DYNAMIC POSITIONING DYNAMICS

BY

A.C. McCLURE – ALAN C. McCLURE ASSOCIATES
S. McCLURE – ALAN C. McCLURE ASSOCIATES
R.Y. EDWARDS, JR. – ARCTEC OFFSHORE, INC.

Abstract

Development of a successful dynamic positioning system requires a means of checking out the performance of the entire system from the controls to the prime movers to the thruster units and to the reaction of the vessel to the environmental and thruster forces on the hull. A complete simulation will yield the performance of the system by means of mathematical analysis before any hardware has been acquired. Then by means of the detailed system simulator, one can vary parameters of the control system, hardware characteristics, propeller design or even hull design to obtain the desired performance in the changing environment and also in response to sudden failure of a component of the system. Sample results are shown comparing analysis with model basin tests.

Introduction

Dynamic positioning systems are expensive to build and operate, and more expensive to change. It is essential of course to build the system right in the first place. Factors such as mathematical design details must be governed by experience, but performance, flexibility, off-design performance, and other factors are amenable to analysis or model testing. This can be done during the design stage, before any hardware is ordered.

The kinds of problems which can be treated by analysis are:

- balance of environmental forces
- variations in number and arrangement of thrusters
- thruster command algorithms
- effect of time delays
- off-design performance
- effect of sudden failure of unit or power source
- effect of fluctuations in the environment

With the aid of model tests for evaluations of parameters, the analysis can be extended to include the effects of hull interaction with thrusters, and interaction of one thruster with another. Model tests and analysis are almost inseparably joined. The analytical side needs calibration by model tests, and the range of test conditions needs to be extended by analysis.

Before any analysis and testing can be done, one has to create a design which can be analyzed. It is not difficult to estimate from model tests or experience the environmental forces due to wind, current, and waves which must be resisted by the dynamic positioning system. The thrust required in each direction can readily be determined, and an allowance made for dynamic effect from experience -- something on the order of 30 to 40% of the static balance. Thrusters can then be arranged to suit the vessel design and arrangement. Add power sources, a position reference system, and a control system and we have at least the makings of a dynamic positioning system.

The variations possible on this basic design are numerous, and each will affect cost and performance:

- Thruster number and type
- Assignment of prime movers
- Type of motor for electric drive and concomitant choice of electric power speed control system.

Practical considerations will usually limit the choices to a small number of alternatives which can be tested by means of the simulator.

The position reference system can take many forms. Such systems are experiencing rapid development. To the early taut wire and acoustic system, can be added micro-wave, satellite, and short-range laser and radar systems. Spanning time between fixes is aided by inertia navigation systems or dead reckoning computers. Position reference systems is subject enough for a series of papers, and will not be further treated here.

Analysis

The brain of the dynamically positioned system is the Controller. Basically, it measures the position of the vessel with respect to the intended position and directs power to the various thrusters to correct any position error.

In its simplest form, the controller will call for thrust in the direction opposite to the position error. Without some modulation of the thrust and provisioning of a "dead band", the system would continually overshoot. Probably the simplest practical system consists of thrust and moment commands proportional to the amount of error. Even this simple controller needs one more level of complexity. In the event the thruster system is saturated, the controller must assign priority to heading control or position control. Usually heading priority is called for, since the proper heading will minimize the translational thrust requirements.

Using successive position error signals, one can determine the step-wise velocity of the vessel. System performance is greatly improved by adding velocity terms to the thrust equations.

$$T = f(\phi,\ x,\ y;\ \dot{\phi},\ \dot{x},\ \dot{y})$$

Finally, in order to bring the vessel back to the zero position, the thrust must take into account the time over which external forces have acted. A term is added related to the integral of the excursion with time.

$$T = f(\phi,\ x,\ y;\ \dot{\phi},\ \dot{x},\ \dot{y};\ \int(\phi,\ x,\ y)dt)$$

Since acceleration is easily measured (although wave-frequency acceleration must be filtered out) the controller can be made to respond to the external forces before they are manifested in a displacement or heading change. However, we have not yet attempted to add this to the simulation.

The foregoing are all feedback systems. A further refinement in performance can be achieved by adding a predictive or feed-forward component. This is particularly vital where significant time delays may be encountered. Examples of time delays are diesel-generator set power build-up, or even starting an additional engine, or starting an additional thruster. The feed-forward element may be wind velocity and possibly current velocity. Aalbers and Nienhuis (Ref. 2) suggest an intriguing wave direction feed-forward system. The simulation procedure can be extended to include this factor. However, in either of these cases, the value of the simulation would depend primarily on the degree to which the simulated wave data represents possible actual wave measurements. (This element has not yet been incorporated in this simulation program.) The thrust equation thus becomes:

$$T = f(V_w,\ V_c;\ \phi,\ x,\ y;\ \dot{\phi},\ \dot{x},\ \dot{y};\ \int(\phi,\ x,\ y)dt)$$

The possibilities for evaluating the generalized function of eleven variables are limitless, hence the need for mathematical simulation. The equations governing the simulation are given in Appendix 1. Examination of the equations will show that the variables which can be selected consist of the time constant, t; and the constants Kp, Kd, and Ki, the proportional derivative and integral constants for each direction; the equations defining the wind, waves, and current variations; and equations governing thruster allocation.

