TOWING TANK TESTS OF A DYNAMIC POSITIONING SYSTEM

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INTRODUCTION

The main purpose of a dynamic positioning system(DPS) is to keep an ocean vehicle on a specified position by proper action of the vessel propulsion system. The DPS is basically composed by three subsystems: the measurement (sensor) system, which provides information about the vehicle position and environment conditions; the logical unit (controller), which processes this information and evaluates the control actions; and the thruster system, which produces the propulsion forces recquired to keep the vessel on station.

Dynamic positioning systems were first introduced in ships and platforms about 25 years ago. In Brazil the application of vehicles with DPS began to rise in the spur of the high prices caused by the first petroleum crisis, and is still increasing since nowadays most of Petrobrás drilling activities are concentred in the continental shelf at deep water conditions.

The authors began to work in a research on DPS in the early 1980's. The initial tasks were concentrated on the system conceptual design and analysis of control methods to perform the controller design. In the last two years the emphasis was focused on the development of a controller prototype and the conduction of model tests in a towing tank. This work was carried out as a part of a interchange program between Berlin Technical University and University of São Paulo. This paper presents an overview of this experimental work. At the beginning we present an overview of the mathematical models and control schemes used to develop the control system prototype.

CONTROL SCHEMES AND MATHEMATICAL MODELS

The control system was developed using two alternative approaches applied to a linear stationary stochastic model. In both cases, using the Separation Principle, the control law is applied taking in consideration the estimate of the system state. The estimation in both cases is obtained through an adaptive filter based on the Kalman-Bucy filter,which incorporates a noise estimation algorithm and a dynamic compensation technique. The first control approach is an optimal control method which uses a quadratic performance index in order to get the control gains for a state feedback scheme. In the second approach, use is made of the duality between the estimator and the controller in such a way to generate an adaptive control scheme, where the control action is evaluated step by step in real time.

Estimator

The following mathematical model was used for the estimation purpose (Grimble,1980):

$$\begin{bmatrix} \dot{X}_b(t) \\ \dot{X}_a(t) \end{bmatrix} = \begin{bmatrix} F_b & 0 \\ 0 & F_a \end{bmatrix} \begin{bmatrix} X_b(t) \\ X_a(t) \end{bmatrix} + \begin{bmatrix} G_b & 0 \\ 0 & G_a \end{bmatrix} \begin{bmatrix} w_b(t) \\ w_a(t) \end{bmatrix} + \begin{bmatrix} L \\ 0 \end{bmatrix} U(t) \tag{1}$$

$$\begin{bmatrix} Y(t) \end{bmatrix} = \begin{bmatrix} H_b & H_a \end{bmatrix} \begin{bmatrix} X_b & X_a \end{bmatrix}^T + \begin{bmatrix} v(t) \end{bmatrix} \tag{2}$$

where X is the state vector, which includes for each variable two components, the low and the high frequency motion parts indicated by the subscripts b and a, respectively; L is the input matrix; U(.) is the control vector; G is the noise mixing matrix; w(.) is the dynamic noise vector, whose components are assumed to be zero mean gaussian white noise processes; Y(.) is the observation vector; H is the output matrix and v(.) is the measurement noise vector, whose components are zero mean gaussian white noise processes.

In the above representation the low frequency component is the vessel motion induced by wind, current and drift

forces, while the high frequency part is due to the oscillatory components of waves and wind forces. The low frequency part of the mathematical model was derived from the manoeuvering equations of the platform , where the added mass and damping coefficients were selected by an oriented search from experimental results (Clauss,1984). The high frequency part was modelled as a damped second order oscillator.
The filter model is kept as simple as possible in order to make it feasible on line estimation. It should be noted that in the model tests, with time variables reduced by the square root of the model scale, the measurement (estimation) step is around 0.14s compared with 1.0s for the full scale trials. The model state is estimated using the Kalman filter approach. Since it is known that model errors can produce the filter divergence, we incorporate to the estimator scheme a dynamic compensation technique (Crisol Donha,1989) and an adaptive noise estimator (Brinati,1976). The dynamic compensator is obtained by the addition of a non modelled acceleration to the state equation (Crisol Donha,1989). This acceleration modelled as a Gauss Markov process is estimated altogether with the model state. The dynamic model covariance is evaluated step by step in such a way to minimize the measurement residue.

