THESIS

OPTIMIZATION OF SURFACE SHIP STEERING
IN SEA STATE

by

Emmanuel Marianopoulos

December 1984

Thesis Advisor: George J. Thaler

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Optimization of Surface Ship Steering in Sea State

Emmanuel Horianopoulos

Naval Postgraduate School
Monterey, California 93943

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116

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Computer models of the ship, Nomoto model, Regular seas, Optimized controller, Irregular seas, Minimization subroutine, Adaptive control.

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A computer model of the 97-7 containership along with a cascaded controller (one pole, one zero) were analyzed to a
function minimization subroutine and a sea state generator program. This scheme provided the appropriate controller parameters in order to accomplish the best performance.

The model was tested in calm waters and sea states (regular and irregular) as well, for a certain speed and different encounter wave angles and encounter frequencies.

Also, an adaptive control was studied which updates the controller parameters while either the environmental conditions or the ship's steering characteristics change in order to maintain optimal steering performance.
Optimization of Surface Ship Steering in Sea State

by

Emmanuel Horianopoulos
Lieutenant, Hellenic Navy
B.S., Naval Academy of Greece, 1975

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December 1984

Author:

Emmanuel Horianopoulos

Approved by:

G. J. Thaler, Thesis Advisor

A. Gerba, Second Reader

Harriett B. Rigas, Chairman,
Department of Electrical and Computer Engineering

John N. Dyer,
Dean of Science and Engineering
ABSTRACT

Propulsion losses are increased by added drag due to steering of the ship. A carefully designed automatic steering control provides the desired heading while it simultaneously minimizes the rudder activity and holds the potential for reducing propulsive losses.

A computer model of the SL-7 containership along with a cascaded controller (one pole, one zero) were coupled to a function minimization subroutine and a sea state generator program. This scheme provided the appropriate controller parameters in order to accomplish the best performance.

The model was tested in calm waters and sea states (regular and irregular) as well, for a certain speed and different encounter wave angles and encounter frequencies.

Also, an adaptive control was studied which updates the controller parameters while either the environmental conditions or the ship's steering characteristics change in order to maintain optimal steering performance.
I. INTRODUCTION ................................................. 11

II. COMPUTER MODELS OF THE SHIP ............................... 13

III. AN ADEQUATE PERFORMANCE CRITERION ..................... 16
    A. CRITERION BASED ON TRUE ADDED RESISTANCE ........... 16
    B. CRITERION BASED ON APPROXIMATE ADDED RESISTANCE .... 18
    C. WEIGHTING FACTOR STUDY .................................. 19

IV. REGULAR SEAS - CONTROLLER DESIGN ......................... 23

V. IRREGULAR SEAS - CONTROLLER DESIGN ....................... 46

VI. MINIMIZATION SUBROUTINE FOR ONBOARD USE .................. 53
    A. GENERAL .................................................. 53
    B. ATTACKING THE PROBLEM ................................... 54
    C. SOLVING THE PROBLEM ..................................... 54

VII. ADAPTIVE CONTROL .......................................... 57
    A. NECESSITY OF ADAPTIVITY .................................. 57
    B. CANDIDATE ADAPTIVE SCHEMES .............................. 57

VIII. CONCLUSIONS AND RECOMMENDATIONS ......................... 62
    A. CONCLUSIONS .............................................. 62
    B. RECOMMENDATIONS FOR FUTURE STUDIES ..................... 63

APPENDIX A: NOMOTO THIRD ORDER MODEL DETERMINATION .......... 65

APPENDIX B: REGULAR SEASTATE FORMULATION ..................... 73

APPENDIX C: SYSTEM'S RESPONSE FOR REGULAR SEAS ............... 81
APPENDIX D: IRREGULAR SEASTATE FORMULATION . . . . . . . 88
APPENDIX E: SYSTEM'S RESPONSE FOR IRREGULAR SEAS . . . . 95
APPENDIX F: MODIFIED MINIMIZATION SUBROUTINE . . . . . 102
LIST OF REFERENCES . . . . . . . . . . . . . . . . . . . . . . 114
INITIAL DISTRIBUTION LIST . . . . . . . . . . . . . . . . 115
### LIST OF TABLES

<table>
<thead>
<tr>
<th></th>
<th>Table Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Weighting factor $\lambda''$</td>
<td>18</td>
</tr>
<tr>
<td>II.</td>
<td>Weighting factor $\lambda'$</td>
<td>19</td>
</tr>
<tr>
<td>III.</td>
<td>Weighting factor $\lambda$</td>
<td>19</td>
</tr>
<tr>
<td>IV.</td>
<td>Sea state vs Wave height</td>
<td>24</td>
</tr>
<tr>
<td>V.</td>
<td>Optimal Controller Parameters for Regular Sea</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Sea State 4</td>
<td></td>
</tr>
<tr>
<td>VI.</td>
<td>Optimal Controller Parameters for Regular Sea</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Sea State 6</td>
<td></td>
</tr>
<tr>
<td>VII.</td>
<td>Optimal Controller Parameters for Regular Sea</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>Sea State 7</td>
<td></td>
</tr>
<tr>
<td>VIII.</td>
<td>Optimal Controller Parameters for Regular Sea</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Sea State 9</td>
<td></td>
</tr>
<tr>
<td>IX.</td>
<td>Optimal Controller Parameters for Random Sea</td>
<td>48</td>
</tr>
<tr>
<td>X.</td>
<td>First Modification in BOXPLX</td>
<td>55</td>
</tr>
<tr>
<td>XI.</td>
<td>Second Modification in BOXPLX</td>
<td>56</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