Results

As an example of the utility of the simulation, we have calculated the response of a 189 meter ship, the GLOMAR EXPLORER, to a sudden squall. The results illustrate the value of feed-forward, the effects of direction, and the consequence of insufficient total thrust capacity. some of these results were published in reference 1, but that paper did not contain the equations on which the simulation is based, limiting its value.

In each of the squall runs, the ship was in equilibrium in 29 knot wind, one-half knot current, and a 15-foot significant sea. The squall is of 600 second duration with wind velocities of about 35 to 60 knots. It is a digitized record of an actual Gulf of Mexico squall as shown in figure 1.

With the squall from directly ahead, the thrusters have sufficient capacity, and the system behaves satisfactorily. The benefit of wind feed-forward is illustrated in figure 2. Without feed-forward, the vessel moves 66 feet off station, and overshoots 40 feet before settling down. Feed-forward can never be 100% effective, so performance at 80% effectiveness, which we believe is a reasonable expectation, is also shown. The data can also be shown on a polar plot which is easier to visualize.

When the squall is imposed from the beam direction, the thrusters are momentarily loaded to capacity, and the system is "saturated." Figure 3 illustrates the necessity of providing thrust in excess of the static balance. The curves shown represent in one case 3 thrusters available, 14,000 HP, and in the other case 6 thrusters totalling 10,500 HP. Either system has more than enough thrust to exceed the equilibrium loading. Both cases include wind feed-forward at 80% effectiveness. Note that the time during which the system is saturated is relatively brief, yet the system allows large drift and overshoot.

The Role of Physical Model Tests

Clearly, the availability of today's computing power and sophisticated graphics engines render the use of digital time domain, nonlinear dynamic simulation programs the best alternative for validating and optimizing the design of modern DP systems.

These simulation programs require reliable functional relationships between environmental parameters such as current wind speed, wave height and period and direction relative to ship's heading and longitudinal force, side force, and yaw moment. In addition to these environmental "forcing functions", the performance of thrusters, rudders, and main propulsors in providing reaction forces and moments in opposition to the environmental forces is required in terms of applied power, thruster orientation, and proximity to other propulsion devices.

Despite the advancement of numerical models for the prediction of hydro- and aerodynamic forces on floating vessels, they still do not posses sufficient precision for providing an adequate function for use in the dynamic simulators, particularly as the requirements to analyze the stationkeeping of permanent systems for deep water and hostile environments emerge.

The logical role of physical model experiments in DP system design, validation, and optimization is analogous to their role in supporting maneuvering simulators for surface ships and submarines. This role can be viewed in comparison with the full physical simulation of a DP system at model scale in a similar way that the use of model tests and maneuvering simulators are compared with free- running maneuvering experiments. Both of these "full physical simulations" are expensive, require physical reproduction of the controller and all of its strategies, and suffer from hydrodynamic and time scale effects. Large models are required to minimize scale effects on control appendage effectiveness and a thorough examination of the sensitivity to overall response to subtle changes in control algorithms is so time consuming as to be virtually impossible. Nonetheless, some test facilities have conducted experiments where a "complete" physical simulation of a DP system was undertaken. We believe that such simulations are useful, only to validate numerical codes and are not a viable design/optimization tool.

A discussion of some aspects of the efficient use of model tests to provide the inputs required by numerical simulators follows:

Wind Forces and Moments

The use of wind tunnel models to establish the longitudinal and lateral wind force coefficients for monohulls and semisubmersibles we well-known. Scale effects due to Reynold's number disparity between the model and full-scale are mitigated somewhat due to the bluffness of the elements of the above water portion of these vessels. While there exists published data for some classes of vessels (3), it is advisable to conduct experiments to determine the "aerodynamic coefficients" when the configuration of above water portion of the vessel departs significantly from that for which published data is available.

Current Forces and Moments

If it were possible to always maintain a nearly zero heading with respect to the current, such information would not be terribly important. However, the likelihood of misalignment between the direction of sea, wind, and current can be high in tidal areas and estuaries and during squalls. So, in order to accurately analyze the response of a dynamically positioned vessel, it is necessary to understand the relationship between the coefficients of longitudinal and lateral forces, and yaw moment and heading. An example of such a set of data derived from physical model tests is shown in Figure 4 for the GLOMAR EXPLORER, extracted from Edwards (4) and in Figure 5 for a fine-hulled Polar Icebreaker from Chilton and Edwards (5). Again, it would be useful to use existing systematic series data to determine these coefficients. Indeed, some data has been assembled for tankers by the Oil Company's International Marine Forum (3). However, this data is for a limited class of hull forms. Changes in many hull form parameters such as length to draft ration, and fore and aft body fineness, as well as the distribution and size of appendages can change these coefficients. Comparison of Figures 4 and 5 demonstrate a variation for the two aforementioned vessels of approximately 80% in the side force coefficient at "stall". Furthermore, the heading angle of "stall" is 45° for the Icebreaker hull and 60° for the GLOMAR EXPLORER. In Figures 6 and 7, the yaw moment coefficient for the same two ships is presented. The magnitude and shape of the yaw moment coefficient versus heading relationship is distinctly different for the two vessels.

