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SIMULINK MODELING OF A MARINE AUTOPILOT FOR TSSE SHIP DESIGNS

by

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This thesis covers the design, simulation and analysis of a SIMULINK system designed to predict the maneuvering characteristics of the Total Ship System Engineering (TSSE) program's first proposed hull design. The system is developed in three degrees of freedom. The ship's hydrodynamic derivatives are predicted in MATLAB code, while the engine is modeled completely in a SIMULINK environment.

To test the system's applicability, an underway replenishment scenario is used to simultaneously test the steering and engine control subsystems.

Two controllers are employed in the system. The first is used to drive the ship in a fashion similar to that of a human conning officer during an underway replenishment. The other is a root locus design used to improve the engine's response.

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SIMULINK MODELING OF A MARINE AUTOPILOT FOR TSSE SHIP DESIGNS

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I. INTRODUCTION

A. BACKGROUND

The prediction of a ship's maneuverability as a part of the design process is becoming a reality. Valuable feedback can be given to a design team during the design process to provide insight regarding a proposed design's performance. Previously, the primary method of testing a hull design involved a scale model subjected to various tests in a wave tank. Construction and testing of models can be expensive and involve many man hours. It is important that once a hull's design reaches this phase that the design be as complete as possible. If a computer model is available for simulating a proposed hull's performance, the design team's productivity can be increased. The result will be a more accurate scale model for tank testing and, ultimately, a better ship design at lower cost.

Toward this end, many studies have been conducted in various formats, with varying degrees of complexity. A low order, easy to reproduce, simplified model, coupled with a scenario to test a hull's design, would prove useful to design teams. This study is aimed at producing a simplified model of ship and power plant dynamics to be used in simulation studies of ship maneuverability and station-keeping. This simulation model will then be used to study a station-keeping control algorithm in the presence of adverse disturbances due to wind and wave conditions. Further, this study is aimed at providing a model for the Total Ship System Engineering (TSSE) program at the Naval Postgraduate School. The TSSE program produces, as a capstone design project, one proposed ship each year by the students in the program. The ships designed by the TSSE program currently have no maneuverability prediction program. It is hoped that the final product of this study will provide the TSSE design teams with a tool enabling further study of their proposed ships form the standpoint of maneuverability and station-keeping.

B. OBJECTIVES

The goal of this study is to construct a ship-steering simulation model, complete with power plant dynamics and wind and wave disturbances, which will be used to assess alternative control laws for autonomous station-keeping during at-sea replenishment. This simulation will ultimately be provided to the TSSE program for use by future ship design teams. Specific objectives include:

1). The development of a mathematical model for ship dynamics, power plant and rudder dynamics, and disturbance factors for wind and wave conditions in various sea states. The relevant mathematical equations appear in Chapter II below.

2). The development of a computer simulation based on the equations derived in the mathematical model. This simulation development is described in Chapter III below.

3). The development of a controller design, as described in Chapter IV below.

4). Test and evaluation of one controller design using the simulation. These results are discussed in Chapter V below.

Input for the simulation study will be taken from the final design report for the first ship designed by the TSSE program: RDS-2010.

II. MATH MODEL DEVELOPMENT

A. COORDINATE SYSTEMS

Two coordinate systems are used in the description of the ship's movement relative to the earth. The first is a system fixed with respect to the earth oriented at some fixed point on the surface; the other is a system fixed with respect to the three major axes of the moving ship. A ship-fixed coordinate system has the advantage of constant moments of inertia and constant moment arm lengths in all three directions. An earth-fixed coordinate system, if used, would constantly change the lengths of moment arms in each direction as the ship turns and rolls. Convention applies control and disturbance forces to the ship in ship-fixed coordinates, resulting in motion of the ship's coordinate origin relative to the earth. The motion of the coordinate axis of the ship represents the ship's movement with respect to the earth. Figure 1 illustrates the coordinate system being used. It is a right hand system positive forward, starboard, and down, using x, y, and z, respectively, to denote the ship fixed axes. Also shown are the Xo and Yo axes, which are considered fixed in the earth. Xo(t) and Yo(t) display a distance the ship has traveled with respect to the earth origin point at a time (t). The rudder angle δ is shown as convention employs; positive rudder is for a port turn. The angle Ψ represents the angle the ship's velocity vector is displaced from a parallel of the Xo axis placed at the ship's center of gravity. For simplicity, the ship's velocity vector will be considered to be along its longitudinal axis, making the angle Ψ representative of the ship's heading with respect to the earth fixed origin (X_{0G},Y_{0G}).

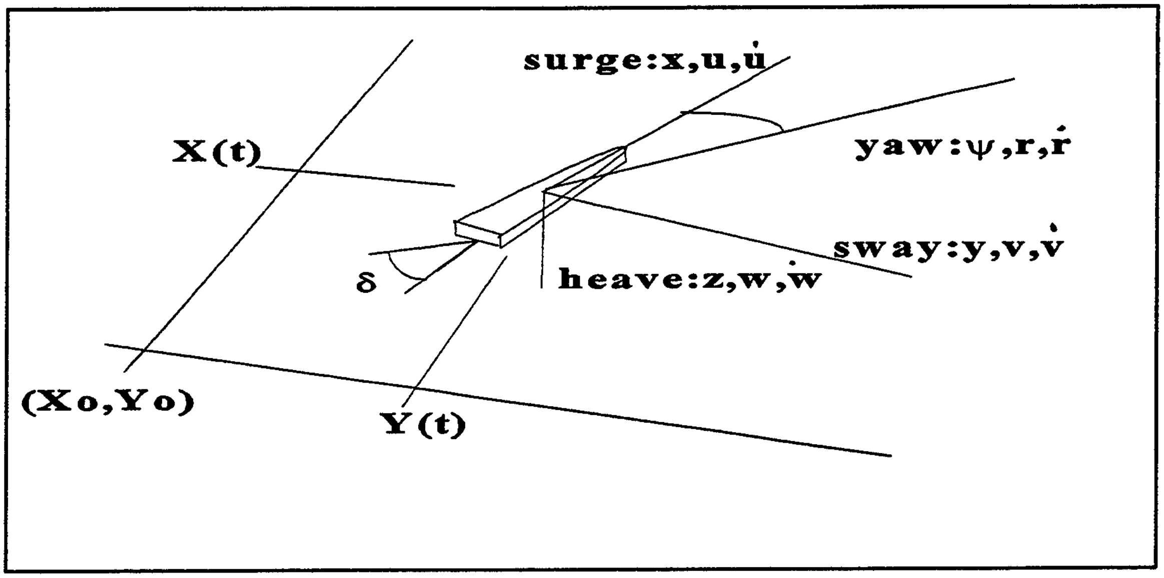

Figure 1. Earth Centered and Ship Centered Coordinate Systems

B. EQUATIONS OF MOTION

An abbreviated presentation is made of a ship's equations of motion. A more in depth discussion of these equations can be found in Principles of Naval Architecture. [Ref. 2:Ch. 8]

1. Earth Fixed Equations

From Principles of Naval Architecture [Ref 2], a ship's movement with respect to an earth fixed reference point (X_{0G}, Y_{0G}) can be described by equations (1a and b) as:

$$\begin{aligned} (a) \quad \dot{X}_{0G} &= u\cos\psi - v\sin\psi \\ (b) \quad \dot{Y}_{0G} &= v\cos\psi + u\sin\psi \end{aligned} \qquad (1)$$

where: x, y, and z are in ship fixed coordinates, and $u = \dot{x}$, $v = \dot{y}$, $\psi = ship's\ heading$, are termed surge, sway and yaw respectively.

2. Ship Fixed Equations

If a moving set of axes is desired, Ref 2 shows that a ship's equations of motion on a horizontal plane are:

$$\begin{aligned}
&(a) \quad X_u\,(u - u_1) + (m - X_{\dot{u}})\,\dot{u} = 0 \\
&(b) \quad -Y_v v + (m - Y_{\dot{v}})\,\dot{v} - (Y_r - m)\,r - (Y_{\dot{r}} - m x_G)\,\dot{r} = Y_\delta \delta \\
&(c) \quad -N_v v - (N_{\dot{v}} - m x_G)\,\dot{v} - (N_r - m x_G)\,r + (I_z - N_{\dot{r}})\,\dot{r} = N_\delta \delta
\end{aligned} \qquad \textbf{(2)}$$

where: X = total force in the x direction

Y = total force in the y direction

N = total moment about the z axis

I_z = mass moment of inertia about the z axis

m = ship's mass

x_G = distance ship's center of gravity is displaced from the centerline (positive forward)

δ = rudder deflection angle

$r = \dot{\Psi}$

Equations (2a-c) assume symmetry about the ship's longitudinal axis, and employs a shorthand notation where:

$$
\begin{aligned}
&(a) \quad Y_v = \partial Y / \partial v \\
&(b) \quad N_{\dot{r}} = \partial N / \partial \dot{r}, \quad etc....
\end{aligned}
\qquad (3)
$$

Assuming linearity of the above, we see that X in equation (2a) is not coupled with second two equations (2a and b), hence it will be dealt with separately.

a. Nondimensionalizing Variables

Equations of (2a and b) has units of force, while equation (2c) has units of a moment. Therefore, it is convenient to nondimensionalize the variables as follows:

$$
\begin{aligned}
&(a) \quad m' = \frac{m}{\rho/2\ L^2} \\
&(b) \quad I_z' = \frac{m}{\rho/2\ L^5} \\
&(c) \quad Y_v' = \frac{Y_v}{\rho/2\ L^2 U^2} \\
&(d) \quad Y_r' = \frac{Y_r}{\rho/2\ L^3 U} \\
&(e) \quad Y_{\dot{v}}' = \frac{Y_{\dot{v}}}{\rho/2\ L^3 U} \\
&(f) \quad Y_{\dot{r}}' = \frac{Y_{\dot{r}}}{\rho/2\ L^4 U} \\
&(g) \quad N_v' = \frac{N_v}{\rho/2\ L^3 U^2} \\
&(h) \quad N_r' = \frac{N_r}{\rho/2\ L^4 U} \\
&(i) \quad N_{\dot{V}}' = \frac{N_{\dot{v}}}{\rho/2\ L^4 U} \\
&(j) \quad N_{\dot{r}}' = \frac{N_r}{\rho/2\ L^5}
\end{aligned}
\qquad (4)
$$

where: ρ = density of seawater

L = ship's length

U = ship operating speed

b. Formulae for Predicting the Hydrodynamic Derivatives

From Regional Deterrence Ship (RDS-2010) [Ref. 1:Ch. 8:Sec. 10], the following formulae are found for deriving hydrodynamic derivatives from hull data:

$$
\begin{aligned}
&(a) \quad Y'_v = (Y'_v)_h + (Y'_v)_f \\
&(b) \quad Y'_r = (Y'_r)_h \quad 1/2(Y'_v)f \\
&(c) \quad Y'_{\dot{v}} = (Y'_{\dot{v}})_h + (Y'_{vDOT})_f \\
&(d) \quad Y_{\dot{r}} = 0 - 1/2(Y_{\dot{v}})_f \\
&(e) \quad N'_v = (N'_v)_h \quad 1/2(Y'_v)_f \\
&(f) \quad N'_r = (N'_r)_h + 1/4(Y'_v)f \\
&(g) \quad N'_{\dot{r}} = (N'_{\dot{r}})_h + 1/4(Y'_{vDOT})_f \\
&(h) \quad N'_{\dot{v}} = 0 - 1/2(Y'_{\dot{v}})_f \\
&(i) \quad Y'_{del} = (Y'_v)_f \\
&(j) \quad N'_{del} = -1/2(Y'_v)_f
\end{aligned}
\qquad (5)
$$

where: $(\,)_h$ denotes the contribution to the variable from the hull, and $(\,)_f$ denotes the sum of contributions to the variable from fins and other appendages as shown in equations (6a-g).