2.1 Controller Optimization Scheme .................................. 14
2.2 Nomoto Transfer Functions ........................................... 14
2.3 Nomoto Model Determination Scheme ................................ 15
3.1 Closed Loop Bandwidth for $\lambda=8.128$ ....................... 21
3.2 Closed Loop Bandwidth for $\lambda=5.734$ ....................... 22
4.1 Controller Used in this Study ....................................... 24
4.2 Yaw vs Time, Sea State 4. Encounter Frequency
    1.5 rads per sec, Encounter Angle 120° ........................ 31
4.3 Rudder vs Time, Sea State 4. Encounter Frequency 1.5 rads per sec, Encounter Angle
    120° .................................................................. 32
4.4 Yaw vs Time, Sea State 6. Encounter Frequency
    1.5 rads per sec, Encounter Angle 120° ........................ 33
4.5 Rudder vs Time, Sea State 6. Encounter Frequency 1.5 rads per sec, Encounter Angle
    120° .................................................................. 34
4.6 Yaw vs Time, Sea State 7. Encounter Frequency
    1.5 rads per sec, Encounter Angle 120° ........................ 35
4.7 Rudder vs Time, Sea State 7. Encounter Frequency 1.5 rads per sec, Encounter Angle
    120° .................................................................. 36
4.8 Yaw vs Time, Sea State 9. Encounter Frequency
    1.5 rads per sec, Encounter Angle 120° ........................ 37
4.9 Rudder vs Time, Sea State 9. Encounter Frequency 1.5 rads per sec, Encounter Angle
    120° .................................................................. 38
4.10 Cost vs K1, Sea State 4. Encounter frequency 1.5
    rads per sec, Encounter Angle 120° ........................... 39
4.11 Cost vs T1, Sea State 4. Encounter frequency 1.5 rads per sec, Encounter Angle 120°

4.12 Cost vs T2, Sea State 4. Encounter frequency 1.5 rads per sec, Encounter Angle 120°

4.13 Cost vs T2, Sea State 6. Encounter Frequency 1.5 rads per sec, Encounter Angle 120°

4.14 Cost vs T2, Sea State 6. Encounter Frequency 0.6 rads per sec, Encounter Angle 120°

4.15 Yaw vs Time, Sea State 4, Frequency 0.4, Angle 60°. Filter for Sea State 9, Frequency 1.5, Angle 120°

4.16 Rudder vs Time, Sea 4, Frequency 0.4, Angle 60°.
Filter for Sea State 9, Frequency 1.5, Angle 120°

5.1 Yaw vs Time, Sea state 6. Encounter Angle 60°

5.2 Rudder vs Time, Sea State 6. Encounter Angle 60°

5.3 Yaw vs Time, Sea State 7. Encounter Angle 60°

5.4 Rudder vs Time, Sea State 7. Encounter Angle 60°

7.1 Adaptive Control Scheme

7.2 On Line Adaptive Scheme
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I. INTRODUCTION

The economics associated with ship operations have necessitated an examination of the losses associated with the motion of an automatically steered ship in a seaway.

Four major areas where fuel losses occur during the operation of a ship have been identified [Ref. 1, 2]. These areas on existing steam/diesel tankers are shown below:

- Power plant and auxiliaries
- Propeller efficiency
- Hull resistance
- Steering and navigation

An optimized autopilot design would provide effective steering control with associated cost savings due to reducing fuel consumption.

An appropriate computer model which represents the ship is necessary for studies leading to appropriate controller design. Chapter 2 introduces the development of two of these models.

Chapter 3 addresses the formulation of a performance criterion which represents the added drag due to steering of the ship.

Using the equations of motion as a model of the ship and a function minimization subroutine we proceed to the controller design for regular seas (deterministic model for the seaway) in Chapter 4, and for irregular seas (nondeterministic model) in Chapter 5. The function minimization subroutine used was BOXPLX and was programmed by R. R. Hilleary of the Naval Postgraduate School Computer Center [Ref. 3]. It will find the minimum of any arbitrary function, linear or nonlinear, subject to explicit constraints of the variables or implicit constraints on functions of the variables.
Chapter 6 introduces another function minimization subroutine appropriate for onboard use.

An adaptive control, which updates the controller parameters when the environmental conditions or the ship's course change, is studied in Chapter 7.

Conclusions drawn from these experiments and recommendations for future studies are addressed in Chapter 8.
II. COMPUTER MODELS OF THE SHIP

A nontrivial part of any control problem is modelling the process. Thus, an appropriate computer model which represents the ship is necessary. The best representation of the ship's steering dynamics is a Taylor's series expansion of the force and moment relationships around a selected steady state operating point. The equations obtained in this way are known as the equations of motion [Ref. 4], and the formulation in the computer program is indicated in Appendix A. This computer program was developed by using known available data for the SL-7 containership and by implementation of the scheme in Figure 2.1 [Ref. 5].

In this scheme the function minimization subroutine is fed by the yaw error $\psi_e$ and rudder angle $\delta$, computes the performance criterion $J$ and adjusts the controller free parameters in order to minimize $J$.

A second model for the ship-steering dynamics representation is the Nomoto model. Figure 2.2 indicates the second and third order Nomoto transfer functions while Figure 2.3 indicates the appropriate scheme used for obtaining these models from the equations of motion. Appendix A includes the computer program used for the Nomoto third order model determination.

A yaw command is applied as input in the scheme in Figure 2.3 and the difference of the signals $\psi_M$ and $\psi_{EQ}$ is fed to the function minimization subroutine which attempts to adjust the free parameters of the Nomoto plant in order to minimize the performance criterion $J$.