The foregoing is no less true for column stabilized floating platforms. PHysical model tests are the best tool today for quantifying these important inputs to the simulator. Nonetheless, the scale of the model experiment must be chosen carefully. It has been shown by Edwards (4) that Reynold's Number (based upon beam) of approximately 500,000 are required to produce reliable results for the current force and moment coefficients. This implied model scales on the order of 1:20 to 1:30.

Wave Induced Forces and Moments

The forces exerted on a floating body by waves at wave frequency are ignored in current DP System designs because it is recognized that response times for the systems cannot approach that necessary to effectively control position at wave frequency and because wave frequency oscillations in the plane of the sea surface are not usually large enough to limit operations. On the other hand, the steady component of wave inducted longitudinal, lateral force, and yaw moment must be reacted out by a the positioning system and the slowly varying component of these forces and moments must at least be attenuated. Numerical models have been developed which provide estimates of the steady and slowly varying components of wave drift forces and moments. Nonetheless, to confirm these estimates for new designs, it is advisable to obtain a semi-empirical relationship between the steady force and moment coefficients and wave period in regular waves. Estimates of the slowly varying drift force and moment coefficients can also be derived from experiments in regular wave "beats" and from irregular wave tests using cross bi-spectral analysis techniques to derive quadratic transfer functions for second order wave forces. These model tests can be conducted using relatively small and inexpensive models, on the order of 1:50, because viscous effects are relatively unimportant in physical simulation of wave drift.

Thruster Effectiveness

The effectiveness of thrusters in producing forces and moments to react out the environmental forces and moments is necessary information for the simulator. It is not adequate to consider the thruster in isolation because depending upon the proximity of thrusters, their inflow and outflow fields can interact, producing deviations in effectiveness from that which would be expected if the thrusters' force and moment applied to the vessel were calculated taking inflow velocity (free stream current), propeller angular speed, and pitch into account, and using performance curves for the isolated thruster. English and Wise (6) describe a series of experiments wherein thruster interaction effects were derived from physical model tests. These tests require the use of a large model typical of that used for self-propulsion tests. For vessels where it is impossible to avoid placing the thrusters where the inflow and outflow fields may interfere, physical model tests are the only reliable way to define the effects.

In addition to thruster/thruster interaction, it has been found that thrusters and particularly main propulsion units in the vicinity of the afterbody can create markedly different reaction forces and moments on vessels at oblique angles, particularly at high current speeds. This is illustrated in Figure 8 from Edwards and Chilton (5). Here the effectiveness of a single main propulsion unit in producing yaw moment is plotted versus heading with respect to current direction. An effectiveness of 1.0 indicates a measured reaction moment equivalent to the calculated thrust times the moment arm, taking into account the observed advance ratio. In can be seen that the measured reaction moment is many times the ideal value. In essence, the propeller operation has drastically changed the pressure distribution around the vessel, aligned obliquely to the flow from that with no propeller in operation. To a lesser extent, this effect may be seen for through-hull thrusters placed at the extremity of the vessel. The only way to assess effects such as this is with physical model tests.

These experiments are carried out best with a large captive model. The model is restrained in surge, sway, and yaw. The model is towed at various speeds and headings and various thruster operating conditions are prescribed. The resulting residual forces and moments are measured. This data base is used in conjunction with a similar data base obtained from towed tests without the thrusters and propulsors operating to derive the effectiveness and interaction polar plots for the thrusters and propulsors.

References

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2. A. B. Albers, and U. Nienhuis, "Wave Direction Feed-Forward on Basis of Relative Motion Measurements to Improve Dynamic Positioning Performance", OTC Paper No. 5445, Houston, Texas, 1987.
3. "Prediction of Wind and Current Loads on VLCCs", Oil Companies International Marine Forum, London, 1977.
4. R. Y. Edwards, Jr., "Hydrodynamic Forces on Vessels Stationed in a Current", OTC Paper No. 5032, Houston, Texas, 1985.
5. R. J. Chilton and R. Y. Edwards, Jr., "Thruster and Main Propulsion Efficiencies of Vessels in a Current", OTC Paper No. 5443, Houston, Texas, 1987.
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APPENDIX 1
GOVERNING EQUATIONS

The nonlinear equations which govern surge, sway, and yaw are:

$$(m+a_x)\dot{u}-(m+a_y)\omega v = R_x(\gamma)V^2+F_x, \tag{1}$$

$$(m+a_y)\dot{v}-(m+a_x)\omega u = R_y(\gamma)V^2+F_y, \tag{2}$$

$$(I_\psi+a_\psi)\dot{\omega}+b_3|\omega|\omega+(a_y-a_x)uv = N_c(\gamma)V^2+M_z\ , \tag{3}$$

where the dot denotes differentiation with respect to time, and:

$\omega \equiv \dot{\psi}$ is the yaw velocity (see sketch below)

u = the vessel velocity in the (local) x direction,

v = the velocity in the (local) y direction,

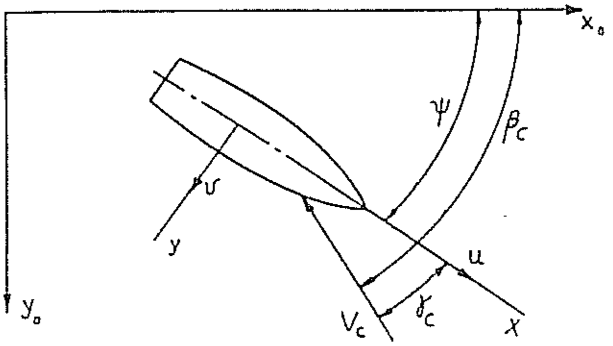
m = basic mass of the vessel,

a_x = added mass in surge,

a_y = added mass in sway,

I_ψ = mass moment of inertia about z axis,

a_ψ = added inertia for yaw,



$R_x(\gamma)$ = the resistance coefficient of the vessel in the x direction due to relative water velocity in the γ direction,

$R_y(\gamma)$ = analogous coefficient for y direction,

$N_c(\gamma)$ = the moment resistance coefficient due to relative water velocity in the γ direction,

b_3 = quadratic moment drag coefficient

V_c = current velocity,

$V = [(u+V_c\cos\gamma_c)+(v+V_c\sin\gamma_c)^2]^{\frac{1}{2}}$ is the relative water velocity,

$\gamma = \tan^{-1}\left(\dfrac{u+V_c\sin\gamma_c}{v+V_c\cos\gamma_c}\right)$

$$F_x = F_{w_x} + F_{d_x} + F_{T_x} + F_{r_x},$$

$$F_y = F_{w_y} + F_{d_y} + F_{T_y} + F_{r_y},$$

$$M_z = \underset{\substack{\uparrow \\ \text{wind}}}{M_{w_z}} + \underset{\substack{\uparrow \\ \text{wave} \\ \text{drift}}}{M_{d_z}} + \underset{\substack{\uparrow \\ \text{thrusters}}}{M_{T_z}} + \underset{\substack{\uparrow \\ \text{riser}}}{M_{r_z}},$$

F_x , F_y = total forces (excluding water drag) in the local x, y directions, respectively,

M_z = the total yaw moment (excluding water drag).

The vessel velocities along the fixed (global) axes (x_o,y_o) are related to the velocities along the local axes by the following transformation relations:

$$\dot{x}_o = u\cos\psi - v\sin\psi \tag{4}$$

$$\dot{y}_o = u\sin\psi + v\cos\psi. \tag{5}$$

In addition, the excursions in surge and sway and the yaw are obtained from

$$x_o = \int \dot{x}_o\,dt, \qquad y_o = \int \dot{y}_o\,dt, \qquad \psi = \int \omega dt. \tag{6}$$

The first-order differential equations governing thrust build-up with time can be written in the form

$$\begin{aligned} \tau\frac{dT_x}{dt} + T_x &= G_x \\ \tau\frac{dT_y}{dt} + T_y &= G_y \\ \tau\frac{dT_z}{dt} + T_z &= G_z \end{aligned} \tag{7}$$

where τ is the time constant and G_x, G_y and G_z are given by

$$\begin{aligned} G_x &= -K_{p_x}x_o - K_{d_x}\dot{x}_o - K_{I_x}\int_o^t x_o dt \\ G_y &= -K_{p_y}y_o - K_{d_y}\dot{y}_o - K_{I_y}\int_o^t y_o dt \\ G_z &= -K_{p_z}z_o - K_{d_z}\dot{z}_o - K_{I_z}\int_o^t z_o dt. \end{aligned} \tag{8}$$

Note that F_{T_x}, F_{t_y} and M_{T_z} used in the definition of F_x, F_y and M_z, are, respectively, identical to T_x, T_y and T_z of Eqs. (7).

Notice also that T_z and G_z are yaw moments.