Controller

Although coupled the estimator and the controller have different orders. First of all it must be pointed out that only the low frequency part of the model should be controlled. Furthermore, the state vector to be controlled does not include the non modelled accelerations, that appears as a state variable in the filter low model part. The low frequency model used to develop the controller is given by

$$\dot{X}(t) = FX(t) + Gw(t) + LU(t) \quad (3)$$

$$Y(t) = HX(t) + v(t) \quad (4)$$

LQG Controller The objective of the optimal control technique is to determine the control law U(.) in equation (3) that minimizes the following scalar quadratic performance index:

$$J = E\left[1/2 \int_{t_0}^{tf} X^T(t) V X(t) + U^T(t) P(t) U(t) \; dt \right]$$

where is the mathematical expectance operator; $V \geqslant 0$ and $P > 0$ are weighting matrices choosed to define the relative importance between the reduction of the state variable values and the reduction of the energy consumption (use of U(.)).

Applying the Separation principle and using, for example, the method of Pontryagin the control solution is given by (Crisol Donha,1983):

$$U(t) = -P^{-1}L^T S(t)\hat{X}(t) \tag{6}$$

$$\dot{S}(t) = -F^T S(t) - S(t)F - S(t)LP^{-1}L^T S(t) - V \;; S(tf)=0 \tag{7}$$

where S(.) is the Riccati matrix and $\hat{X}(.)$ is the filter estimation for X(.).
It is important to observe that the control gains resulted from this method are only function of the plant matrix and of the choice of V and T in equation (5), allowing the " a priori " (out of line) calculation of the optimal gains. The best controller performance for the surge motion, determined by an interactive process, was achieved using the following matrices:

$$V = \begin{bmatrix} 10^{-15} & 0.0 \\ 0.0 & 10^{-1} \end{bmatrix} \qquad\qquad T = \begin{bmatrix} 10^{+7} \end{bmatrix}$$

Typical values for velocity and displacement control gains are, respectively, $G_v = -0.2247115$ and $G_X = -0.0387304$.

Adaptive Controller To find the adaptive control law it is used a discret model, obtained from the time discretization of equations (3) and (4) in the control interval, defined as the minimum time between two value modifications from function U(.). The control objective is to induce the time evolution of the discret state to satisfy the following relation:

$$\Phi\left[X(k+1)\right] = 0 \tag{8}$$

where $\Phi(\cdot)$ is a vector of control functionals and k is the present interval.

The essence of this method is the determination of the control value U(k) that leads X(.) to satisfy the equation (8). For that it is used a reference state $X_R(.)$ resulted from the propagation of the last state estimation using the control value of the previous interval, U(k-1). The new value of U(k) is estimated from the deviation of the reference state from the desired state variable values.
The discret control function is given by (Crisol Donha 1989):

$$U(k) = \left[\Omega^T N^{-1}(k+1)\Omega\right]^{-1} \Omega^T N^{-1}(k+1) O(k+1) \qquad (9)$$

where Ω is the discret input matrix; N(.) is an adaptive variance and

$$O(k) = \frac{d\,\Phi}{d\,X}\bigg|_{X_R(k+1)} \Omega U(k-1) \quad - \Phi\left[X_R(k+1)\right] \qquad (10)$$