Simulation runs indicate that the resulting Nomoto models are obtained with resulting $J$ close to zero. However, in this study the equations of motion
Figure 2.1 Controller Optimization Scheme

\[ J = \int_0^T \left( \lambda \psi_e^2 + \delta^2 \right) dt \]

Figure 2.2 Nomoto Transfer Functions

Second order

\[ \frac{\psi}{\delta} = \frac{K}{s(Ts+1)} \]

Third order

\[ \frac{\psi}{\delta} = \frac{K(T_z s + 1)}{s(T_1 s + 1)(T_2 s + 1)} \]
Figure 2.3 Nomoto Model Determination Scheme

representation was adopted because the system is dynamic and use of the Nomoto model representation implies additional computer use. On the other hand, frequency domain studies were carried out using the Nomoto representation since this representation is easier handled.
III. AN ADEQUATE PERFORMANCE CRITERION

A. CRITERION BASED ON TRUE ADDED RESISTANCE

The performance criterion which characterizes propulsion losses due to steering may be shown to be that derived from excess power consumption per unit distance caused due to steering [Ref. 1, 6]. The added resistance due to steering can be related to the surge or thrust equation where the total instantaneous surge relevant to steering is

\[ \Delta X = \left[ m \left( \frac{\rho}{2} \right) L A X_v r \right] \nu r - \frac{1}{2} \left[ \left( \frac{\rho}{2} \right) A X_{vv} \nu \right] \nu^2 + \frac{1}{2} \left( \frac{\rho}{2} \right) A X_{\delta \delta} \left( U^2 \right) \delta^2 \] (3.1)

where
- \( m \) = mass of ship
- \( \rho \) = density of sea water
- \( L \) = ship's length between perpendiculars
- \( A = L^2 \)
- \( U \) = ship's water speed
- \( \nu \) = sway velocity
- \( r \) = yaw rate of ship
- \( \delta \) = rudder angle
- \( X_v^r \) = force coefficient due to yaw/sway (positive)
- \( X_{\delta \delta} \) = force coefficient due to rudder angle (negative)
- \( X_{vv} \) = force coefficient due to sway

Since the sway velocity of the ship is small we can neglect the term which includes the square of the sway velocity in the previous equation. From this the mean surge relevant to steering may be written as
\[
\bar{\Delta} = [m - (\rho/2)LA_{\nu r}'][u_{a} r_{a}'] / 2 \cos(\phi_{v} - \phi'_{r}) + [(\rho/2)A_{\delta}U^{2}]/(\delta'^{2}/2)
\]  

(3.2)

Where  
- \(u_{a}\) = amplitude of sway velocity  
- \(r_{a}\) = amplitude of yaw rate  
- \(\delta_{a}\) = amplitude of rudder angle  
- \(\phi_{v} - \phi'_{r}\) = phase difference between sway and yaw rate

A performance criterion for added resistance due to steering may be formulated as

\[
J = \lim_{T \to \infty} \frac{1}{2T} \int_{0}^{T} (-\sigma v_{r} + \gamma U^{2} \delta^{2}) dt
\]  

(3.3)

where \(\sigma\) and \(\gamma\) are constants.

Accurate knowledge of the nonlinear coefficients \(X_{\nu r}'\) and \(X_{\delta}''\) is required for the accuracy of such a criterion. In addition the criterion itself suffers from the disadvantage that sway velocity measurements are not available. Normalizing the last equation the performance criterion will be

\[
J_{\text{norm}} = \lim_{T \to \infty} \frac{1}{2T} \int_{0}^{T} (-\bar{\lambda} v_{r} + \delta^{2}) dt
\]  

(3.4)

where \(\bar{\lambda} = (2[m + (\rho/2)LA]_{\nu r}'') / [(\rho/2)A_{\delta}'] U^{2}\)

Table I indicates the values of \(\bar{\lambda}\) for the operating range of speed of the ship studied.
TABLE I

<table>
<thead>
<tr>
<th>Ship's speed (knots)</th>
<th>( \lambda'' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>21.5350</td>
</tr>
<tr>
<td>23</td>
<td>10.4215</td>
</tr>
<tr>
<td>32</td>
<td>5.3900</td>
</tr>
</tbody>
</table>

B. CRITERION BASED ON APPROXIMATE ADDED RESISTANCE

Empirical criteria based on an approximation to added resistance may also be derived. A semiempirical criterion for measuring the relative performance was developed [Ref. 7], based on the assumption of small amplitude oscillations around the steady-state pivot point of the ship during yawing at the ship/steering system natural frequency. This may be extended and an alternative criterion for added resistance will be

\[
J = \lim_{T \to \infty} \frac{1}{2T} \int_0^T (\lambda \psi_e^2 + \delta^2) \, dt
\]  

where

\[
\lambda = \lambda' \omega = \frac{[2m(1+X_\psi')L]OP/(L\omega^2)}{[(\rho/2)LX_\psi^2U^2]} \\
X_\psi' = \frac{[(\rho/2)LX_\psi^2]}{m} \\
\delta = \text{distance from center of gravity to pivot center} \\
\omega = \text{natural frequency (closed loop ship steering control)} \\
\psi_e = \text{ship's perturbation yaw angle}
\]

The values of \( \lambda' \) as a function of ship's speed are given by Table II.

A closed loop system natural frequency \( \omega \) of around 0.05 rads per sec has the potential to attenuate the effects of
TABLE II

<table>
<thead>
<tr>
<th>Weighting factor $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship's speed (knots)</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>23</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>6.720</td>
</tr>
<tr>
<td>3.251</td>
</tr>
<tr>
<td>1.680</td>
</tr>
</tbody>
</table>

Seaway disturbance in the range of encounter angles where added resistance due to steering is important [Ref. 6]. The weighting factor for the operating range of the ship is shown in Table III.