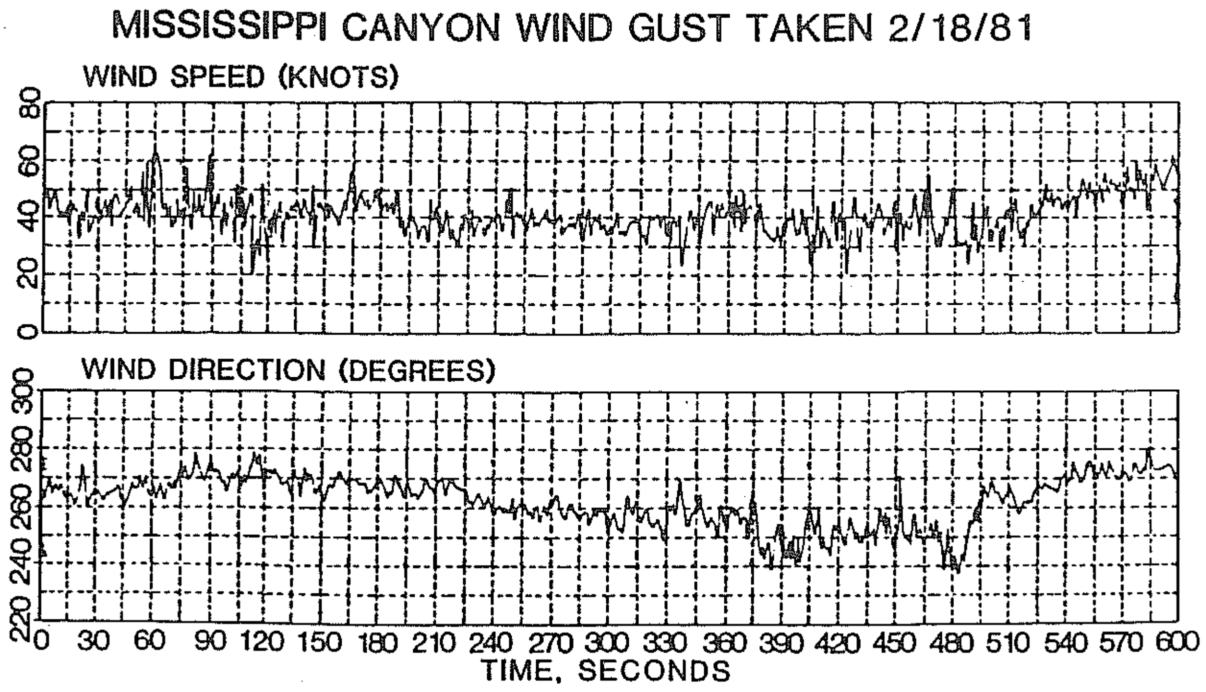
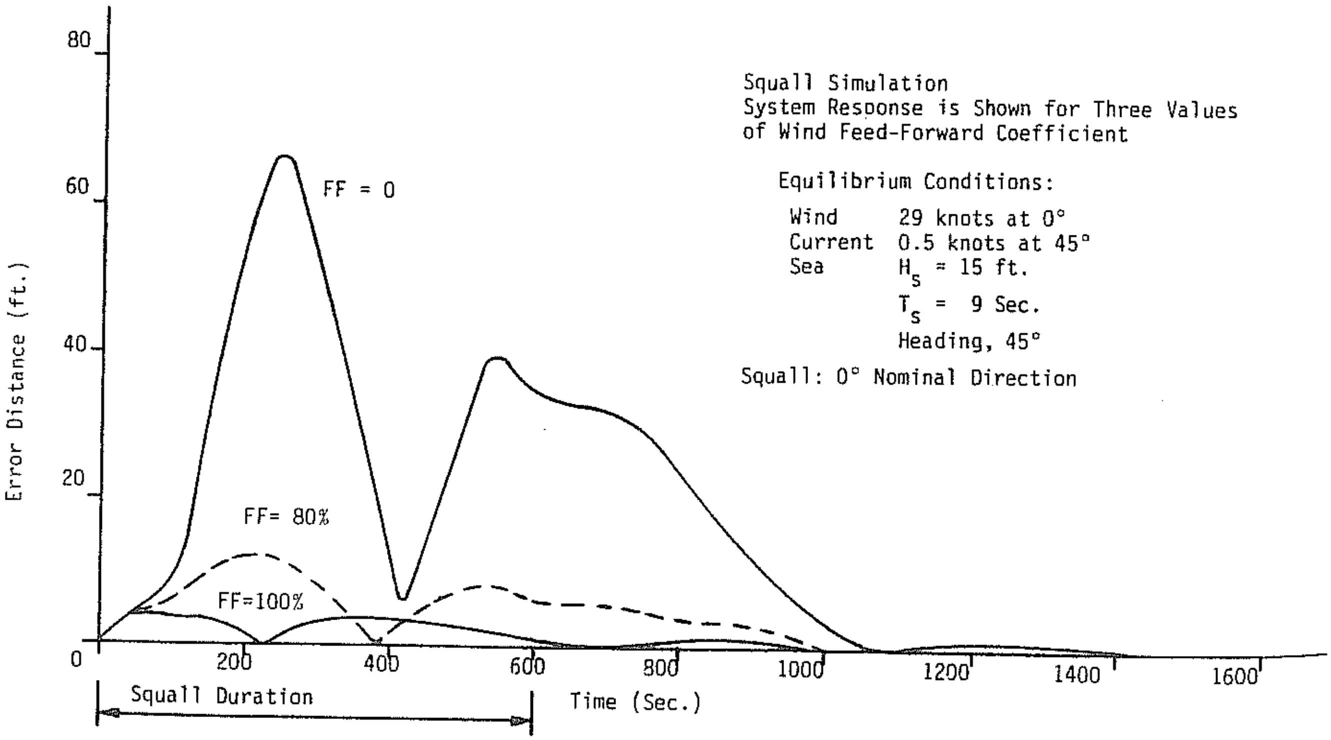


Figure 1 Squall Data



Squall Simulation
System Response is Shown for Three Values of Wind Feed-Forward Coefficient

Equilibrium Conditions:

Wind 29 knots at 0°
Current 0.5 knots at 45°
Sea H_s = 15 ft.
T_s = 9 Sec.
Heading, 45°