TEST FACILITIES AND TRIAL PROGRAM

The model tests were carried out in the 90m long, 4m wide and 2.5m deep wave tank of Berlin Technical University. The wave generator is controlled by an Unix-PCS Cadmus Computer, and driven by a hydraulic system, being able to generate regular and irregular waves, according to a desired sea spectrum. It was used an aluminium model of the RS-35 platform (Clauss,1984) in a 1:53 scale. The RS-35 is a 37000t platform at operation conditions, which configuration is displayed in figure 1. It is composed of a toroidal horizontal body (with outer diameter of 99.5m and seccional diameter of 10.6m), that supports four equally spaced stabilization columns (with 12.0m diameter) sustainning an integrated deck, available for drilling and production purposes.
The four predicted propulsion units for transit and dynamic positioning conditions are installed under the columns and are provided with steerable kort-nozzle pitch ajustable and speed variable propellers driven by DC-electric motors, each propeller absorving till 6945 HP.
The model of the RS-35 platform in the DPS tests was not provided with the specified propulsion system. The tests were carried out with an available thruster sys-

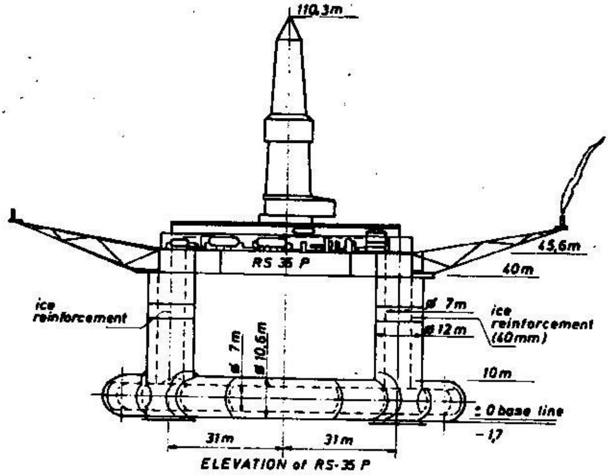


Figure 1 - RS-35 Platform

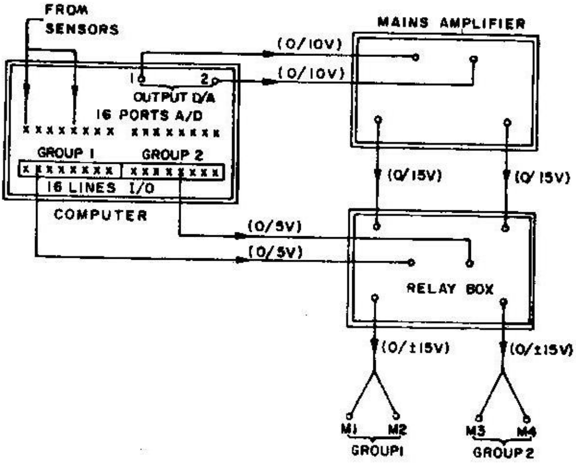


Figure 2 : Controller, Amplifier and Relay Box Arrangement

tem composed by three non-steerable, fixed pitch and speed variable propellers installed in kort-nozzle. The thrust modulation was performed by the variation of the propeller speed, driven by DC-motors directly mounted in the propeller shafts.The performance characteristic of the thruster units was obtained from captive model tests with a propelled platform model, leading to a curve relating the input voltage of the motors to the output propeller thrust. The propeller thrusts were measured by specially constructed balances, using the "Wheatstone Bridge" principle, in order to relate the deformation of the balance structure, measured by strategically installed strain-gauges, to its output voltage.

The incident waves amplitudes were measured by a resistance type probe placed near the model stern. The model displacement was measured by inductive pick-ups attached to the model by strings, running across guide rollers, that results in a precise frictionless system. The rollers worked too like motion reductors, allowing larger model displacement in the tank.