TABLE III

<table>
<thead>
<tr>
<th>Weighting factor $\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship's speed (knots)</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>23</td>
</tr>
<tr>
<td>32</td>
</tr>
<tr>
<td>16.796</td>
</tr>
<tr>
<td>8.128</td>
</tr>
<tr>
<td>4.2</td>
</tr>
</tbody>
</table>

Equation 3.5 is used as a performance criterion for this study. It is an approximation but it is convenient for onboard use since ship's perturbation yaw angle $\psi$ and rudder angle $\delta$ are measurable.

C. WEIGHTING FACTOR STUDY.

The weighting factor $\lambda$ given by Table III used in equation 3.5, plays an important role in terms of the optimal controller parameters determination. Some investigation is necessary in order to verify the accuracy of the results, since the values of $\lambda$ of Table III are determined based on the assumption that the closed loop system's natural frequency is around 0.05 rads per sec [Ref. 1]. Frequency domain techniques were used for this purpose. Using the Nomoto third order model representation of the ship and available controller parameters from Chapter 4 for sea state
4, encounter frequency 1.5 rads per sec, encounter angle 150° and ship’s speed 23 knots we found that the closed loop bandwidth of the system is 0.04 rads per sec, as indicated in Figure 3.1, which is not close enough to 0.05 rads per sec.

For the same sea conditions and ship speed, with the assumption that the closed loop natural frequency of the system is not 0.05 rads per sec but 0.04 rads per sec, a new value $\lambda=5.734$ was obtained and the frequency domain techniques result in a new bandwidth 0.035 rads per sec as is indicated in Figure 3.2.

Clearly, the values of $\lambda$ given by Table III and used in this study are not the best. Unfortunately, since the full hydrodynamic coefficients of the SL-7 containership are not known we can't develop the surge equation and thus it is still impossible to determine accurate values for the weighting factor $\lambda$. 

20°S
Figure 3.1  Closed Loop Bandwidth for $\lambda=8.128$
Figure 3.2  Closed Loop Bandwidth for $\lambda=5.734$
IV. REGULAR SEAS - CONTROLLER DESIGN

We have already defined a suitable and sufficiently accurate ship computer model and the system's performance criterion, as well. The remaining task is to determine a representation of the external disturbances imparted to the ship by the sea, before the system's performance in a seaway can be evaluated. A correct model of the seaway itself is essential to representative modeling of forces and moments exerted on the ship by it.

At this point we will use the regular sea model as sea representation. The properties of regular seas are well defined. The wave crests are assumed to be straight, infinitely long, parallel and equally spaced with constant wave height. The waves progress in a direction perpendicular to the crest line at a uniform velocity. However the sea is never regular. It is a random phenomenon where waves are continually changing in height, length and breadth [Ref. 8].

The forces exerted by the regular sea have the form

\[ F = \omega_d R_j \cos(\omega_e t + \psi_j) \]  \hspace{1cm} (4.1)

where
\[ \omega_d \] = significant wave height
\[ R_j \] = exciting force
\[ \omega_e \] = encounter frequency
\[ \psi_j \] = phase angle

The correspondence between sea state and wave height is indicated in Table IV [Ref. 9].

The exciting forces \( R_j \) for different encounter frequencies and encounter angles were obtained from the sea state generator program [Ref. 10].
TABLE IV
Sea state vs Wave height

<table>
<thead>
<tr>
<th>Sea state (Beaufort scale)</th>
<th>Range for wave height (Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>0.32</td>
</tr>
<tr>
<td>2</td>
<td>0.65-0.98</td>
</tr>
<tr>
<td>3</td>
<td>1.96-3.28</td>
</tr>
<tr>
<td>4</td>
<td>3.28-4.92</td>
</tr>
<tr>
<td>5</td>
<td>6.56-8.20</td>
</tr>
<tr>
<td>6</td>
<td>9.84-13.1</td>
</tr>
<tr>
<td>7</td>
<td>13.1-16.2</td>
</tr>
<tr>
<td>8</td>
<td>16.2-24.6</td>
</tr>
<tr>
<td>9</td>
<td>23.0-32.9</td>
</tr>
</tbody>
</table>

Appendix B indicates the regular seastate formulation in the FORTRAN program used for obtaining the controller parameters.

The controller used in the entire study has one pole-one zero and the form is indicated in Figure 4.1. This controller seems to have the best performance in calm waters and in seaway [Ref. 5].

Figure 4.1 Controller Used in this Study

The optimized controller parameters and the cost J for 23 knots speed, sea states 4-6-7-9, different encounter angles and various encounter frequencies are indicated in Tables V, VI, VII and VIII.
Studying the Tables V through VIII we can draw the following conclusions:

- For a particular encounter angle and encounter frequency the higher the sea state the higher the cost.
- For the same sea state the cost becomes smaller for higher encounter frequencies.
- For encounter frequency 0.2 rads per sec the maximum cost occurs at 60° encounter angle for all tested sea states.
- For 0.6 and 0.75 rads per sec encounter frequency the maximum cost occurs at 120° encounter angle for all tested sea states.
- For 1.5 rads per sec encounter frequency the maximum cost occurs at 90° encounter angle for all tested sea states.
- For 0.4 rads per sec encounter frequency the maximum cost occurs at 90° encounter angle for sea states 4, 6 and 7 while at sea state 9 the maximum cost occurs at 60° encounter angle.

Appendix C provides the computer program necessary to achieve the system's response. Some typical responses are indicated in Figures 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9. It is obvious that as the sea state goes to heavier seas the rudder and yaw perturbations become larger.

An attempt to determine how accurate the controller parameters must be for a particular situation, leads to the conclusion that high accuracy isn't required. Keeping two parameters fixed each time and vary the third we can see (Figures 4.10, 4.11, 4.12, 4.13, 4.14) that the cost doesn't change appreciably in the vicinity of the actual value.