Squall: 0° Nominal Direction

Figure 2 Squall Simulation

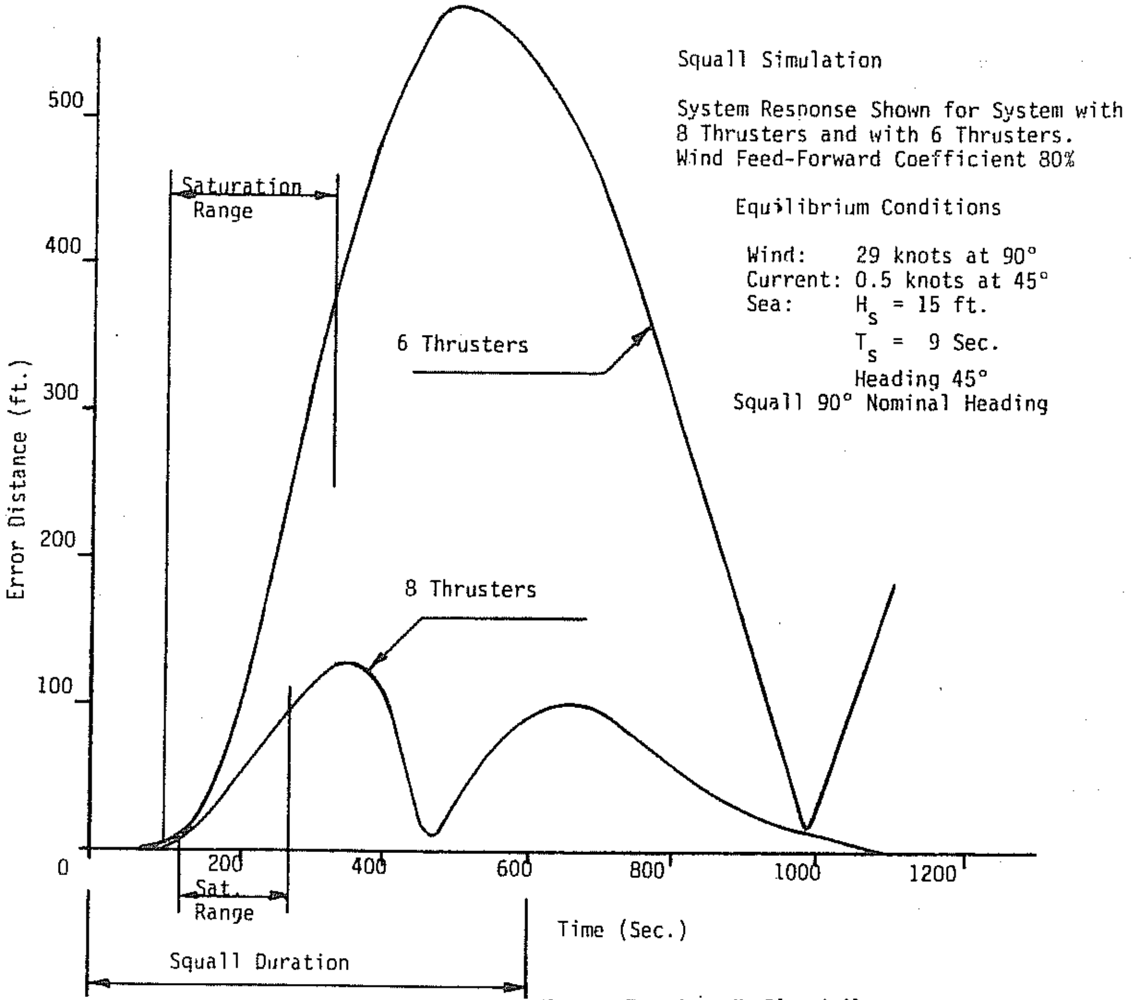


Figure 3 Squall Simulation

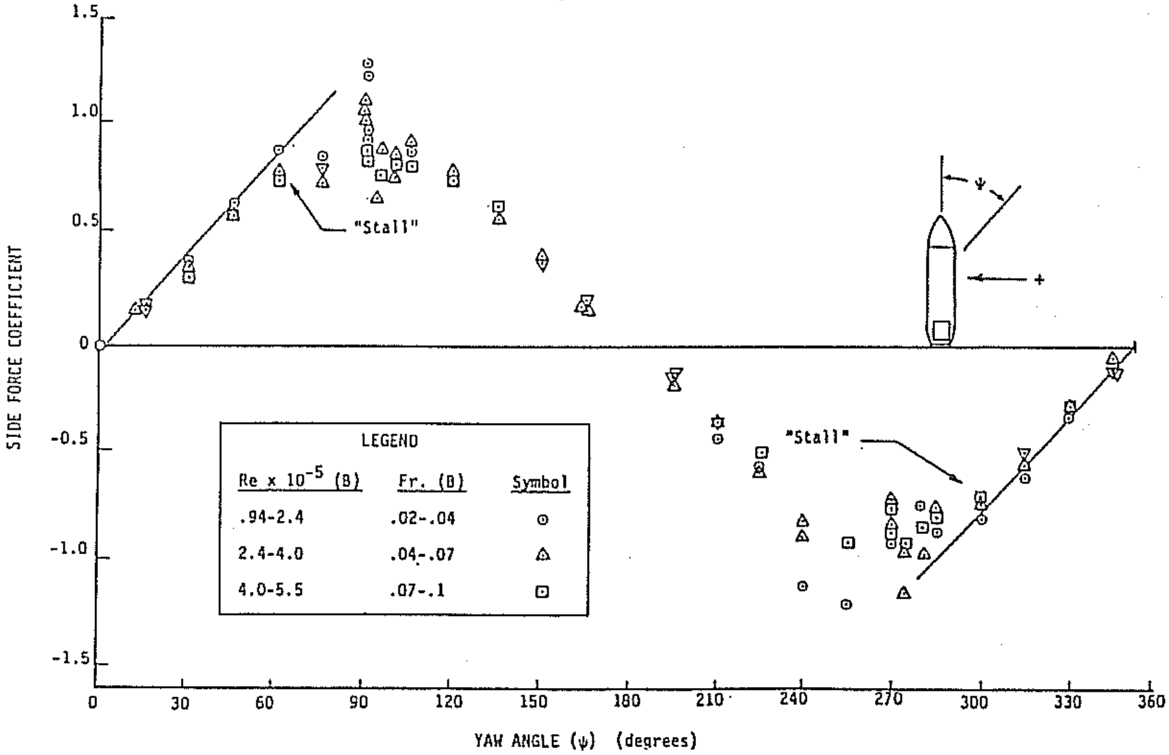


Figure 4 Plot of Side Force Coefficient