$$
\begin{aligned}
&(a) \quad (Y_v')_h = -\Pi T/L + C_D \\
&(b) \quad (Y_r')_h = k_1 m' + x_p/L(Y_v')_h \\
&(c) \quad (N_v')_h = -(m_2' - k_1 m') + x_p/L(Y_v')_h \\
&(d) \quad (N_r')_h = m_z' \,\bar{x}/L + (x_o/L)^2 (Y_v')_h \\
&(e) \quad (Y_{\dot{v}}')_h = -k_2 \frac{\Pi}{LT^2} \int_{bow}^{stern} C_s d^2 dx \\
&(f) \quad (N_{\dot{r}}')_h = k' \frac{\Pi}{L^3 T^2} \int_{bow}^{stern} C_s d^2 x^2 dx \\
&(g) \quad (Y_v')_f = 2A_f' \left(\frac{\Pi}{1 + 2/a}\right)
\end{aligned}
\qquad (6)
$$

where:

$$
\begin{aligned}
&(a) \quad m_2' = k_2 \frac{\pi}{LT^2} \int_{bow}^{stern} C_s \, d^2 \, dx \\
&(b) \quad m_z' = (k'/k_2) \, m_2 \\
&(c) \quad \bar{x} = \frac{\int_{bow}^{stern} C_s \, d^2 \, x \, dx}{\int_{bow}^{stern} C_s d^2 dx}
\end{aligned}
\qquad (7)
$$

and as empirically derived by Vann [Ref. 3]:

$$\begin{aligned}
&(a) \quad k_1 = 0.3(2T/L) \\
&(b) \quad k_2 = 1.0 - 0.5(2T/L) \\
&(c) \quad k' = 1 - 1.333(2T/L) \\
&(d) \quad C_s = C_0 + C_1(sa/bd) + C_2(sa/bd)^2 \\
&(e) \quad C_0 = 0.8572 + 0.5330(4d/b) \\
&(f) \quad C_1 = 3.374 - 1.3661(4d/b) \\
&(g) \quad C_2 = -1.7323 + 0.8670(4d/d)
\end{aligned} \tag{8}$$

where:

T= ship's draft

C_D = ship's coefficient of drag

k_1 = longitudinal coefficient of accession to inertia

k_2 = lateral coefficient of accession to inertia

k' = rotational coefficient of accession to inertia

C_s = two dimensional sectional inertia coefficient, calculated using strip integration along the ship's hull.

sa = section area of section being considered

d = draft at section being considered

b = beam at section being considered

C_0, C_1, C_2 = interim variables used in the calculation of C_s.

x_p = distance from centerline to point of application of fluid force

x_o/L = ½ prismatic coefficient

A_f = profile area of the appendage

A_f' = nondimensionalized profile area of fin or appendage (A_f/LT)

a = aspect ratio of the fin or appendage, defined by Gillmer [Ref. 4] as:

$$a = \frac{h}{A_F^2} \tag{9}$$

h = span of the appendage

Calculation of the above derivatives is accomplished in MATLAB code with the files HYDROGEN.M and CSGEN.M that are listed in appendices A and B.

3. Propulsion Equations

To solve for motion along the ship's longitudinal axis, equations (10a and b) for gas turbine engines are used, as presented by Tozzi. [Ref. 5]

$$\begin{aligned} &(a) \quad \dot{V} = g/m(T_p - R_s) \\ &(b) \quad \dot{N} = \frac{1}{2\Pi I}(Q_t - Q_f - Q_p) \end{aligned} \tag{10}$$

where: V = ship velocity in feet per second

N = Propeller shaft speed in rotations per second

g = acceleration due to gravity in feet per second squared

m = ship mass in pounds mass

T_p = propeller thrust in pounds force

R_s = resistance of the ship in pounds force

I = moment of inertia of the drive train referred to the propeller shaft

Q_t = engine torque available at the propeller shaft in foot pounds force

Q_f = friction torque losses in foot pounds force

Q_p = propeller torque losses in foot pounds force

a. Propeller Thrust

The thrust is a measure of force developed by the propeller in the direction of the shaft. Mathematically, it is expressed as:

$$T_P = k_T \rho D^4 N^2 \tag{11}$$

where: k_T = thrust coefficient

ρ = density of seawater in slugs per cubic foot

D = propeller diameter in feet

b. Ship Resistance

The resistance a hull form has is normally found during scale model tests in a wave tank. For the RDS-2010 the resistance is estimated as a function of speed. From data provided by Alexander [Ref. 1] it is seen that ship resistance varies as:

$$R_S = 172 V^2 \tag{12}$$

c. Drive Train Moment of Inertia

As presented by Tozzi [Ref. 5], the moment of inertia includes the contributions of all drive train components referred to the propeller shaft. For this simulation, Equation (13) is used to estimate the moment of inertia, based on Ref. 5.

$$I = 2.0 \times 10^5 \quad \textbf{(13)}$$

d. Shaft Torque

The shaft torque (Q_T) as supplied in the report on the RDS-2010 includes the effect of the reduction gears in the drive train, and is a measure of the torque, in foot pounds force, provided to the propeller shaft.

e. Friction Torque

Friction in the entire drive train can be modeled as a loss in torque developed to produce thrust. From Ref 2 it is seen that friction torque can be approximated as:

$$Q_F = 6000\ N \quad \textbf{(14)}$$

f. Propeller Torque

The torque required to rotate a propeller under various conditions is normally measured during open water tests. For the subject ship it can be calculated using data provided in Ref. 1 as:

$$Q_P = K_Q\ \rho\ N^2\ D^5 \quad \textbf{(15)}$$

where: K_Q = Torque coefficient for the hull under consideration.

4. Steering Equations

A low order rudder model can be developed similar to Ref. 6. It is modeled as an integrator with gain K_g' as follows:

$$
\begin{aligned}
(a) \quad & K_g' = \frac{K_g L}{U} \\
(b) \quad & K_g = \frac{\dot{\delta}_m}{\delta_{emax}}
\end{aligned}
\tag{16}
$$

where: δ_m = maximum rudder angle

δ_{emax} = maximum error input.

5. Ship Dynamics

To convert the Y and N equations of Equations (2a and b) to a form usable in the simulation it is necessary to develop matrices as follows:

$$
\begin{aligned}
(a) \quad & [M]\,\dot{x} = [H]\,x + [R]\,u \\
(b) \quad & \dot{x} = [M]^{-1}\,[H]\,x + [M]^{-1}\,[R]\,u
\end{aligned}
\tag{17}
$$

where:

$$
\begin{aligned}
&(a) \quad [M] = \begin{bmatrix} (m' - Y'_{\dot{v}}) & (m'x'_g - Y'_{\dot{r}}) \\ (m'x'_g - N'_{\dot{v}}) & (I'_z - N'_{\dot{r}}) \end{bmatrix} \\
&(b) \quad [H] = \begin{bmatrix} Y'_v & (Y'_r - m') \\ N'_v & (N'_r \quad m'x'_g) \end{bmatrix} \\
&(c) \quad [R] = \begin{bmatrix} Y'_\delta \\ N'_\delta \end{bmatrix} \\
&(d) \quad x = [v \; r]^T \\
&(e) \quad u = \delta
\end{aligned}
\qquad \textbf{(18)}
$$

The new matrices formed are implemented as follows:

$$
\begin{aligned}
&(a) \quad \dot{x} = Ax + Bu \\
&(b) \quad A = [M]^{-1} \, [H] \\
&(c) \quad B = [M]^{-1} \, [R]
\end{aligned}
\qquad \textbf{(19)}
$$

C. DISTURBANCES

To test the system's performance under varying conditions, wind and sea disturbances are added to model the effect of increasing sea state on the system. Also included is the venturi effect, a phenomenon affecting the sway forces and yaw moments of ships as they pass each other in close quarters.

Lastly, measurement noise is added to the observation of the supply ship's position to model the effect of winds and seas acting on the supply ship. This noise models the effect of sea state by increasing position estimate error as sea state increases.

1. Sea Disturbances

In order to simply model what can be made infinitely complex, Uhrin [Ref. 7] employs formulas (20a-f) for a wave. These formulas generate a disturbance at a primary frequency and its second harmonic:

$$
\begin{aligned}
&(a) \quad W = WF\,(1 + WRV)\,\sin(WEF) + \frac{\pi\, WF^2}{WL}\,\sin(2\, WEF) \\
&(b) \quad WEF = \frac{2\,\Pi}{U\, WL}\,(u + WS\,\cos(\Psi_{RS})) \\
&(c) \quad \Psi_{RS} = \Psi_{TS} - \Psi_{SHIP} \\
&(d) \quad X_S = W\,\cos\Psi_{RS} \\
&(e) \quad Y_S = W\,\sin\Psi_{RS} \\
&(f) \quad N_S = W\,\sin(2\,\Psi_{RS})Xs
\end{aligned}
\qquad \textbf{(20)}
$$

where: W = total wave force

WEF = wave encounter frequency

WF = maximum wave force

WL = wave length, normalized by WLT/LOA

WLT = true wave length

LOA = ship length overall

WS = wave speed in feet per second

Ψ_{RS} = relative seas heading

Ψ_{TS} = true seas heading

Ψ_{SHIP} = ship heading

X_s = sea force in x direction

Y_s = sea force in y direction

N_s = sea moment in N direction

WRV = wave random variable

The wave random variable is added to model the randomness of the sea. It is implemented as zero mean gaussian white noise with a variance of 0.01.

2. Wind Disturbances

To account for the wind's effect on the ship, a model is designed similar to that employed by Clark. [Ref. 8] It is necessary to take wind true velocity and speed in the earth fixed reference frame, and translate each component of the forces and moment to the ship fixed reference frame.

First, the relative velocity and direction must be found:

$$\begin{aligned} &(a)\ V_{RW} = \sqrt{(V_W \cos(\psi_w - \psi_{SHIP}) - u)^2 + (V_W \sin(\psi_w - \psi_{SHIP}) - v)^2} \\ &(b)\ \psi_{RW} = aratan\frac{V_W \sin(\psi_w - \psi_{SHIP}) - v}{V_W \cos(\psi_w - \psi_{SHIP}) - u} \end{aligned} \qquad \textbf{(21)}$$

Coefficients for each component of wind effect are developed as follows:

$$\begin{aligned} &(a) \quad C_{WX} = \frac{\rho_a A_f}{7000\rho_w LBP^2} \\ &(b) \quad C_{WY} = \frac{\rho_a A_s}{8000\rho_w LBP^2} \\ &(c) \quad C_{WN} = \frac{\rho_a A_s LOA}{\rho_w LBP^3} \end{aligned} \qquad \textbf{(22)}$$

Lastly, the nondimensional forces and moment are developed in equations (23a-c):

$$(a) \quad X_W' = \left(\frac{V_{RW}}{U}\right)^2 C_{WX} \sin[9/7(|\psi_{RW}| - \pi)]$$
$$(b) \quad Y_W' = \left(\frac{V_{RW}}{U}\right)^2 C_{WY} \sin(\psi_{RW}) \qquad \textbf{(23)}$$
$$(c) \quad N_W' = \left(\frac{V_{RW}}{U}\right)^2 C_{WN} \sin(2\ \psi_{RW})$$

where: X_W' = wind force in x direction

Y_W' = wind force in y direction

N_W' = wind moment about yaw axis

V_{RW} = relative wind velocity

Ψ_{RW} = relative wind direction

V_W = true wind velocity

Ψ_{TW} = true wind direction

Ψ_{SHIP} = ship heading

u = ship surge

v = ship sway

C_{WX} = x direction wind coefficient

C_{WY} = y direction wind coefficient

C_{WN} = N direction wind moment

ρ_a = mass density of air

ρ_w = mass density of water

A_f = ship frontal area

A_s = ship side area (estimated as $10A_f$)

LOA = ship length overall

LBP = ship length between perpendiculars

X_W' = nondimensional x direction wind force component

Y_W' = nondimensional y direction wind force component

N_W' = nondimensional N direction wind force component.