Figures 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 indicate that the yaw and rudder excursions are less than 1°. This just seems strange, though it may be because of the optimization of the filter. We tried to investigate that by
using the optimal filter for sea state 9, encounter frequency 1.5 rads per sec, encounter angle 120° and run it in sea state 4, keeping the same encounter frequency and angle. The yaw and rudder excursion, even if they became larger, remained less than 1°. The parameters of those two filters are close and the reason might be the flatness of the cost surface. Second attempt led to more interesting results. Using the same filter and run it in sea state 4, encounter frequency 0.4 rads per sec and encounter angle 060°, the system becomes unstable (Figures 4.15, 4.16).
TABLE V
Optimal Controller Parameters for Regular Sea
Sea State 4

Encounter Frequency 0.2 rads per sec

<table>
<thead>
<tr>
<th>angle(degrees)</th>
<th>K1</th>
<th>T1</th>
<th>T2</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5221067</td>
<td>66.3312231</td>
<td>12.8332741</td>
<td>0.609E-33</td>
</tr>
<tr>
<td>30</td>
<td>1.0488701</td>
<td>61.9309387</td>
<td>15.9266357</td>
<td>2.481E-3</td>
</tr>
<tr>
<td>60</td>
<td>1.2036362</td>
<td>54.5333295</td>
<td>16.0245972</td>
<td>3.611E-3</td>
</tr>
<tr>
<td>90</td>
<td>1.3178606</td>
<td>49.7324953</td>
<td>14.8329315</td>
<td>2.703E-3</td>
</tr>
<tr>
<td>120</td>
<td>1.3986499</td>
<td>46.9797058</td>
<td>13.5345757</td>
<td>1.355E-3</td>
</tr>
<tr>
<td>150</td>
<td>1.450153</td>
<td>45.4265306</td>
<td>13.3515599</td>
<td>0.356E-3</td>
</tr>
<tr>
<td>180</td>
<td>0.7195223</td>
<td>25.2119598</td>
<td>14.1219782</td>
<td>0.345E-2</td>
</tr>
</tbody>
</table>

Encounter Frequency 0.4 rads per sec

<table>
<thead>
<tr>
<th>angle(degrees)</th>
<th>K1</th>
<th>T1</th>
<th>T2</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.5221067</td>
<td>66.3312231</td>
<td>12.8332741</td>
<td>0.517E-35</td>
</tr>
<tr>
<td>30</td>
<td>0.7234516</td>
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27
## TABLE VI
Optimal Controller Parameters for Regular Sea
Sea State 6

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TABLE VII
Optimal Controller Parameters for Regular Sea
Sea State 7

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29
TABLE VIII
Optimal Controller Parameters for Regular Sea
Sea State 9

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Figure 4.2. Yaw vs Time, Sea State 4.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°.
Figure 4.3  Rudder vs Time, Sea State 4.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°
Figure 4.4  Yaw vs Time, Sea State 6.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°
Figure 4.5: Rudder vs Time, Sea State 6, Encounter Angle 120°
Figure 4.6. Yaw vs Time, Sea State 7.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°
Figure 4.7: Rudder vs Time, Sea State 7, Encounter Angle 42°
Figure 4.8  Yaw vs Time, Sea State 9.
Encounter Frequency 1.5 rads per sec, Encounter Angle 120°
Figure 4.10  Cost vs K1, Sea State 4.
Encounter frequency 1.5 rads per sec; Encounter Angle 120°
Figure 4.11. Cost vs T1, Sea State 4.
Encounter frequency 1.5 rads per sec, Encounter Angle 120°.
Figure 4.12  Cost vs T2, Sea State 4.  
Encounter frequency 1.5 rads per sec, Encounter Angle 120°
Figure 4.14: Cost vs $T^2$, Sea State 6. Encounter Angle 90°
V. IRREGULAR SEAS - CONTROLLER DESIGN

The major characteristic of the sea is its irregularity. This irregularity can be described by statistical methods by assuming that a large number of regular (sinusoidal) waves having different wavelengths, directions, phases and amplitudes are superimposed to form the randomly varying sea.

The presence of the irregular sea was obtained by coupling a sea state generator program to the FORTRAN program as is indicated in Appendix D. The sea state generator program generates added mass and added inertia values as function of the encounter frequency and also calculates forces and moments imparted to the shiphull by the sea. The forces and moments are stored in a look up table which was coupled to the equations of motion. The irregular sea waves impinging on the ship contain the total energy density spectrum composed of many frequencies and the ship responds to an average value of added mass and added inertia, while in the regular sea the added mass and added inertia were known for a given encounter frequency. We decided to use values for added mass and added inertia corresponded to encounter frequency 0.75 rads per sec, since the energy density is maximum in the vicinity of this frequency [Ref. 5]. This frequency gave us values representative of an average value for added mass and added inertia.

The controller used for this study was the controller described in Chapter 4 (Figure 4.1). The optimized controller parameters and the cost $J$ for sea states 4, 6, 7, 9 and $0^\circ$, $30^\circ$, $60^\circ$, $90^\circ$, $120^\circ$, $150^\circ$, $180^\circ$ encounter angles are indicated in Table IX.

Studying the Table IX we can draw the following conclusions:
• For sea states 6, 7, 9, the higher the sea state the higher the cost, for every particular encounter angle.

• Comparing costs for sea states 4 and 6 we discover some anomaly. The cost for a specific encounter angle in sea state 4 is higher than the cost for the same encounter angle in sea state 6. Logically, we expect higher cost for higher sea state.

• The reason for this anomaly may be the method we used in order to obtain the added mass and added inertia values. The average, we consider, might not represent the actual average.

