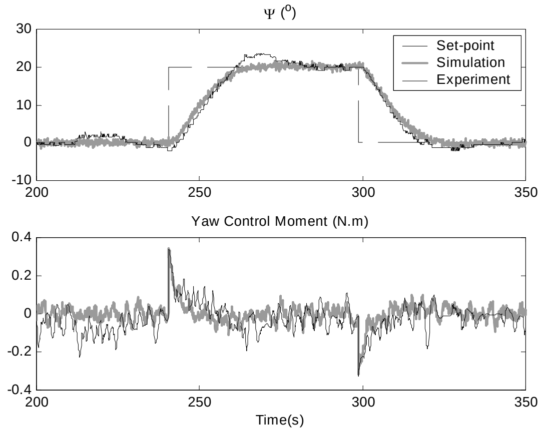


Figure 6. Full condition, no environmental action

Finally, Figure 7 presents the ballasted ship with current and wind. Again, the ship horizontal motion is very well recovered by the simulation. Others results can be found in Tannuri et al. (2006).

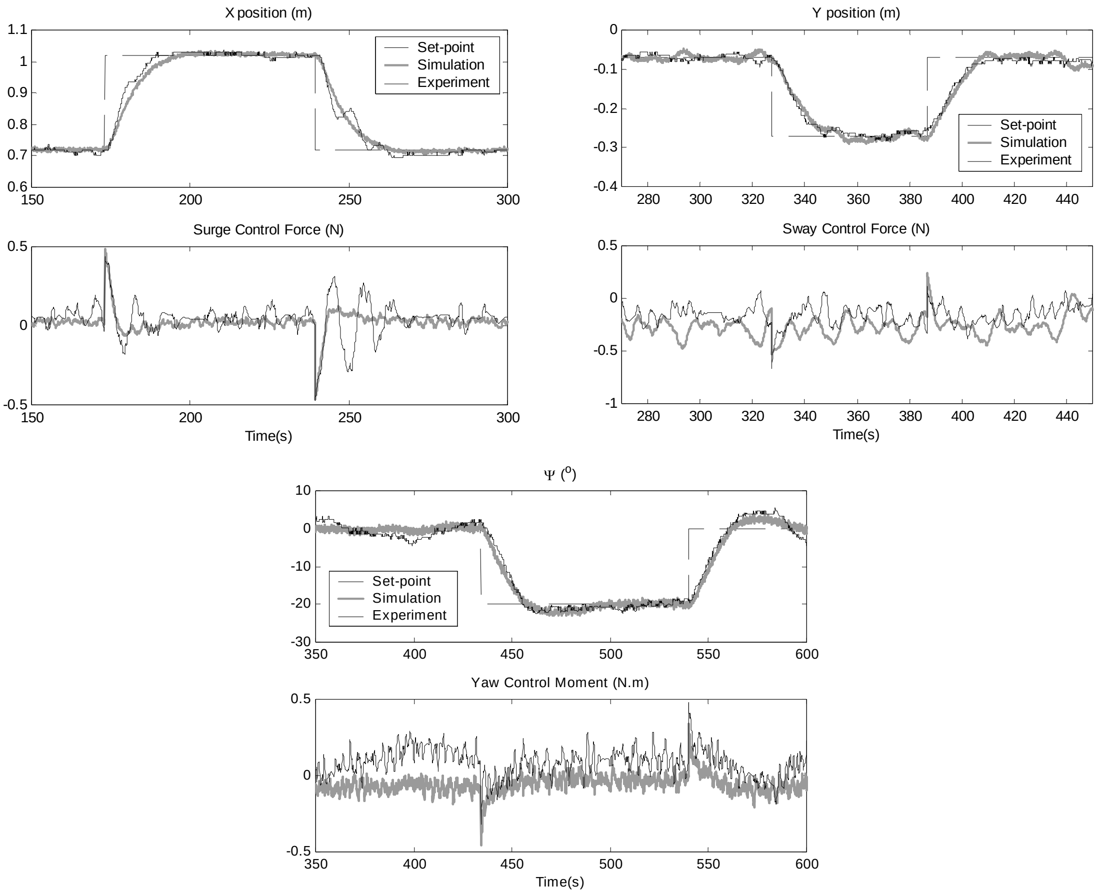


Figure 7. Ballasted condition, current and wind actions

6. Conclusions

The present paper described two facilities that can be used to analyze, design and predict the performance of DPS aided offshore operations.

The simulator comprises models for main DPS sub-systems, namely control logic, filtering, thrust allocation and propulsion. It enables the simulation of three DP operations: station keeping, path following, and DP assisted offloading. The conventional control and filtering algorithm was implemented, namely an Extended Kalman Filter cascaded with a 3-axis uncoupled PD controller. The simulator also considers fixed and azimuthing propellers modeling, as well as controllable or fixed pitch propellers. It takes into account their dynamics and time response characteristics. Finally, the thrust allocation algorithm is included, minimizing fuel consumption.

A simple experimental set-up was implemented and used to pre-validate the simulator. Several experiments with a reduced model of a DP tanker with 3 thrusters subjected to current and wind actions were performed. The experimental and simulation results were compared in detail, and shown to be in good agreement, considering the simplicity of the experimental set-up.

7. Acknowledgments

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