3. Venturi Disturbances

The venturi effect can be closely estimated as a nonlinear function of longitudinal separation that is inversely proportional to lateral separation as seen in Ref. 6. Equations (24a and b) are used to approximate this:

$$\begin{aligned} &(a) \quad Y'_{VENT} = 0.451 \times 10^{-5} \, [sinc\ (0.0029\ LS)]\ Q \\ &(b) \quad N'_{VENT} = -\ Y'_{VENT} \end{aligned} \qquad \textbf{(24)}$$

where:

Y_{VENT}' = nondimensional venturi force

N_{VENT}' = nondimensional venturi moment

LS = longitudinal separation in feet

Q = lateral separation multiplier (varies linearly from 1 to 0.5 as separation increases from 100 to 200 feet).

4. Measurement Noise

The measurement noise, as described above, is simply modeled as gaussian white noise with a variance of 5, 10 or 20, which will vary with sea states 0, 3, and 6, respectively.

III. SIMULATION DEVELOPMENT

A. PROBLEM GEOMETRY

The underway replenishment scenario considered in this research will place the supply ship at an earth fixed origin (Xo,Yo) at problem start. Throughout the problem the supply ship will remain at the relative origin. The receive (subject) ship will start the problem in waiting station, one thousand yards astern of the supply ship. Both ships will begin the problem on base course, at base speed (course 000 at 14 knots). This system will drive to a starboard/ port supply/ receive geometry. The system will seek to drive the receive ship to a position one hundred and thirty feet abreast of the supply ship, at (0,130) relative position.

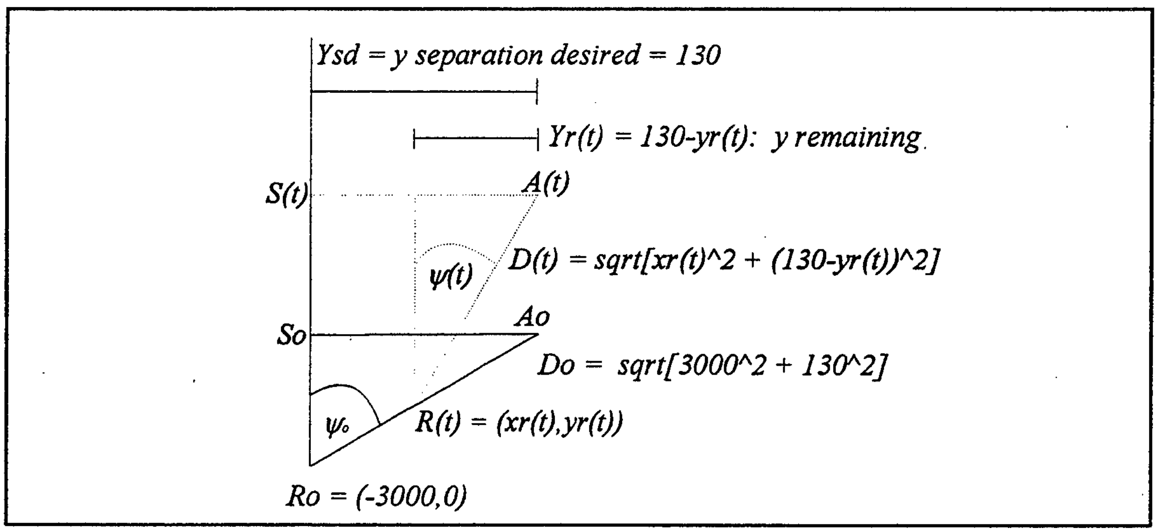

Figure 2. Problem geometry.

The initial positions of the supply and receive ships is displayed in Figure 2 as S_o and R_o respectively. The initial aim point is denoted as A_o. From the figure it is evident that the aim point moves with the supply ship at base course and speed. As the problem progresses, the ship is at a relative position (xr(t),yr(t)), steers an angle $\psi(t)$, and has a distance to travel D(t). Thus, the initial angle ψ_o and distance D_o are not constantly fixed with respect to the absolute origin, and must be computed and fed into the system as command signals for all time (t).

B. SHIP'S PLANTS

1. Rudder

As previously mentioned, a low order model for a rudder plant was designed in Ref. 6, and is shown as Figure 3. Heading error is input to the system at the in block. The rudder stops limit the amount of travel and is modeled as a saturation block. The rate limit block simulates a hydraulic pump that limits the amount of error into the rudder, which is modeled as an integrator with gain Kg'. The rudder angle (δ) is the output of the subsystem at the out block. The SIMULINK implementation requires renaming the variable K_g' in the rudder subsystem as Kgpri.

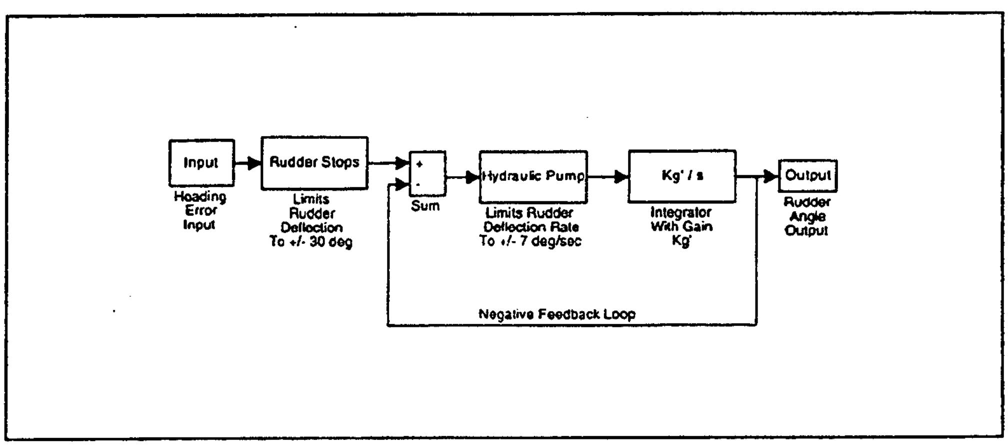

Figure 3. Rudder subsystem.

2. Ship's Engine

The Engine model is designed to output the thrust necessary to drive the ship. Input is the desired torque. Next, the subsystem develops the shaft acceleration as defined earlier. An integrator is used to generate the propeller rotations per second, which is then converted to a thrust value. The initial condition set on the integrator starts the problem with the ship already at base speed. The thrust output is then calculated as a function of shaft rotations as noted previously. From Equations (10a and b) the conversion into a SIMULINK environment is relatively straightforward as seen in Figure 4.

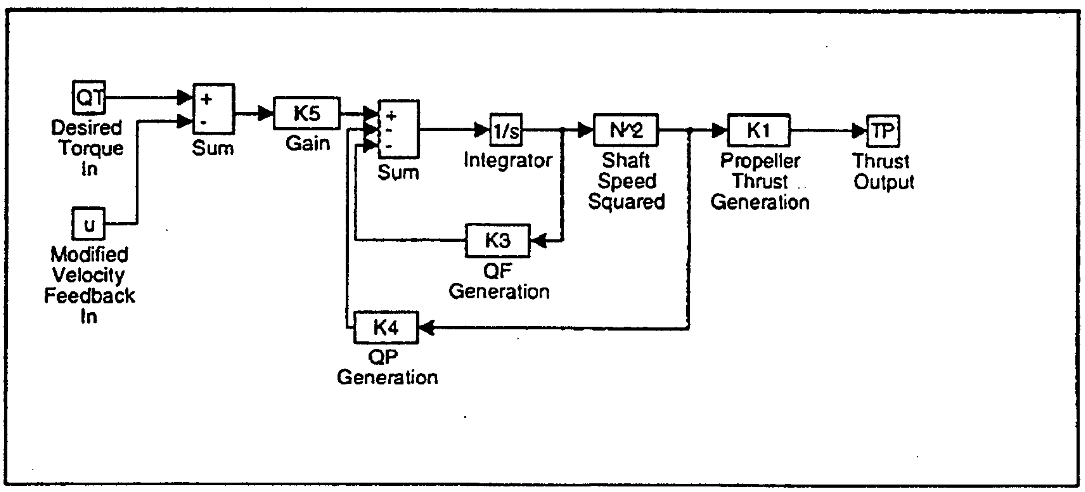

Figure 4. Engine Subsystem.

C. SHIP'S DYNAMICS

1. Steering Dynamics

To model the ship dynamics in SIMULINK, the matrices in Equations (19a-c) are used in the subsystem. These matrices lend themselves very well to a SIMULINK implementation. The subsystem also adds the Y and N disturbances to the accelerations. Figure 5 displays the ship dynamics subsystem.

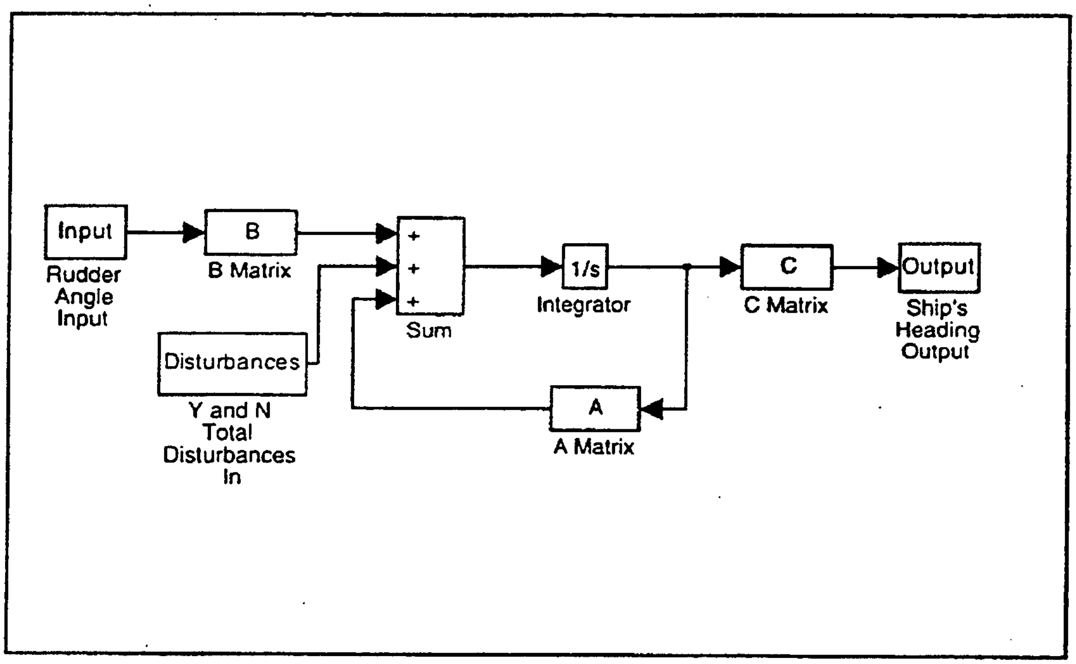

Figure 5. Steering dynamics subsystem.

2. Propulsion Dynamics

Equation (10A) is used to produce the ship's longitudinal velocity from the developed propeller thrust. Again, the conversion is uncomplicated as seen in Figure 6.