Appendix E provides the computer program necessary to achieve the system’s response. Some typical responses are indicated in Figures 5.1, 5.2, 5.3, 5.4.
### TABLE IX
Optimal Controller Parameters for Random Sea

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<th>Encounter Angle (degrees)</th>
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<th>Sea State 6</th>
<th>Sea State 7</th>
<th>Sea State 9</th>
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<th>Sea State 9</th>
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Figure 5.1 Yaw vs Time, Sea state 6.
Figure 5.2. Rudder vs Time, Sea State 6.
Figure 5.4: Rudder vs. Time, Sea State 7.
VI. MINIMIZATION SUBROUTINE FOR ONBOARD USE

A. GENERAL

As is mentioned earlier in Chapter 1 the function minimization subroutine used for these studies was BOXPLX. This subroutine will find the minimum of any function, linear or nonlinear, subject to explicit constraints of the variables or implicit constraints on functions of the variables. It will handle a maximum of 25 variables but can handle up to 50 variables with user modification.

The variables in BOXPLX are allowed to move within a feasible region (n-dimensional space, where n is the number of variables) defined by upper and lower bounds on their values. The choices for upper and lower bounds for the parameters are based on an understanding of the function of each coefficient of the system. Experience indicates that while accurate selections of these bounds are not necessary, intelligent selection of these as well as the starting values (guesses) can considerably reduce the computer number of trials needed for solution convergence. This conclusion was drawn trying to obtain the controller parameters for Tables V, VI, VII, VIII in Chapter 4. The function minimization subroutine, when starting the minimization process with arbitrary chosen guesses, required more than 100 trials for convergence while by choosing guesses close to the optimal parameter required more than 50 and less than 100 trials. Considering that every trial lasted 600 seconds (10 minutes) and the function minimization subroutine requires about 60 samples (trials) before telling us it had found the minimum this would mean 10 hours for the control to adjust itself. For obvious reasons, such operation is not acceptable for onboard use.
For obvious reasons, such operation is not acceptable for on board use.

B. ATTACKING THE PROBLEM

We started to investigate ways to improve this. These efforts include:

- Finding a more efficient function minimization subroutine
- Studying the flatness of the cost surface
- Reducing sampling time

C. SOLVING THE PROBLEM

Switching to another function minimization subroutine we found that the new one (ZXMWD) suffered from the same disadvantages.

The experiments carried out, more than two hundred, indicated that the cost surface is really flat. The BOXPLX after a few trials started to focus on the minimum but before it converged, it needed more than 50 trials, even if the guesses were close to the optimal. The reason is the way BOXPLX itself tries to find the minimum of a function of NV variables. It converges when the cost FE remains unchanged for $2^{20}$ consecutive trials with accuracy $10^6$. An effort to modify this termination criterion in terms of the consecutive trials was successful. Table X indicates the comparison between modified and unmodified BOXPLX, for sea state 6, encounter frequency 1.5 rads per sec and encounter angle 120°. As we can observe in Table X the cost in each case remains almost the same while the trials required for convergence are dependent on the guesses made and the termination criterion established.

The value of the cost is in general the summation of incremental contributions for each integration step and is

54
TABLE X
First Modification in BOXPLX

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<th>BOXPLX</th>
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<th>Trials</th>
<th>Termination Criterion</th>
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</table>

therefore dependent on the total time of the simulation. This is important in that the optimal gain coefficients arrived at in this manner are not optimal for steady-state performance but only for the time frame covered. This should be adequate provided the time frame selected is long relative to the time required for the initial condition response to die out. This is the reason Reid has chosen time frame 600 seconds [Ref. 1,2]. Of course this time period is large and we expect steady-state behaviour faster than 10 minutes. Simulation studies indicate that the ship, controlled by the controller described in Figure 4.1, reaches the steady-state situation in less than 100 seconds. So, we can reduce the 600 seconds time frame to 200 seconds, safely. This is very important since now the modified function minimization subroutine BOXPLX, uses samples of 200 seconds long instead of 600 seconds, converges in less than 30 minutes which is reasonable for on board use. Since the value of the cost is dependent on the time frame taken we expect reduced cost for 200 seconds samples long, in any case.

As we discussed earlier the BOXPLX compares the consecutive trials with accuracy $10^{-4}$. Since we do not need so big accuracy a second modification is necessary. We decided to change the existing accuracy to $10^{-5}$.

Table XI indicates the trials required for BOXPLX convergence, after the second and last modification, for sea
TABLE XI
Second Modification in BOXPLX

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<td>5</td>
<td>2</td>
<td>0.004024354</td>
</tr>
<tr>
<td>Optimal</td>
<td>1</td>
<td>2</td>
<td>0.003995247</td>
</tr>
</tbody>
</table>

state 6, encounter frequency 1.5 rads per sec and encounter angle 120°. By comparing Tables X and XI we can see the further improvement for the function minimization subroutine convergence. The difference in the cost is due to the different time frames used. The modified function minimization subroutine BOXPLX is indicated in Appendix F.
VII. ADAPTIVE CONTROL

A. NECESSITY OF ADAPTIVITY

The plant, the system which is supposed to be controlled, is normally exposed to a time varying environment. The ship's speed, the wave encounter angle and the sea state are changing drastically during the seaway. Since changes encountered are not completely predictable an optimum preprogrammed time-varying controller is not possible.

If we assume-and it is apparent from the previous discussion in this study-that no feasible fixed parameter controller provides acceptable response over the entire performance spectrum, it is necessary that some means is provided for adjusting controller parameters according to the sea conditions and ship's operational characteristics. Adaptive control is thus an effort to extend basic optimum control concepts to these studies.