The control system prototype was built using a Compaq Portable AT-type microcomputer equiped with an analogical/digital (AD/DA) interface board. This computer has a 80286 processor and a 80287 mathematical coprocessor working at 12MHz clock frequency, enabling the protype to perform the estimation and control cycles in the right scaled time, at least for the tests with one degree of freedom. The interface board used in the model tests was provided with 16 analogical input channels (DA), 2 analogical output channels (AD) and 16 digital intercomunication channels (I/O), divided in two on-off groups of eight channels, what means, if one group is active all its channels provide an output voltage of 5V. The DA output channels, depending on hardware modifications, can operate in two ways: producing -5V till +5V or 0 till +10V. The driver motors can absorve till 15V, then it was necessary to introduce a mains amplifier to elevate the board output tension. This amplifier can only receive positive inputs, thus, the board was modified to give outputs varying between 0 and 10V. When necessary, negative thrust was produced by propeller reversion, obtained by introducing negative voltages into the driver motors. To obtain negative tensions it was introduced

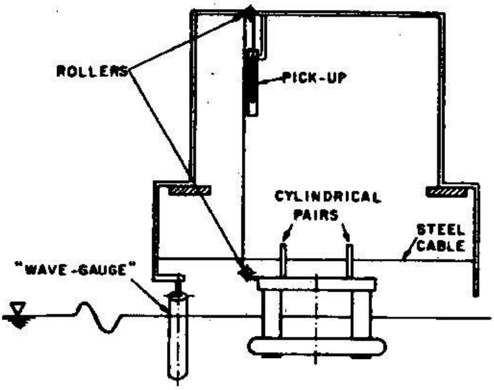


Figure 3 Model, Sensors and Restraints

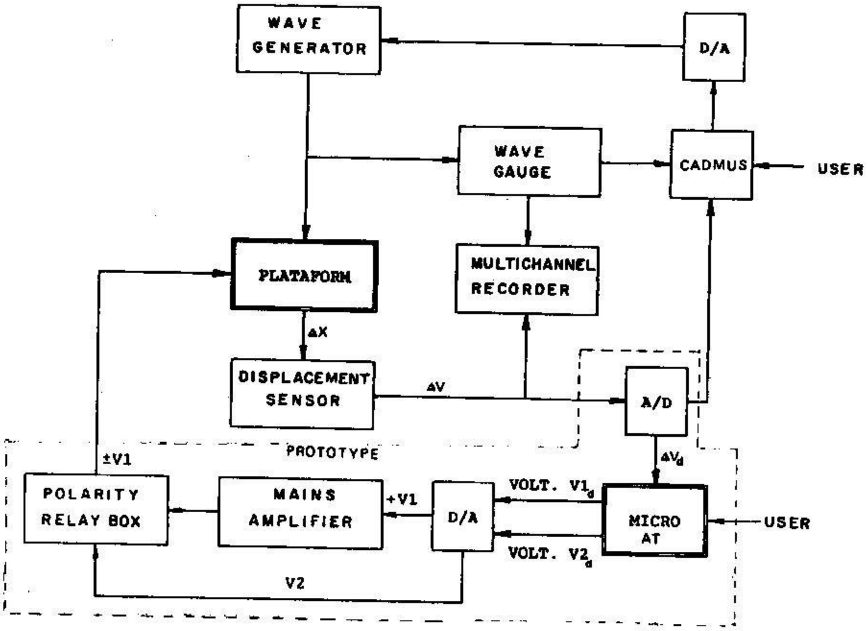


Figure 4 Action Flow Diagram

a set of relays between the amplifier and the motors. The action of the relays were commanded via the microcomputer software, through one of the I/O channels. The interface board was provided with only two analogical output channels (DA). Since the tests were carried out with at least two propellers, each channel was used to control more than one unit through a parallel connection.

Figure 2 shows the way the computer+board, mains amplifier and relay box were linked.

The thruster units used in the tests, although similars, had not equal performance characteristics, producing for the same input tension different thrust. To avoid an undesired yawing moment, the thrust supplied by each unit was equalized via computer software using the results of the captive tests described before.