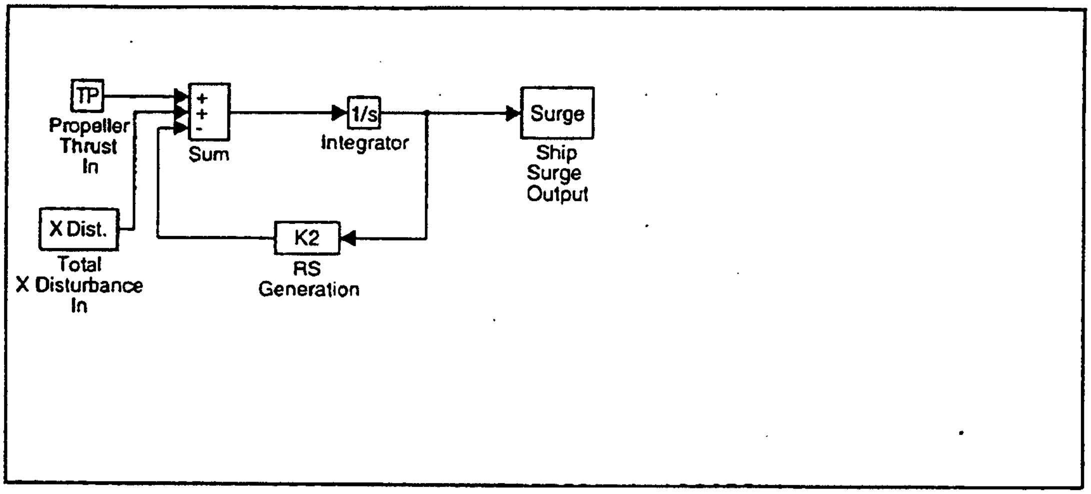

Figure 6. Propulsion dynamics subsystem.

D. EARTH ORIENTED POSITION GENERATION

Equations (1a and b) are very simply translated into a SIMULINK subsystem to solve for velocities in the Xo and Yo directions. These velocities are integrated to obtain the positions with respect to the earth fixed origin. Figure 7 shows the earth position generation subsystem as implemented.

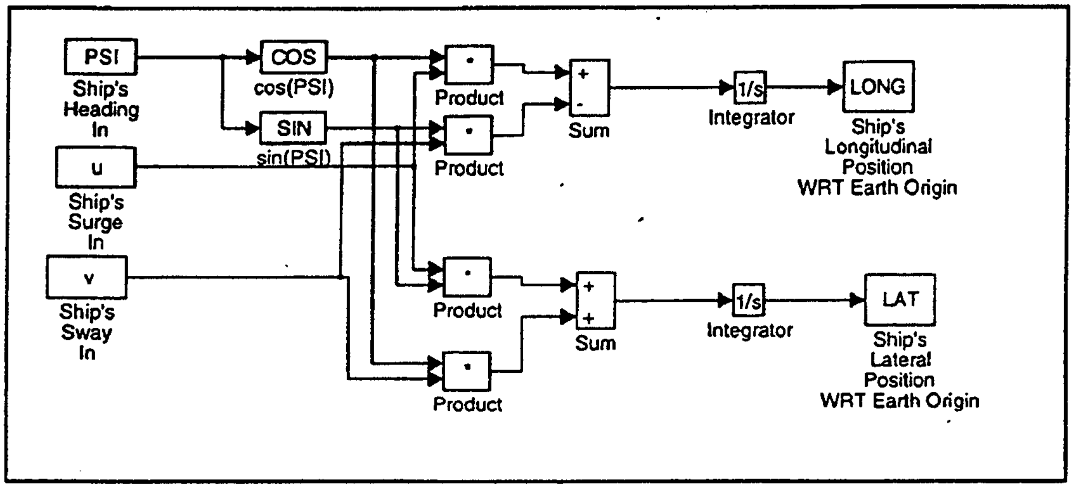

Figure 7. Earth oriented position generation subsystem.

E. RELATIVE POSITION GENERATION

In order to generate the ship's position relative to the supply ship, the position of the supply ship with respect to the earth fixed origin must be compared with the receive ship's position with respect to the same origin at each time interval. This is accomplished by using base speed as the ideal supply ship motion along the Xo axis. The supply ship's motion along the Yo axis is ideally zero. To both position estimates of the supply ship, the measurement noise is added. This effectively models a ship's sensor (radar), and accounts for the supply ship's motion in an increasing sea state. The relative position generator subsystem is shown in Figure 8 as implemented.

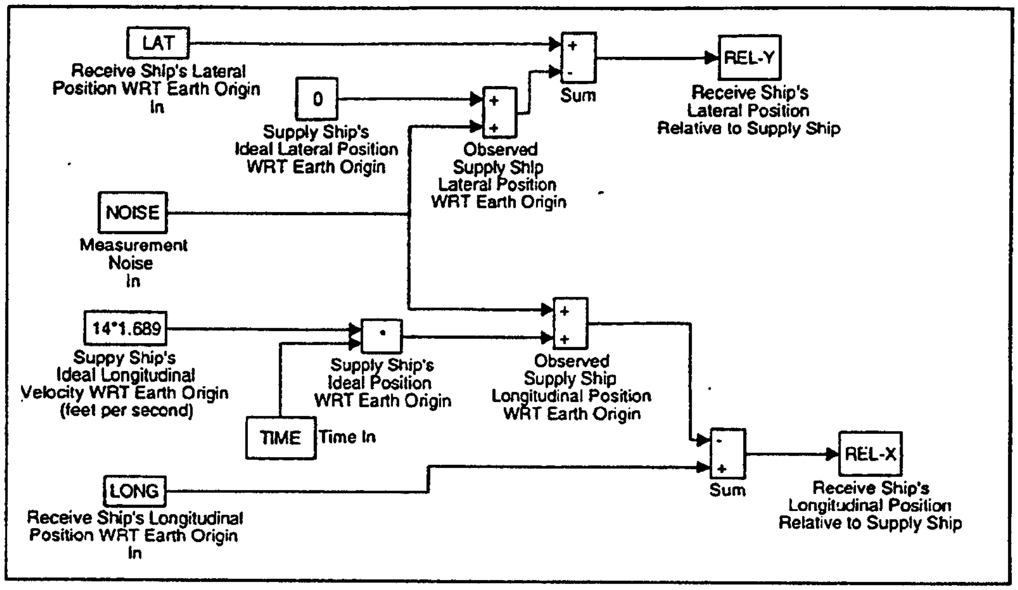

Figure 8. Relative position generation subsystem.

F. DISTURBANCE GENERATION

As discussed in the previous chapter the disturbances are to test the system's performance under less than ideal conditions. The forces and moments generated are summed from each component.

1. Wind Disturbance

From the previous chapter the Figure 9 shows the subsystem developed to generate wind disturbances.

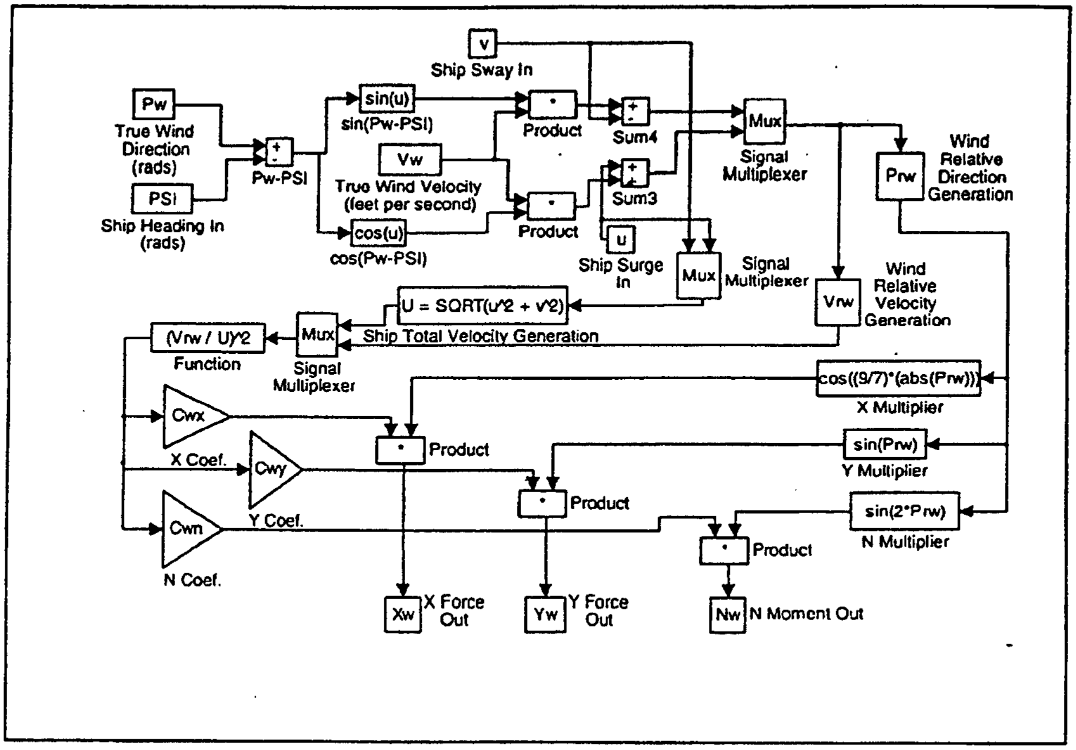

Figure 9. Wind disturbance subsystem.

2. Sea Disturbance

The mathematical model for seas as developed previously translates very well into a SIMULINK subsystem, and is shown in Figure 10.

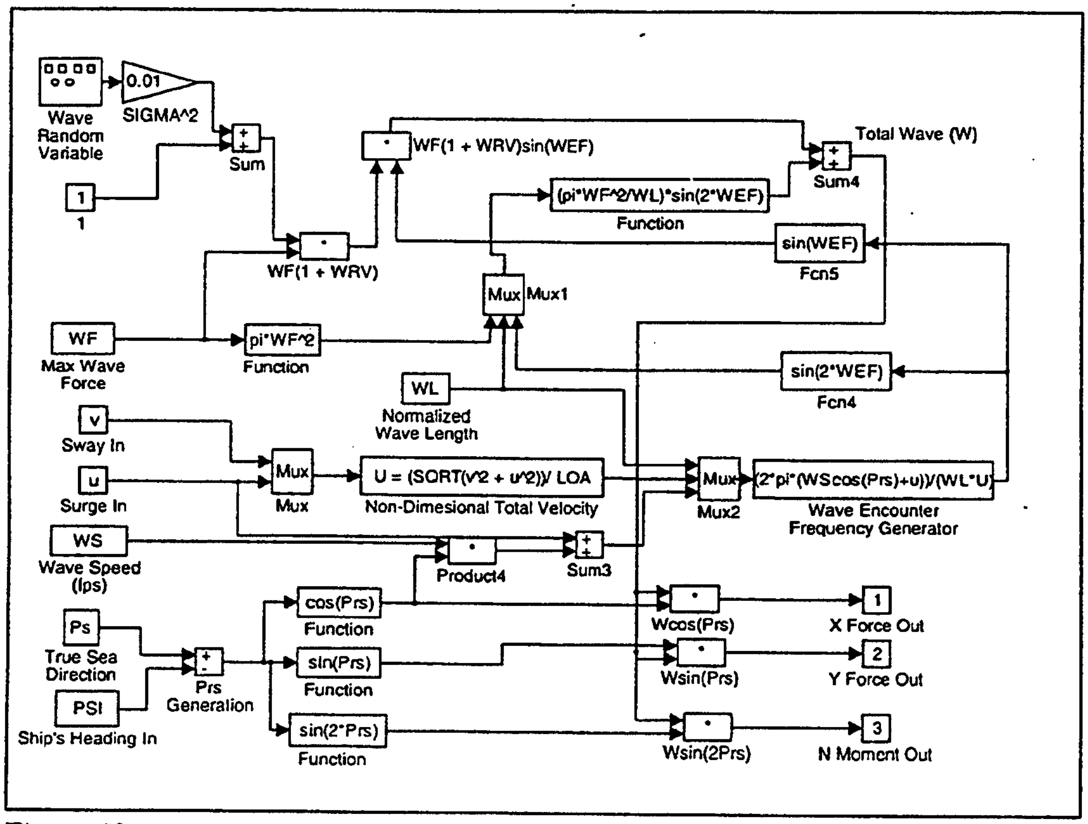

Figure 10. Sea disturbance subsystem.