B. CANDIDATE ADAPTIVE SCHEMES

Since we are looking for 1% or 2% savings in fuel cost, we have to feed the system with precise information. Exact knowledge of the sea state, the wave encounter angle and the ship's ground speed is vital for this purpose. Currently the Navy is involved in a program that will provide precision navigation data. Garcia [Ref. 5], provides very good information on this subject.

An adaptive control scheme is indicated in Figure 7.1. Once the adaptive part of the scheme is set up the sea state, encounter wave angle and ship's speed are fed to the filters box by the appropriate sensors. The filters box
Figure 7.1 Adaptive Control Scheme
includes predetermined optimal filter sets for different
discrete sea states, wave angles and ship's speed. Actually,
it is a look up table similar to those of Tables V, VI, VII
and VIII. The output of the filter's box is a filter which
corresponds to discrete conditions close to those fed by the
sensors. The function minimization subroutine accepting the
rudder angle, yaw error and the predetermined filter set as
initial guesses tries to obtain the optimal filter for the
exact sea state, wave encounter angle and ship's speed. At
the same time the plant is controlled by the controller with
the optimal predetermined set of parameters for conditions
close to the actual. When the function minimization subrou-
tine reaches the minimum, it supplies the controller with a
new set of parameters which is the optimal set for the
present conditions.

But, what happens if either some or all the sensors
provide new inputs to the system? A decision device placed
after the sensors decides whether or not the change is
appreciable. This device compares the current conditions
with those used to obtain the controller which currently
governs the system. If the change is higher than some
desired percentage then a new predetermined filter is passed
to the controller and the function minimization subroutine
tries to find the optimal controller parameters for the new
situation.

From the scheme of Figure 7.1 we can eliminate the
predetermined filters device which provides a less expensive
system. In this case the function minimization subroutine
will need a much longer time to determine the optimal filter
for rapid changes in course and speed, even if we assume
that rapid changes in sea state don't occur. Finally, the
function minimization subroutine might work continually "on
line" as is indicated in Figure 7.2. In this scheme a new
controller set is obtained in every subroutine iteration and
Figure 7.2  On Line Adaptive Scheme
some constraints for the controller parameters are necessary in order to avoid operation in unstable regions. Thus, the filter supplied by the subroutine for controlling the plant must be tested for characteristic equation roots in the right half S-plane. In that case a default option must exist, and a special device for such purposes is necessary. This device will permit change in the filter parameters only when the new set still keeps the system in a stable situation.

Whichever adaptive scheme we adopt, we must provide for manual operation for the system. Manual operation will be desired in the following cases:

- Arriving ports
- Leaving ports
- Restricted waters
- Avoid collision in open seas
- Computer down

For the first two situations, since we usually expect no heavy seas, the optimal filter for sea state 1 seems to be more suitable. Also, this filter can serve as initial condition for the adaptive schemes described before, when we are leaving ports. For the rest of the situations the last operating optimal filter is the most appropriate.
VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The principal conclusions from this study of the SL-7 containership as they related to steering may be stated as follows:

- It is evident that a control system which provides the ship heading and simultaneously reduces the propulsive losses does exist and therefore such a controller saves fuel. We can't conclude how much the savings are, since there is no reference for comparison between the conventional autopilot and the autopilot which, in addition, holds the potential for reducing the propulsive losses. The literature says that savings 1% or 2% is possible.
- An adaptive controller, that minimizes propulsion losses as ship characteristics and environmental conditions change, may be designed using a self-optimalizing technique employing a suitable performance criterion.
- Studying every particular situation we conclude that the cost surface is flat and therefore accurate determination of the controller parameters is not required. So, if we decide to use the adaptive control scheme of Figure 7.1 we don't have to store every particular filter in the look up table since one filter may be suitable for different ship characteristics and sea conditions.
- The weighting factor $\lambda$ used in the performance criterion equation 3.5 plays an exceptional and important role in the optimal controller parameters determination. However, it is obtained from studies based on
many assumptions and therefore isn't predicted accurately. As a consequence the controller found does not minimize added resistance unless the proper value of the weighting factor $\lambda$ has been used.

- The method used to obtain the average for the added mass and added inertia for the irregular seas studies might not represent the actual average.
- The function minimization subroutine BOXPLX after two modifications seems to be pretty suitable for on board use working as a main part of the adaptive scheme.

B. RECOMMENDATIONS FOR FUTURE STUDIES

The following recommendations for future work to gain a fuller and deeper understanding of the problem are made as follows:

- Some studies are necessary in order to investigate why part of the obtained controllers in Tables V, VI, VII, VIII are lag and part of them are lead filters.
- As we stated in chapter 4 the yaw and rudder excursions in Figures 4.2 through 4.9 are less than 1°. It is necessary to investigate the reason for that. It might be because of the optimization of the filter or the forces and moments have not been sealed properly.
- It is necessary to find out the appropriate average values for the added mass and added inertia before we attempt further studies in irregular seas.
- The full hydrodynamic coefficients for the SL-7 are necessary in order to develop and include the surge equation in our ship model. So far we ignore the surge equation and we assumed constant ship speed while in reality the added resistance due to steering must reduce the ship speed.
• By developing the surge equation in our ship model we may be able to determine a good value for the weighting factor to be used in the performance criterion.

• Also, with the surge equation available in our model we should be able to calculate actual energy losses and savings in fuel.