vs Yaw Angle GLOMAR EXPLORER

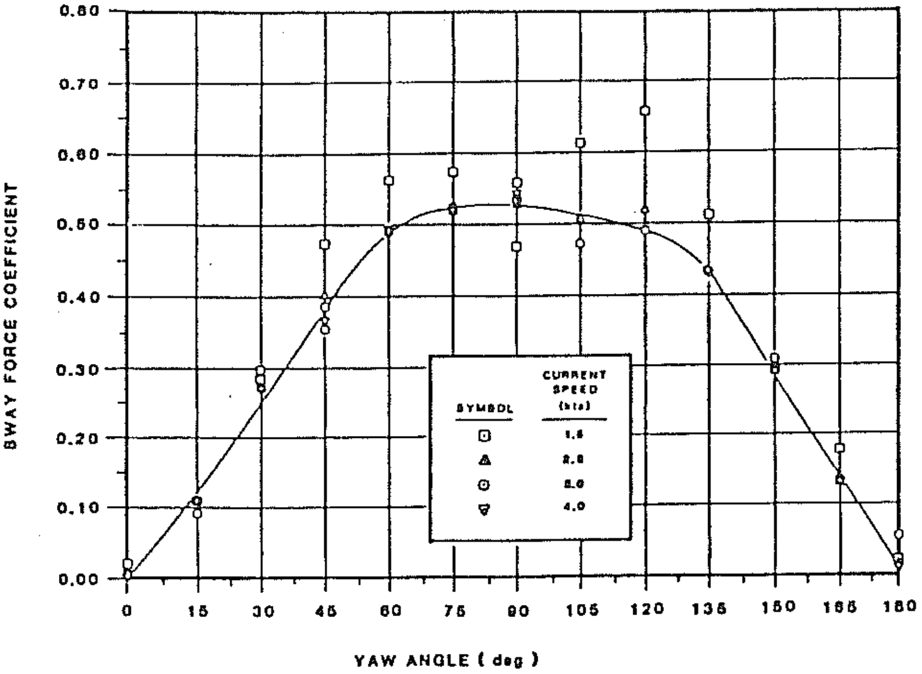


Figure 5 Icebreaker Sway Current Force Coefficient

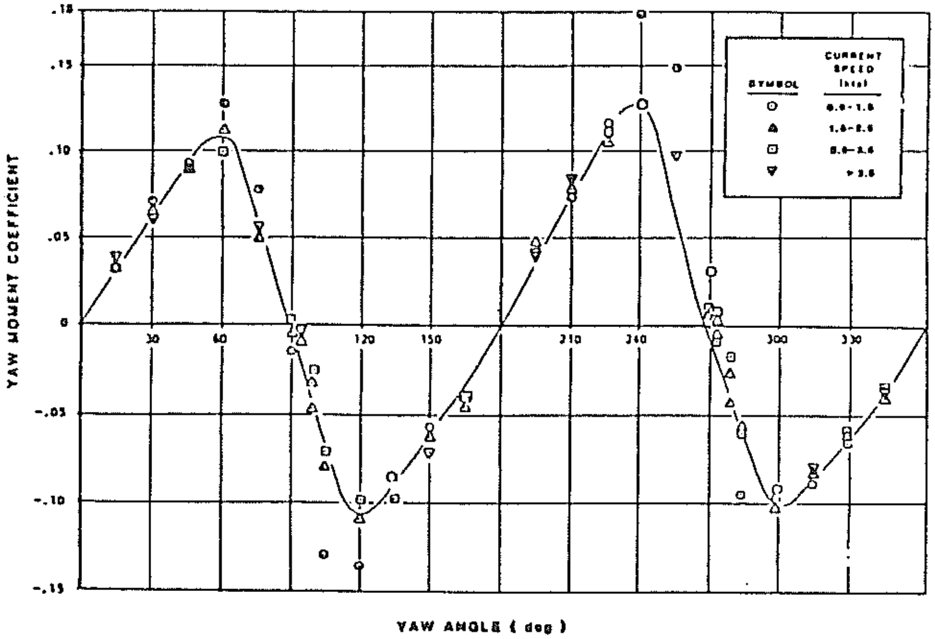


Figure 6 Drillship Yaw Current Moment Coefficient