3. Venturi Disturbance

The venturi phenomenon is modeled in SIMULINK with the subsystem shown as Figure 11. The subsystem follows directly from Equations (27a and b).

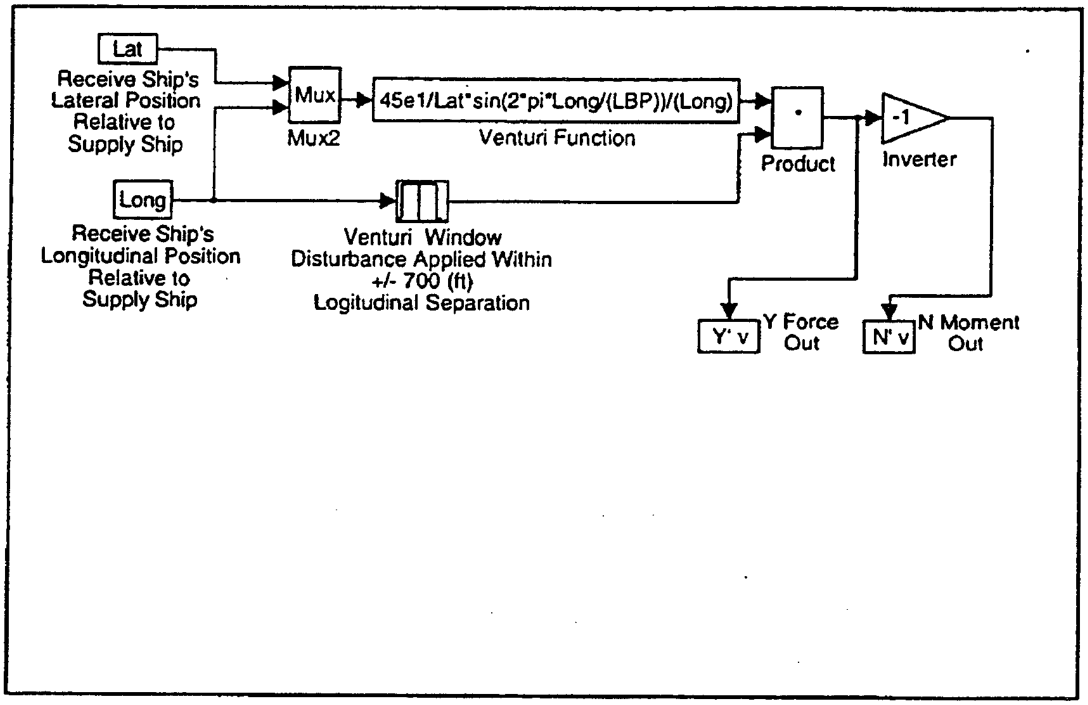

Figure 11. Venturi disturbance subsystem.

IV. CONTROLLER DESIGNS

Two types of controllers are employed within the system designed. The first is a command guidance signal styled to drive the ship similar to a conning officer during an underway replenishment. This is accomplished by the conversion of the receive ship's position relative to the supply ship into command signals to the rudder and engine. The second is a root locus design for the engine plant to drive the ship more efficiently.

A. COMMAND SIGNAL GENERATION

This first controller design is implemented as a separate subsystem, converting the receive ship's relative X and Y positions into rudder and engine command signals as mentioned above. In order to achieve the desired goal of imitating a conning officer, the first goal is to have the ship open the lateral separation in order to safely close the longitudinal distance without danger of collision. While the rudder steers the ship towards the aim point, the engine must be sped up to close the longitudinal separation. A typical conning officer will bring the ship up to a speed of 20 knots to expeditiously gain station. Once the ship is within approximately 200 feet of station, the ship is slowed to 1 knot above base speed to avoid going past the station.

Once the ship is in station, the goal is to stay there. This requires small, continual adjustments in both the rudder and the engine in response to the effects of the wind, sea, and the presence of the supply ship.

To gain and then maintain station defines two separate problems as defined above. The first is an approach problem requiring large corrections. The second is a station-keeping problem requiring finer adjustments to maintain the desired position and avoid dangerous maneuvers while in close quarters to the supply ship.

During the approach phase, the desired heading is conveyed to the rudder subsystem as $\Psi(t)$, as defined previously. The distance D(t) is used to generate a velocity command signal ordering the engine to 20 knots until within 200 feet of station. The velocity command signal is also converted to a torque command signal based on the predicted torques at various speeds for the subject ship.

The lateral separation, being opened to the proper distance, is employed as the division between approach and station-keeping phases. Once the lateral distance is within 5 feet of the desired setting, the command generation subsystem toggles to the station-keeping phase. During this phase the rudder is restricted to a maximum amplitude of one-fifth of Ψ_0. The rudder will steer the ship with minute adjustments when within 20 feet of the desired lateral separation. The station keeping phase also restricts the engine response by basing the D(t) on only the longitudinal separation. Further, the velocity command is regulated to within 1 knot of base speed when within 40 feet of station. The engine will respond to gradually speed up or slow down in response to the relative longitudinal position. The rather complicated verbal description above is actually very simple to implement in SIMULINK. The relative positions are used as input and converted to $\Psi(t)$ and D(t) signals as described in the problem geometry. These are used with look-up tables to accomplish the intent of the subsystem. The subsystem is pictured in Figure 12 as implemented.

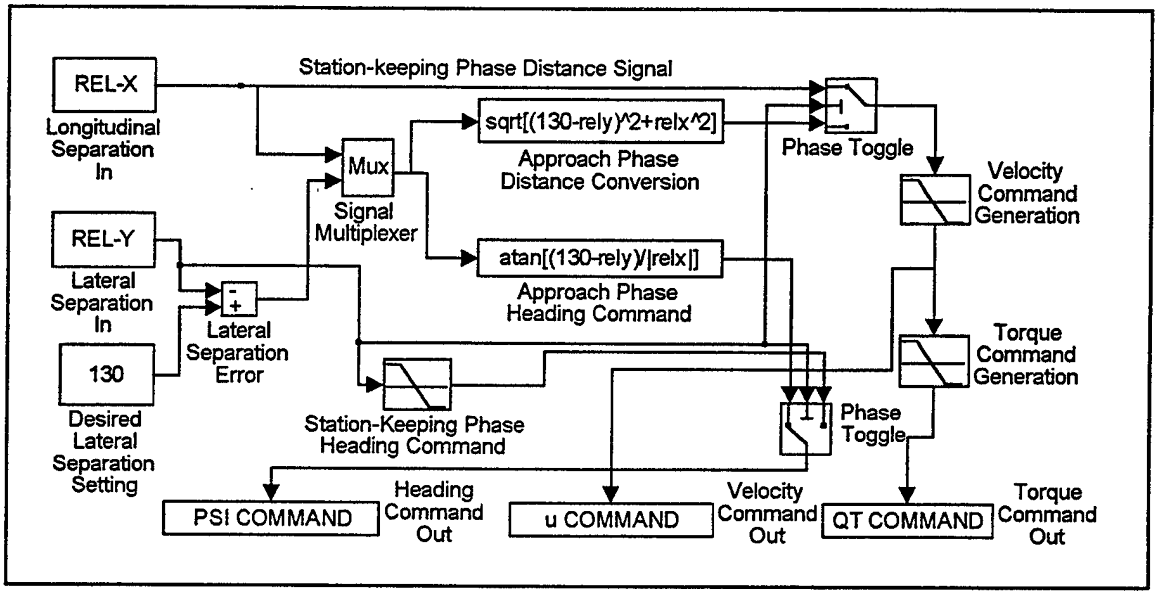

Figure 12. Command signal generation subsystem.

B. ROOT LOCUS CONTROLLER

The engine requires a separate controller developed to improve the response of the plant. Figure 13 displays the actual plant implemented.

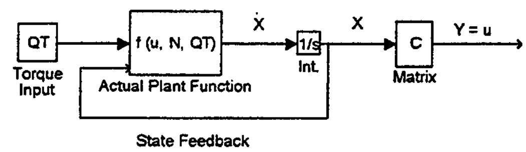

Figure 13. Actual engine plant.

where:

$$\begin{aligned} &(a) \quad X \equiv \begin{bmatrix} u \\ N \end{bmatrix} \\ &(b) \quad Y \equiv C \\ &(c) \quad X = u \\ &(d) \quad C = [1 \;\; 0] \end{aligned} \qquad \textbf{(25)}$$

The actual plant above may be approximated by the following equation:

$$f(u, N, Q_T) \cong f(u_0, N_0, Q_{T_0}) + \nabla_{u,N} f(u_0, N_0, Q_{T_0})\, \delta X + \nabla_{Q_T} f(u_0, N_0, Q_{T_0})\, \delta Q_T \qquad \textbf{(26)}$$

where:

$$(a) \quad \delta X \equiv \begin{bmatrix} u - u_0 \\ N - N_0 \end{bmatrix}$$
$$(b) \quad \delta Q_T \equiv Q_T - Q_{T_0} \qquad \textbf{(27)}$$

The first term in the above non-linear Equation (27b) is assumed to go to zero, leaving a linear equation. The second term defines the plant's A matrix. The third term defines the plant's B matrix. For the controller design, a new δQ_T is defined as below.

$$\delta Q_T = K\ (u - u_0) = K\ \delta u \qquad \textbf{(28)}$$

Then for the approximate system:

$$\delta \dot{x} = A\ \delta x + B\ K\ \delta u = A\ \delta x + B\ K\ C\ \delta x \qquad \textbf{(29)}$$

hence:

$$(a) \quad \delta \dot{x} = [A - K\ B\ C]\ \delta x$$
$$(b) \quad \delta y = C\ \delta x \qquad \textbf{(30)}$$

because K is a scalar.

The poles of this system are at:

$$DET(sI - A + KBC) \qquad \textbf{(31)}$$

and, the system transfer function is:

$$C\ [sI - A = + KBC]^{-1}\ B \qquad \textbf{(32)}$$

A suitable value for K was found, experimentally to be 100000. This was employed in the system as displayed in Figure 14.