Towing tanks are not recommended to perform dynamic positioning tests, since in general, they are too narrow to allow larger sway motions of the model. Therefore, as a first step, it was decided to carry out the positioning tests constrainning the model sway and yaw motions. In order to prevent these motions the model was fitted with two pairs of specially constructed cylindrical elements, mounted on ball bearings at the diagonal opposite points in the model deck. A 0.02m diameter tensioned steel cable is attached to the tank carriage and ran between the cylindrical elements. Figure 3 shows a side view of the platform in the tank with particular emphasis on the cylindrical elements and sensor units.

Refering to figure 4, that shows how the equipment are linked to each other, it is presented a brief description of a typical test. The user starts the two computers via keyboard. The Unix computer is supervised by a software developed to control the wave generator, that will produce a determined wave group, following the specified wave spectrum. The model motions, measured by the displacement sensor, and the wave amplitude measured by the wave gauge, are collected in a desired acquisition rate by the Unix computer, where they are stored. The same motion information is send to the controller (Compaq), who makes an acquisition every 0.1374s(1.0), through one of the AD channels of interface board (the numbers in parenthesis from know on are the full scale values). In the control system prototype this information is processed by the installed software, which determines the input voltages to the propeller driver motors. At each 2.88s(21.0) the modulation of the driver motors input tension is provided through the DA channels of the board, enabling the propellers to generate the desired thrust level. The magnitude of the input motor voltage is determined as follows: a) if an acquisition interval is elapsed, the prototype makes an observation of the instantaneous position, if not it waits till the interval is overcome;b) the adaptive filter estimates the state variables, separeted in the low and high frequency components. The low frequency velocity and displacement estimations are sent to the controller;c) if the thrust modulation interval is elapsed a new value for the control function U(t) is determined, if not, the procedure is started again,as in a). The determination of U(.) may be done by two different ways. If the LQG control law is active, the desired thrust level is directly evaluated, since the optimal control gains were " a priori " determined. If the adaptive control algorithm is being applied, the control function is evaluated in real time using the estimate of the low frequency state, without need of any earlier information;d) knowing the actual value of the control function, ie, the required level of propeller thrust to keep the platform in the desired position, we may evaluate the input motor tensions V_{1d} (one for each group) by a set of subroutines, which were developed using the propeller performance characteristics;e) these voltage signals are transmitted through the DA output channels of the interface board to the mains amplifier which produces positive tension signals V_1 that will drive the motors. If the desired thrust is negative, meanning that the propeller speed must be reversed and a negative tension signal produced, the controller (computer+board) sends an order to the relay box, through a digital I/O group, in form of a positive (+5V) voltage signal (V_2) in a specified channel, that will act on the desired motor feed line. Then a new cycle is started as in a).

To make possible later analysis, the microcomputer stores all the position acquisitions, filter estimations and desired thrust levels. As a redundancy and to allow analysis during the tests the wave amplitudes, model displacements and input tensions of the motor groups are sent to a multi-channel graphical recorder. The trial program included, besides the positioning tests, also free model tests, when the DPS was inactive. Free conditions tests were carried out in order to check the platform behaviour under the action of regular and irregular waves and to evaluate the mathematical models. These tests were also used to calibrate the filter.

Irregular sea conditions were generated from Pierson-Moskowitz and Jonswap spectra, for significant wave heights ($H_{1/3}$) varying between 3.0 and 9.0m. Pierson-Moskowitz spectrum modal frequency (w_m) was defined by:

$$w_m = 0.4\sqrt{\frac{g}{H_{1/3}}} \qquad (11)$$

where g is the gravity acceleration.When using Jonswap the modal frequencies were chosen in a lower range (around 1.25Hz) than given by equation (11),since it was observed an amplification of model drift motions when wave trains were generated using modal frequencies in that range. The positioning tests, which had the main purpose of controller performance evaluation were carried out only for irregular waves, considering that this case is more realistic than if used regular wave trains.

Although the RS35 platform had been designed to operate with four propellers, the positioning tests were made using two or three units. When using only two propellers, a lower significant wave height was choiced, in order to avoid the power overcoming of the installed units. As shown in figure 5, the model was positioned with its center line forming 45° with the tank center line, aiming an interference reduction between propellers.