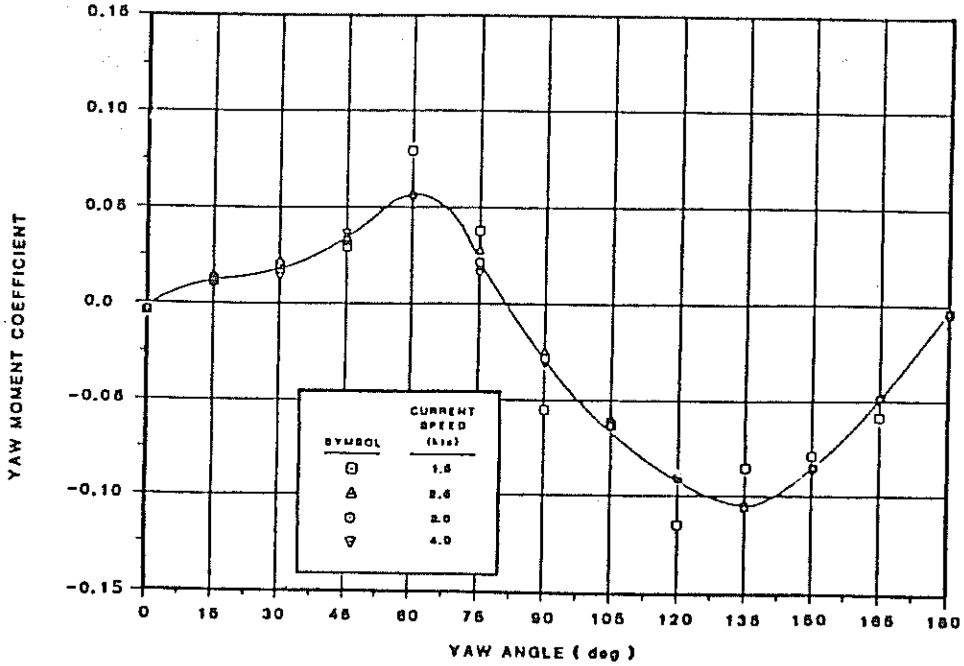


Figure 7 Icebreaker Yaw Current Moment Coefficient

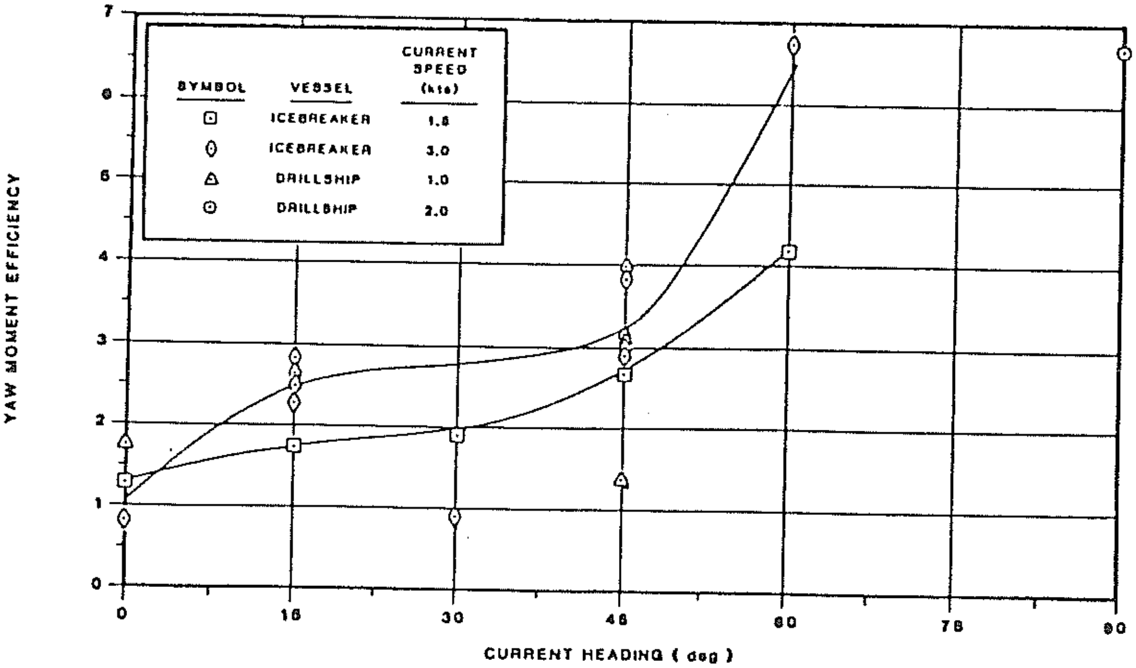


Figure 8 Starboard Main Propulsion Unit Yaw Moment Efficiency