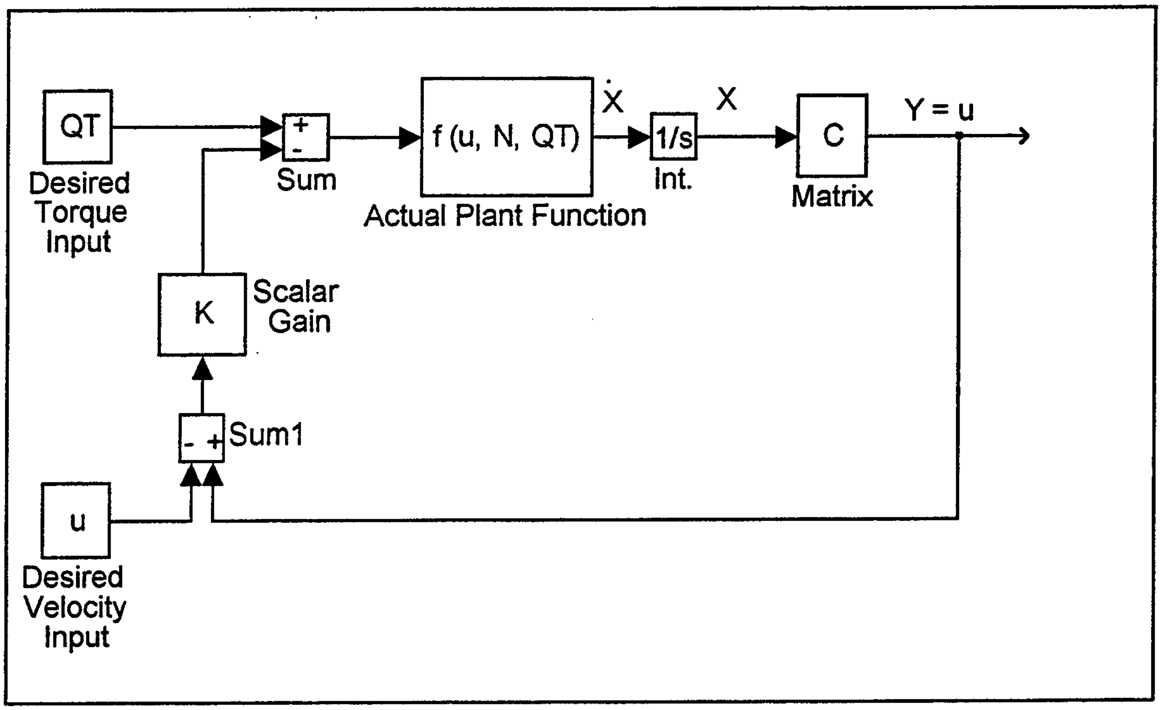

Figure 14. Engine plant as implemented.

V. SIMULATION RESULTS

The system was run several times to demonstrate its performance under varying conditions. First the system was run without disturbances as shown in Figures 15-17.. Next, the system was run with only the measurement noise applied as a disturbance seen in Figures 18-20. For this run the measurement noise was increased to 20 to better display its effects on the system. Lastly, the system was run with wind, sea, and venturi disturbances applied in addition to the measurement noise shown in Figures 20-23. For the last run the wind and seas were set at 5 knots, the normalized wavelength set at 0.1, and the true direction set at 000 degrees true (on the bow). For each run three plots are shown. The first plot presents the relative trajectory of the receive ship (a bird's eye view of the track taken by the receive ship). The next two plots display the lateral and longitudinal trajectories plotted against time to compare settling times of the different cases.

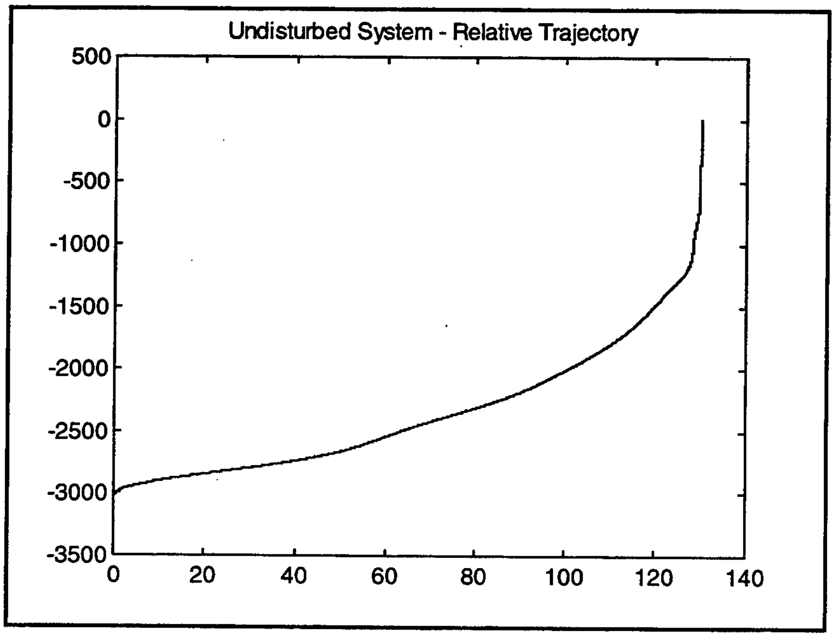

Figure 15. Undisturbed system relative trajectory

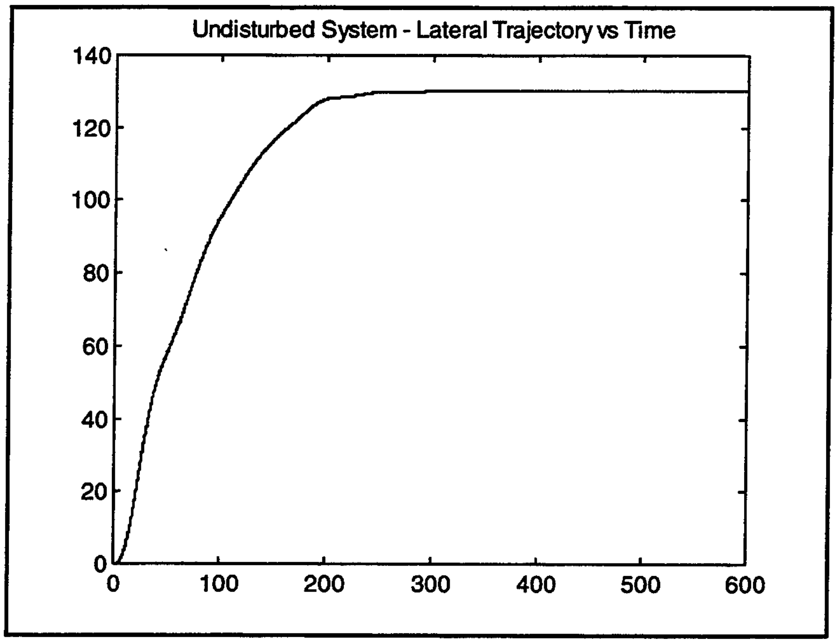

Figure 16. Undisturbed system lateral trajectory.

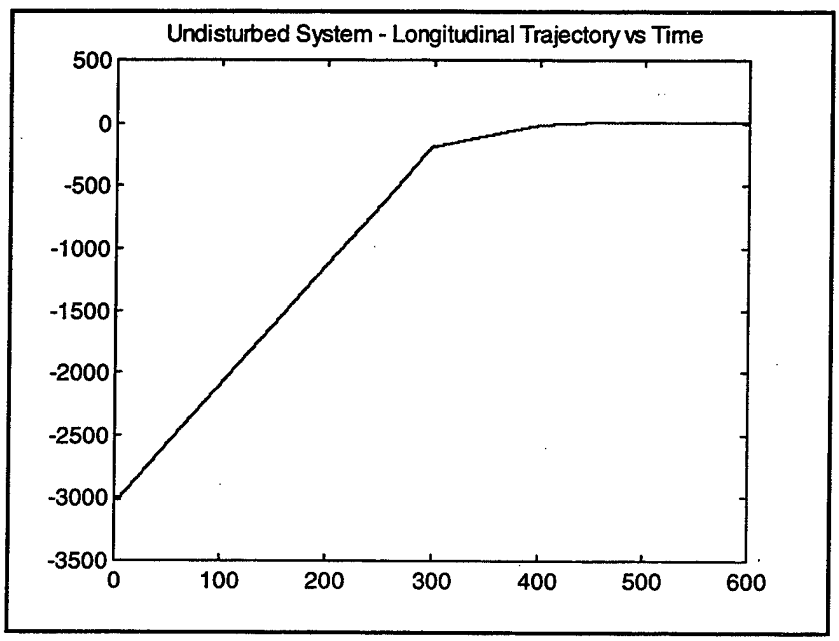

Figure 17. Undisturbed system longitudinal trajectory.

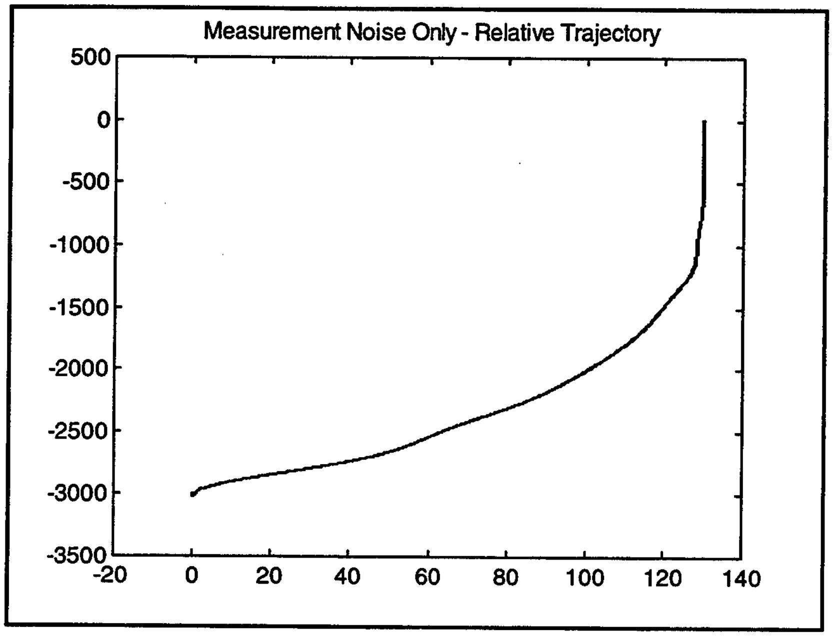

Figure 18. Measurement disturbance relative trajectory.

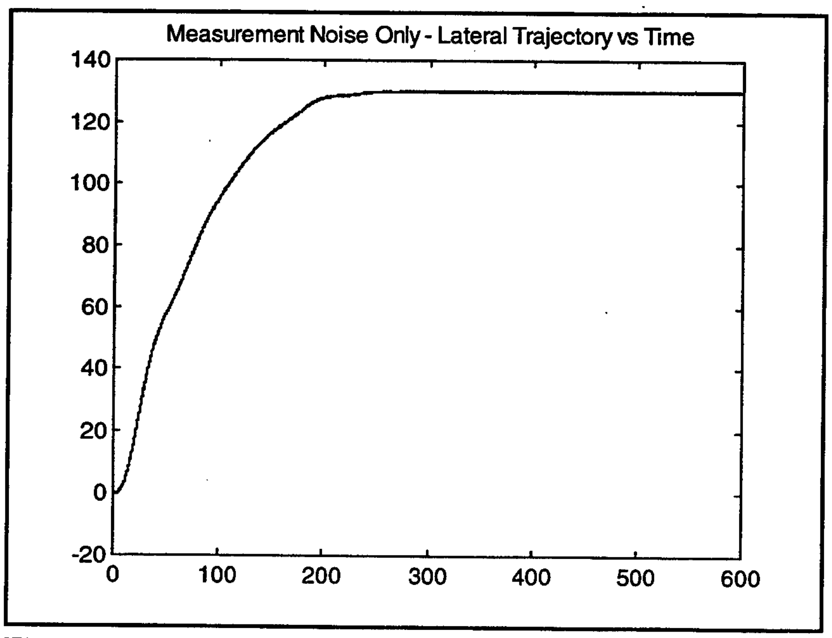

Figure 19. Measurement disturbance lateral trajectory.