A typical test lasted 250s (30.0min), from which 200s were developed with the wave generator active. This procedure was used to verify the adaptability of the controller when a very different condition begins to dominate.

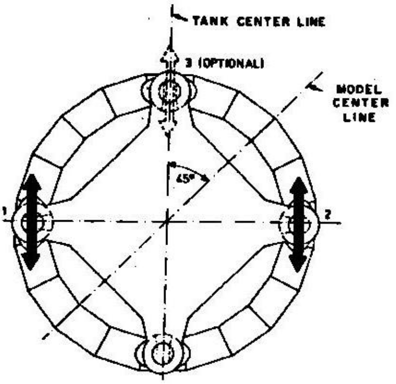


Figure 5: Model Attitude in the Tank
And Propeller Thrust Directions

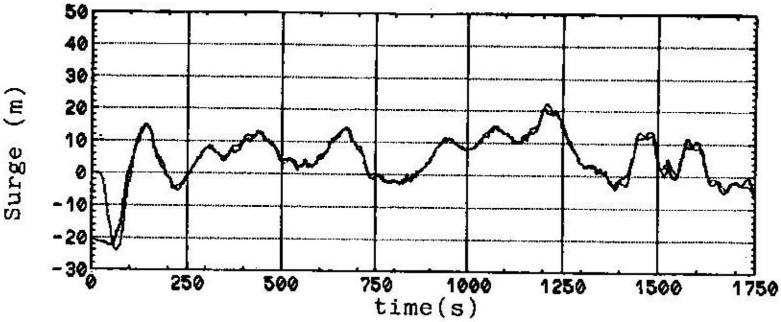


Figure 7a: Displacement Using the LQG controller
Light Line: Estimated
Heavy Line: Measured

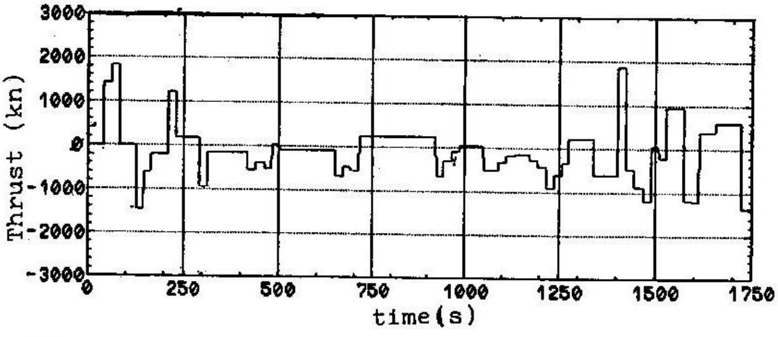
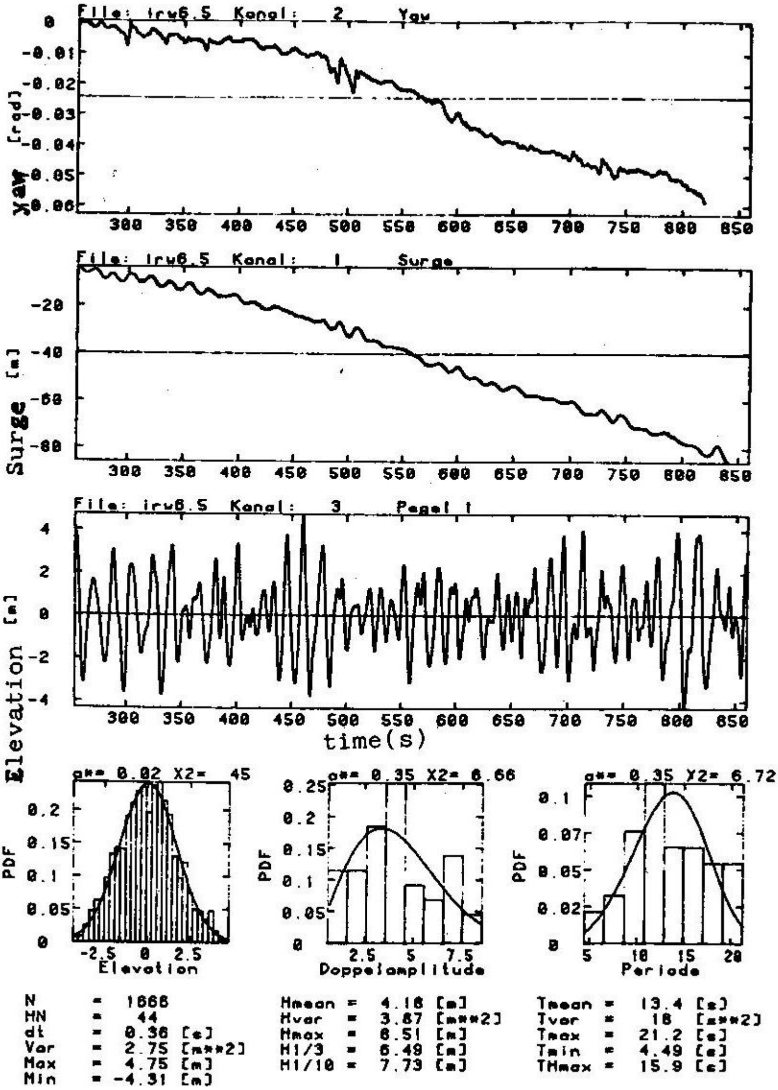