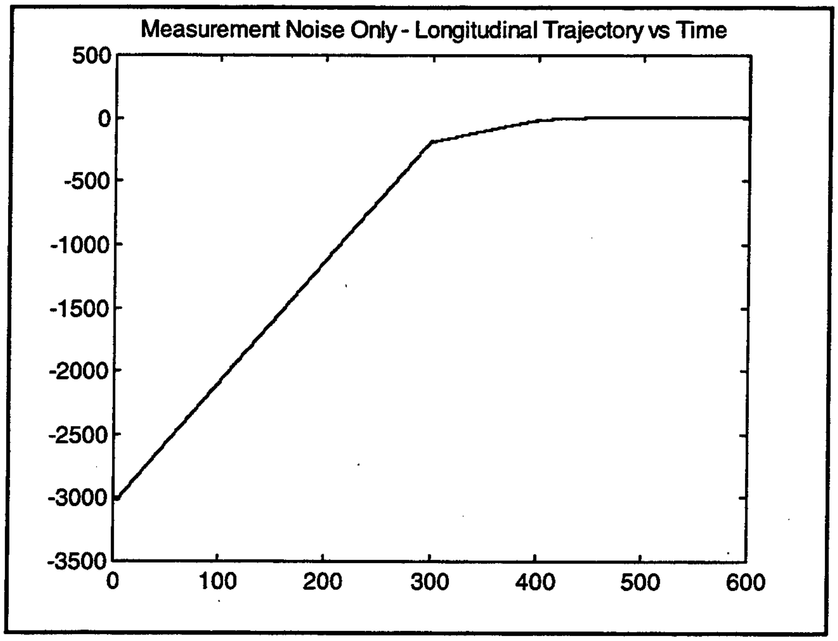

Figure 20. Measurement disturbance longitudinal trajectory.

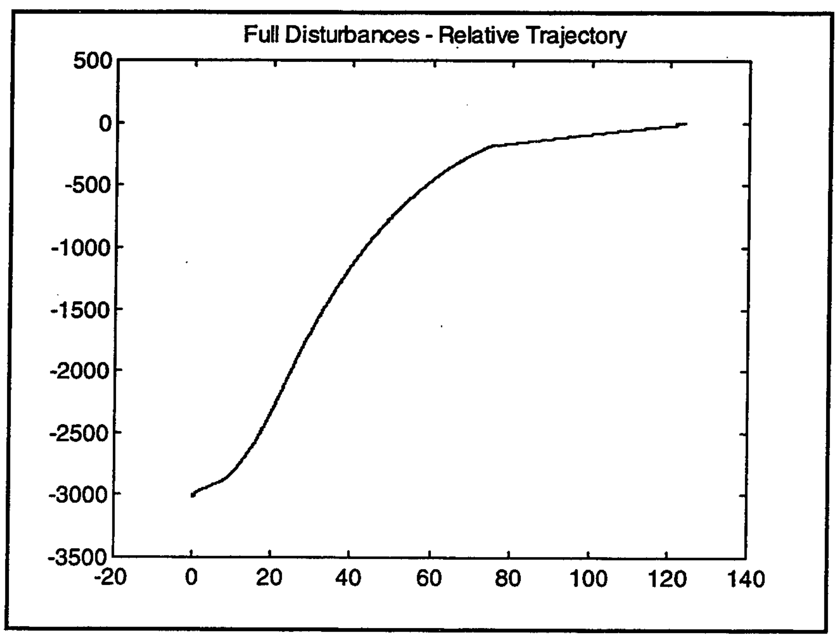

Figure 21. Full disturbances relative trajectory.

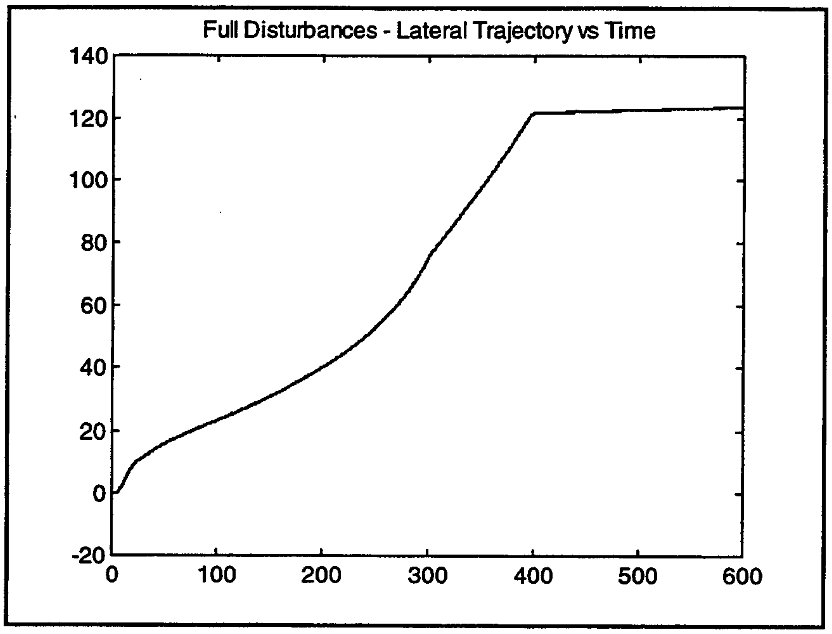

Figure 22. Full disturbances lateral trajectory.

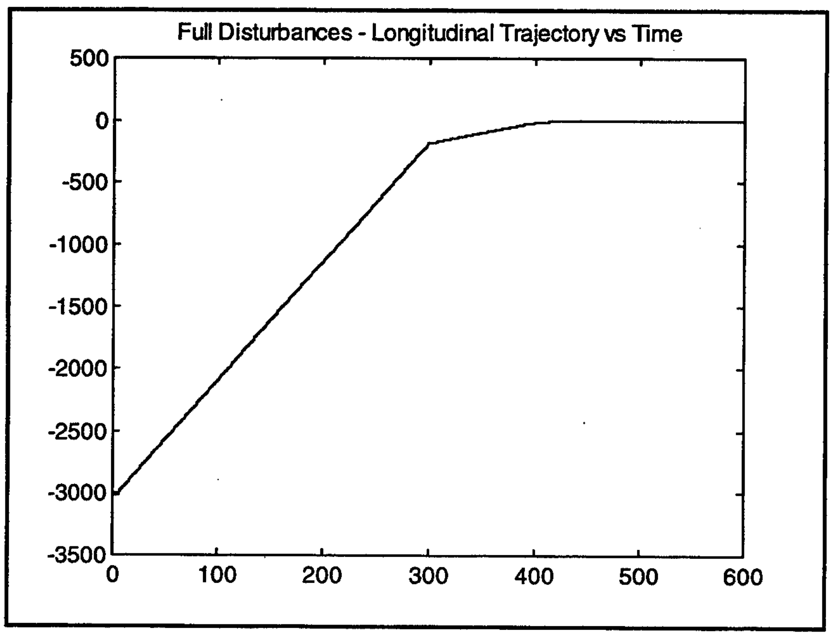

Figure 23. Full disturbances longitudinal trajectory.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

From the simulation results in the previous chapter it is evident that the system performs as desired when undisturbed. The lateral separation is opened safely while closing the longitudinal distance. And, once the station is attained, the system keeps the ship at the desired point. Additionally, it is shown that the measurement noise has little effect on the system. In each of these first two cases the system has a time to station of 420 seconds.

However, it is also evident that the system does not comfortably open the lateral separation while being exposed to the wind, sea, and venturi disturbances. But, the system still has a satisfactory time to station of 430 seconds, which is very comparable to the undisturbed case. And, once on station the system still keeps the ship in place.

B. RECOMMENDATIONS FOR FURTHER STUDY

Based on the above conclusions, the first recommendation is to design a controller to better handle the rudder during exposure to disturbances. Further, many different control schemes for both the engine and the rudder may be designed and compared using classical as well as optimal control approaches.

As the TSSE program has designed two additional ships since the RDS-2010, it may be desired to apply this study to the other ships. This may require the development of different propulsion plants which could be stored and modified for future use by the TSSE program. Additionally, the TSSE program could employ this system to test more fundamental performance measures of their proposed ships, such as tactical diameter. It should also be noted that this system would be applicable to a commercial vessel design.

Finally, the disturbance model would prove useful to any design team wishing to test the sturdiness of a proposed hull design. The forces and moments the hull would be exposed to can be measured, and compared to the maximum levels the structure should be exposed to.

APPENDIX A HYDROGEN.M

```
% HYDROGEN.M: FILE TO GENERATE HYDRODYNAMIC DERIVATIVES, WIND
% COEFFICIENTS, WIND AND SEAS TRUE DIRECTION, AND ENGINE
% SIMULATION CONSTANTS FOR SIMULINK FILE "SHIPSIM".
% VALUES REQUIRING USER INPUT FOR SYSTEM CUSTOMIZATION ARE
% NOTED AS (input) IN THE COMMENT LINE.
% THIS FILE MUST BE RUN PRIOR TO "SHIPSIM" TO GENERATE THE
% NECESSARY INPUTS


rho=1.9914*0.0311;% Density of H2O in Slugs/Cub. Ft.
        % at 55 deg F * (Slugs/Lb Mass)
U = 14*1.689    ;% Nominal Ship's FWD Speed
        % (14 knots) in Feet per Sec.


% HULL COEFFICIENT OF DRAG AT ZERO ANGLE OF ATTACK CALCULATION


rhos=1.9914    ;% Density of H2O
vs=1.3535      ;% Kinematic Viscosity of H2O
q=.5*rhos*vs^2 ;% Dynamic Pressure of H2O
Do=123559      ;% Drag Force at 16 Knots
```

```
WSA=24204.1    ;% Wetted Surface Area at Displacement

Cdo=Do/(q*WSA)  ;% Hull Coefficient of Drag


% NECESSARY INPUTS FOR HYDRODYNAMIC DERIVATIVE GENERATOR


D    = 5721.8          ;% (input) Ship Disp. in Long Tons (5721.8)

T    = 15.01           ;% (input) Ship's Draft in Feet (15.01)

L    = 409.315          ;% (input) Ship's Length (LOA) (409.315)

B    = 55.09           ;% (input) Ship's Beam in Feet (55.09)

Cb   = 0.599           ;% (input) Ship's Block Coefficient (0.599)

mship = (2240*D)/32.2     ;% Ship's Mass Calculator

delmaxdot = 2           ;% (input) maximum rudder rate

delemax  = 7            ;% (input) maximum error input

Kg   = delmaxdot/delemax  ;% Rudder Gain Calculator

Xg   = -5.85           ;% (input) Estimate of Xg (LCB for Disp.)

xp   =-22.5            ;% (input) Long. Center of Float. (LCF)

                         % at Disp.

Priz= 0.650             ;% (input)Prismatic Coefficient


% APPENDAGE DATA: CALCULATED FOR RUDDERS AND THE SONAR DOME,

% MAY BE CUSTOMIZED FOR OTHER APPENDAGES BY ADDING THE
```

```
NECESSARY

% CALCULATIONS SIMILAR TO THOSE BELOW.


ProfArud1 = 117.4        ;% (input) Rudder Profile Area (117.4)

PAnond1 = ProfArud1/(L*T)  ;% Non Dimensionalized Profile Area

hrud1  = 11.95           ;% (input) Rudder Height

arud1  = hrud1^2/ProfArud1 ;% (input) Rud Eff Aspect Ratio

hrudnd1= hrud1/L         ;% Non Dimensionalized Height

Cdrud1 = 0.008           ;% (input) Rudder's Coef of Drag (0.008)

mrud1  = (2*pi)/(1+2/arud1);% (input) Rudder's Lift Curve Slope Calc

ProfArud2 = 117.4        ;% (input) Rudder Profile Area (117.4)

PAnond2 = ProfArud2/(L*T)  ;% Non Dimensionalized Profile Area

hrud2  = 11.95           ;% (input) Rudder Height

arud2  = hrud2^2/ProfArud2 ;% (input) Rud Eff Aspect Ratio

hrudnd2= hrud2/L         ;% Non Dimensionalized Height

Cdrud2 = 0.008           ;% (input) Rudder's Coefficient of Drag (0.008)

mrud2  = (2*pi)/(1+2/arud2);% (input) Rudder's Lift Curve Slope Calc

ProfAdom = 1400          ;% (input) Sonar Dome Profile Area (1400)

PAnond = ProfAdom/(L*T)    ;% Non Dimensionalized Profile Area

adom   = 0.35            ;% (input) Sonar Dome Aspect Ratio

hdom   = 22.26           ;% (input) Sonar Dome Height
```

```
hdomnd= hdom/L          ;% Non Dimensionalized Height


% CALL TO INERTIAL COEFFICIENT GENERATOR

csgen


% DERIVATIVE GENERATOR FOLLOWS EQN'S FROM REF. 1 CHAP-8 pp525

% EQN'S 67 FOR HULL WITH SMALL DEADWOOD


% NON-DIMENSIONAL HULL HYDRODYNAMIC DERIVATIVE GENERATOR

mpri   = mship/(0.5*L^3*rho);

Yvh    = -pi*(T/L)*Cdo;

Yrh    = -(k1*mpri) + ((xp/L)*Yvh);

Nvh    = -(m2 -(k1*mpri)) + ((xp/L)*Yvh);

Nrh    = -(mz*(xbar/L)) + ((.5*Priz)^2*Yvh);

Yvdoth = -m2;

Yrdoth = 0;

Nvdoth = 0;

Nrdoth = -((kprime*pi)/(L^3*T^2))*int3;

Izh    = mship/(0.5*L^5*rho);

Kgpri  = Kg*(L/U);

Xgpri  = Xg/L;
```

```
% NON DIMENSIONAL RUDDER (CONTROL) HYDRODYNAMIC DERIVATIVE GENERATOR

Ydel  =(4/3)*PAnond1*((2*pi)/(1+(2/arud1))); % 4/3 ACCOUNTS FOR TWO RUDDERS
Ndel  = -.5*(Ydel);


% NON DIMENSIONAL APPENDAGE HYDRODYNAMIC DERIVATIVE GENERATOR

Yvfr1  = -PAnond1*((2*pi)/(1+(2/arud1)));
Yvfr2  = -PAnond2*((2*pi)/(1+(2/arud2)));
Yvfd   = -PAnond*((2*pi)/(1+(2/adom)));
Yvap   = Yvfr1+Yvfr2+Yvfd;
Yrfr1  = -.5*Yvfr1;
Yrfr2  = -.5*Yvfr2;
Yrfd   = -.5*Yvfd;
Yrap   = Yrfr1+Yrfr2+Yrfd;
Nvfr1  = Yrfr1;
Nvfr2  = Yrfr2;
Nvfd   = Yrfd;
Nvap   = Nvfr1+Nvfr2+Nvfd;
Nrfr1  = .25*Yvfr1;
Nrfr2  = .25*Yvfr2;
```

```
Nrfd  = .25*Yvfd;

Nrap  = Nrfr1+Nrfr2+Nrfd;

Yvdotfr1 = -4*pi*PAnond1*hrudnd1/sqrt(arud1+1);

Yvdotfr2 = -4*pi*PAnond2*hrudnd2/sqrt(arud2+1);

Yvdotfdm = -4*pi*PAnond*hdomnd/sqrt(adom+1);

Yvdotap  = Yvdotfr1+Yvdotfr2+Yvdotfdm;

Yrdotfr1 = 2*pi*PAnond1*hrudnd1/sqrt(arud1+1);

Yrdotfr2 = 2*pi*PAnond2*hrudnd2/sqrt(arud2+1);

Yrdotfdm = 2*pi*PAnond*hdomnd/sqrt(adom+1);

Yrdotap  = Yrdotfr1+Yrdotfr2+Yrdotfdm;

Nvdotfr1 = Yrdotfr1;

Nvdotfr2 = Yrdotfr2;

Nvdotfdm = Yrdotfdm;

Nvdotap  = Nvdotfr1+Nvdotfr2+Nvdotfdm;

Nrdotfr1 = .25*Yvdotfr1;

Nrdotfr2 = .25*Yvdotfr2;

Nrdotfdm = .25*Yvdotfdm;

Nrdotap  = Nrdotfr1+Nrdotfr2+Nrdotfdm;


% TOTAL HYDRODYNAMIC GENERATOR

Yvtot = Yvh + Yvap;
```

```
Yrtot = Yrh + Yrap;

Nvtot = Nvh + Nvap;

Nrtot = Nrh + Nrap;

Yvdot = Yvdoth + Yvdotap;

Yrdot = Yrdoth + Yrdotap;

Nvdot = Nvdoth + Nvdotap;

Nrdot = Nrdoth +Nrdotap;


% MATRIX GENERATION

a11 = mpri-Yvdot;

a12 = (mpri*Xgpri)-Yrdot;

a21 = (mpri*Xgpri)-Nvdot;

a22 = Izh-Nrdot;


b11 = Yvtot;

b12 = Yrtot-mpri;

b21 = Nvtot;

b22 = Nrtot-(mpri*Xgpri);


c11 = Ydel;

c21 = Ndel;
```

```
A = [a11 a12;a21 a22];

B = [b11 b12;b21 b22];

C = [c11 ;c21];


Apri = inv(A)*B;

Bpri=(inv(A)*C);

Cpri =  [1 0;0 -1];

Dpri=[0;0];


% WIND COEFFICIENT GENERATOR FOR POOR THESIS

% CONSTANTS


rhow = 64     ;% Density of H2O in lbs/ft^3

rhoa = 0.0752 ;% Density of Air in lbs/ft^3

LBP  = 390.00 ;% (input) Ship Length Between Perpendiculars

LOA  = 409.31 ;% (input) Ship Length Overall

Af   = 2037.9 ;% (input) Ship Frontal Area

As   = 10*Af  ;% (input) Ship Side Area (Estimate)

q=rhoa/rhow;


% COEFFICIENT GENERATION
```

```
Cwx = q*Af/LBP^2*7000    ;% Wind Surge Force Coefficient

Cwy = q*As/LBP^2*8000    ;% Wind Sway  Force Coefficient

Cwn = q*As*LOA/LBP^3*1000 ;% Wind Yaw  Moment Coefficient


% ENGINE CONSTANTS AND TORQUE GENERATION

I=1.9e5              ;% Prop shaft moment of inertia

gm=(32.2^2/(5721*2240))  ;% Equivalent form of g/m


Qt=219597            ;% Input torque at 16 knots

K1=2*gm*0.185*1.9914*15.5^4 ;% Tp, Prop Thrust Calc.

K2=gm*171.7658          ;% Rs, Ship Resistance Calc.


K3=(6000/(2*pi*I))              ;% Qf, Fric. Torque Loss Calc.

K4=(0.0417*1.9914*15.5^5/0.985)*(1/(2*pi*I)) ;% Qp, Prop. Torque Loss Calc.

K5=1/(2*pi*I)                 ;% Qt Multiplier


Aeng=[-2*K2*27.024 2*K1*1.72;0 (-2*K4*1.72)-K3];

Beng=[0 K5]';

Ceng=[1 0];

Deng=[0];

[numeng,deneng]=ss2tf(Aeng,Beng,Ceng,Deng);
```

```
%%% torquefit

Torq = [219597 586322 689169];% Shaft Torques at Vel, Speeds From

Vel = [16 25.26 26.49]      ;% RDS-2010 Final Report

Speeds = linspace(16,22,60)  ;%

Torques = interp1(Vel,Torq,Speeds,'linear');%

%plot(Speeds,Torques)

vin = [16 17 18 19 20 21];

tout = interp1(Vel,Torq,vin,'linear');
```

APPENDIX B CSGEN.M

```
% FILE TO GENERATE k1,k2,kprime, AND Cs FOR RDS 2010

k1=0.3*(2*T/L);          % Empirical Formulae

k2=1-(.5*(2*T/L));       % From Vann Thesis

kprime= 1-(1.33*(2*T/L)); %


% SECTION AREA AT EACH STATION

secar=[0 0 0 25.69 52.5 158.7 271.48 382.65 485.27 574.11...

    646.09 700.07 736.36 755.95 759.89 748.75 722.26...

    668.83 585.81 470.15 324.39 164.23 30.00];


% LOCAL DRAFT AT EACH STATION

d=  [0 0 0 9.611 15.006 15.006 15.006 15.006 15.006 15.006...

    15.006 15.006 15.006 15.006 15.006 15.006 15.006 14.743...

    13.861 12.187 9.516 5.716 1.308];


% LOCAL BEAM AT EACH STATION (PAD W/ 1'S TO AVOID DIVIDE BY 0 ERROR)

b=  [0 0  0 2.452 4.82 14.418 24.208 33.062 40.386 45.984 49.934...

    52.488 53.978 54.734 55.032 55.050 54.844 54.196 52.798 50.206...

    45.996 39.996 32.574];
```

```
% DISTANCE x FROM CL AT EACH STATION

x=   [204.655 194.997 185.34 179.93 174.521 154.704 134.887 115.069...

      95.252 75.435 55.618 35.801 15.984 -3.834 -23.651 -43.468...

      -63.285 -86.848 -110.410 -130.973 -157.535 -181.098 -204.66];


for i=1:length(d)

   if d(i) == 0

      mult(i) = 0;

   else

      mult(i) = secar(i)/(b(i)*d(i));

   end

   if b(i) == 0

      mult2(i) =0;

   else

      mult2(i) = (4*d(i)/b(i));

   end

   co(i) = -0.8572 + 0.5339*mult2(i);    % FROM FORMULAE IN REF. 3

   c1(i) =  3.734  - 1.3661*mult2(i);

   c2(i) = -1.7323 + 0.8679*mult2(i);

   Cs(i) = co(i)+(c1(i)*mult(i))+(c2(i)*mult(i)^2);

   if Cs(i) > 0.918
```

```
    Cs(i) = 0.918                ;% CAPS MAX Cs VALUE AT MAX AREA STA.
  end
  Csdsq(i) = Cs(i)* d(i)^2;        % CALCULATES VECTORS FOR INTEGRATION
  Csdsqx(i) =Cs(i)*d(i)^2*x(i);
  Csdsqxsq(i)=Cs(i)*d(i)^2*x(i)^2;
end
% DISTANCE OF EACH ALONG HULL FROM BOW TO STERN
huldist= [0 9.658 19.315 24.725 30.134 49.91 69.768 89.586 109.403...
     129.22 149.037 168.854 188.671 208.489 228.306 248.123...
     267.94 291.502 315.065 335.628 362.19 385.753 409.315];
xi=linspace(0,409,409);


Csdsqfit=interp1(huldist,Csdsq,xi)     ;% FIT STATION DATA TO LENGTH OF HULL
Csdsqxfit=interp1(huldist,Csdsqx,xi)   ;% FIT STATION DATA TO LENGTH OF HULL
Csdsqxsqfit=interp1(huldist,Csdsqxsq,xi);% FIT STATION DATA TO LENGTH OF HULL
int1=trapz(Csdsqfit);
int2=trapz(Csdsqxfit);
int3=trapz(Csdsqxsqfit);
m2= (k2*pi)/(L*T^2)*int1;
xbar=(int2)/int1;
```

```
mz=(kprime/k2)*m2;

k1;

k2;

kprime;

%subplot(211),plot(Cs)

%subplot(212),plot(Csfit)
```

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