Figure 7b: Thrust Level Using the Lqg Controller



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N      =  1666            Hmean =  4.16 [m]        Tmean =  13.4 [s]
HN     =   44             Hvar  =  3.87 [m**2]     Tvar  =   18  [s**2]
dt     =  0.36 [s]        Hmax  =  8.51 [m]        Tmax  =  21.2 [s]
Var    =  2.75 [m**2]     H1/3  =  6.49 [m]        Tmin  =  4.49 [s]
Max    =  4.75 [m]        H1/10 =  7.73 [m]        THmax =  15.9 [s]
Min    = -4.31 [m]
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Figure 6: Free Condition Test

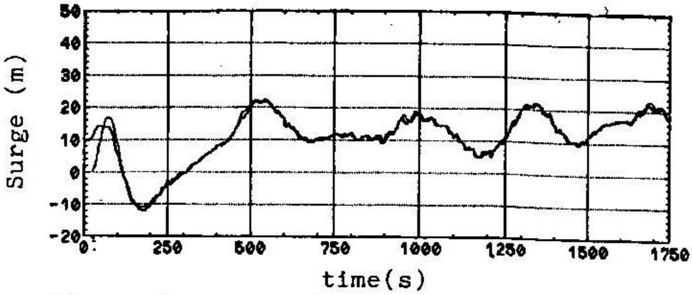

Figure 8a: Displacement Using the Adaptive Controller-Heavy Line:Measured Light Line:Estimated

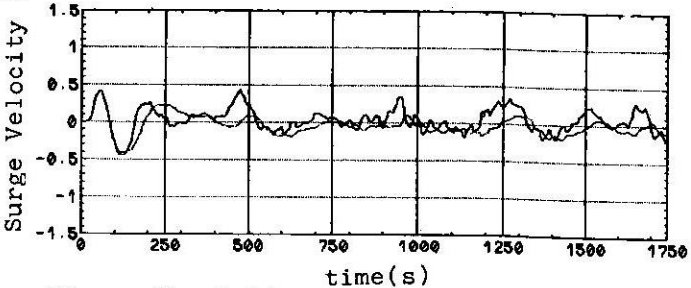

Figure 8b: Estimated Velocities Heavy Line: Low+High Frequency Light Line: Low Frequency

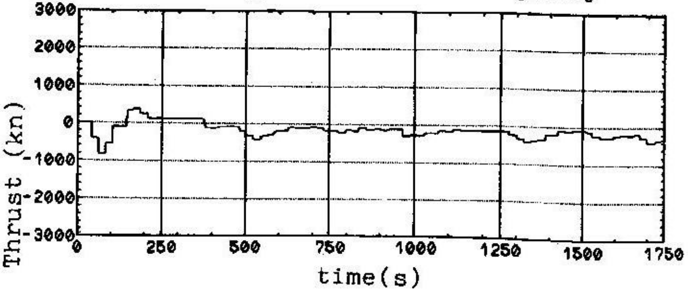

Figure 8c: Thrust Level Using the Adaptive Controller

RESULTS

In this paper we present only some selected results from the free and controlled condition tests under irregular wave excitation corresponding with a 6.5 m significant sea, generated only using the Pierson-Moskowitz spectrum, with no current or wind. For facility, all tests results are given in full scale.
Figure 6 shows a typical test result got of a free condition test. As said, in these tests the model had 6 degree of freedom, but only the yaw and surge motions were capted, using two sets of displacement sensors described before.In this figure the graphic on the top illustrates the model yawing in radians, the graphic in the middle shows the surging in meters,the third graphic shows the wave elevation in meters and the last set a graphical analysis of the wave train, including it PDF (probability density function) for elevations, heights (doppelamplitude) and period distributions. Other characteristics of the wave train - like Hmean (mean height), $H_{1/3}$, Hmax (maximum heigt) and Tmean (mean period) - can be found under the lower graphic set. We see that platform had a little yaw motion, around 0.06rad (3.5°) in 840s, which means a low yaw drift rate, observed in all others tests. This can be explained by the symmetry of this platform to the water flow. In the same time interval the platform moved 40.0m, which gives a surge drift velocity of about 0.15m/s. As expected, the elevation PDF curve is very near of a zero mean gaussian one, whereas the heights are more or less distributed as a Railegh curve. The mean period of waves in this test was 13.4s.
Figures 7a-b show the test result when the prototype was running under the optimal control law (LQG) software. Light line in figure 7a is the filter estimation, while heavy line represents the real (measured) motion. This figure shows that the filter matches the state very well and that the platform had a maximum deviation of about 20.0m from the desired position (zero).
Figure 7b shows the amount of thrust used in this task. Some violents responses are still to be investigated, but the thrust level is reasonable, considering the excitation magnitude.
Figures 8a-c show the controller performance using the adaptive controller. Figure 8a shows that the filter

also matches the state very well, and that the maximum deviation is more or less the same as achieved when the LQG controller was used. Figure 8b shows the filter velocity estimations, where the heavy line is the total velocity (high+low frequency), while the light line represents the low velocity estimation only,which is a very smoothed signal, consequently a good feed signal for the controllers. It must be observed that this is not a measured variable,since it is expected a worst performance of the filter estimation of this variable. Figure 8c shows also a very smoothed time series for propeller thrust in this case, leading to the conclusion that this control law has a better performance, since with less energy consumption an equal deviation from desired position was achieved. As it could be expected, since the designed controllers are a kind of proportional derivative one, the test resuts show a considerable offset. As a consequence a integral component was added to the controller. It was not possible to run a new set of model trials with that controller version but computer simulation tests showed much better results.

CONCLUSIONS

A controller protype for the dynamic positioning system of a semisubmersible platform has been sucessfully developed and its performance was considered satisfactory in a program of model tests, even without using a proper set of thruster units. The adaptive control law seems to offer a greater possibility of improvement than the LQG one. The adaptive filter based on Kalman approach provides effectivelly adaptive action through the use of dynamic compensation of its model and the introduction of an adaptive dynamic noise. Computational performed tests show that the offset observed in all performed tests can be eliminated using an integral control gain (Grimble,1979) and with modifications of some parameters of equation (9) (Crisol Donha,1989).

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