• As we stated in chapter 6 the time frames (samples) used by the BOXPLX must be long relative to the time required for the initial condition response to die out. Reid [Ref. 1,2] has chosen time frame 600 seconds long. This time frame is long and it is necessary to find out the sufficient time frame since the time required by the function minimization subroutine for convergence is directly proportional to the sample duration.
APPENDIX A
NOMOTO THIRD ORDER MODEL DETERMINATION

//NOMOTO JOB (XXXX,XXXX), 'RESEARCH', CLASS=J
//*MAIN ORG=NPGVM1.XXXP
// EXEC FORTXCG, PARM.FORT='OPT(2)', IMSL=DP, REGION=1024K
//FORT.SYSIN DD *

C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*) AND XL(*)

DIMENSION XS(4), XU(4), XL(4)
XS(1) = 0.1
XS(2) = 15.13
XS(3) = 15.675
XS(4) = 9.014

C XS(I) IS THE STARTING GUESS

C XL(I) IS THE LOWER LIMIT FOR THE I' TH VARIABLE

C XU(I) IS THE UPPER LIMIT FOR THE I' TH VARIABLE

XL(1) = .01
XU(1) = 1.0
XL(2) = 1.0
XU(2) = 20.
XL(3) = 1.0
XU(3) = 100.
XL(4) = 1.0
XU(4) = 100.0

C A DESCRIPTION OF THE FOLLOWING PARAMETERS
C IS DISCUSSED IN BOXPLX

R = 9./13.
NTA = 1000
NPR = 0
NAV = 0
NV = 4
IP = 0
C THE FOLLOWING STATEMENT MUST BE CHANGED TO
C CALL PLANT(XX)
C IF ONLY SIMULATION IS WANTED
    CALL BOXPLX(NV, NAV, NPR, NTA, R, XS, IP, XU, XL, YMN, IER)
    WRITE (6, 25)
    25 FORMAT(1X, 'OPTIMAL GAINS', /)
    DO 30 I = 1, 4
    30 WRITE(6, 40)I, XS(I)
    40 FORMAT(1X, 'X(', I2, ')=', F14.7)
    WRITE (6, 77) TDIFF
    77 FORMAT(1X, 'COST=', F14.7)
STOP
END
C SUBROUTINE PLANT(XX) SIMULATES THE SHIP
SUBROUTINE PLANT(XX)
COMMON TDIFF
REAL*8 L, L2, L3, L4, L5, L6, RXR, RXI, RYR, RYI, MZR, MZI, RX, RY
REAL*8 X, XDOT, Y, YDOT, U, UDOT, V, VDOT, YAW, R, RDOT, TX, TY
REAL*8 TIME, ETIME, XUDOT, XU, XUU, XV, XVVR, XVVR, XVVV, YV, YVR, YVRR, YVVR, YVRV, YVVR, YVRR, YDDD, YVDOT, TZ
REAL*8 NV, NR, ND, NVVR, NVVR, NVVV, NRRR, NDDD, NRRR
REAL*8 RHO, IZ, FX, FY, MZ, XP, MASS, DELT
REAL*8 YAWE, YAWC, D2, D
REAL*8 K, TP1, TP2, Z, X1, X2, X3, X4, X5, YAW2, S
DIMENSION XX(4)
C INITIAL CONDITIONS FOR INTEGRATION
C SIMULATION END TIME IN SECONDS
ETIME = 600.
TIME = 0.0
ICOUNT = 1
C INITIALIZE THE COST FUNCTION
TDIFF = 0.0
C GAIN COEFFICIENTS TO BE OPTIMIZED
K = XX(1)
Z = XX(2)
TP1=XX(3)
TP2=XX(4)

C X, XDOT, Y, YDOT ARE FIX COORDINATES ON EARTH
  X=0.0
  Y=0.0
  XDOT=0.0
  YDOT=0.0

C U, UDOT, V, VDOT ARE FIX COORDINATES ON SHIP
  V=0.0
  UDOT=0.0
  VDOT=0.0
  YAW=0.0
  R=0.0
  RDOT=0.0

C ORDERED SPEED IN FEET/SEC
C 38.81 FT/SEC=23 KNOTS
UC=38.81

C AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
U=UC

C D = RUDDER ANGLE
  D=0.0
  L=880.5
  L2=L**2
  L3=L*L*L
  L4=L*L3
  L5=L*L4
  L6=L*L5

C SEA DISTURBANCE
C FORCES IN X, Y DIRECTION COMPUTED IN FORCES
C MOMENTS IN Z
  FX=0.0
  FY=0.0
  MZ=0.0

C RXR=-.15744D-05
C RXI=-.19950D-06

67
C  
C  RYR=0.52365D-04
C  RYI=0.18699D+06
C  MZR=-.29870D-08
C  MZI=-.37751D+07
RXR=-.50230D-04
RXI=0.12712D+05
RYR=0.35290D+04
RYI=-.31909D+05
MZR=0.38826D+07
MZI=-.64313D+07
C  RXR=0.28540D-04
C  RXI=-.99574D+04
C  RYR=-.85441D+04
C  RYI=0.39595D+05
C  MZR=-.13014D+08
C  MZI=0.11348D-08
C  RXR=-.75642D+04
C  RXI=0.83497D+04
C  RYR=0.23379D+05
C  RYI=-.81502D+05
C  MZR=0.28622D+07
C  MZI=-.19388D+08
C  RXR=-.37916D+04
C  RXI=0.16381D+04
C  RYR=-.76647D+05
C  RYI=-.37685D+05
C  MZR=-.83915D-07
C  MZI=-.53176D+07
RX=DSQRT(RXR**2+RXI**2)
RY=DSQRT(RYR**2+RYI**2)
RZ=DSQRT(MZR**2+MZI**2)
TX=DATAN2(RXI,RXR)
TY=DATAN2(RYI,RYR)
TZ=DATAN2(MZI,MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32, 2-0.75, 3-2.5,
C 4-5.0, 5-7.0, 6-10.0, 7-17.5, 8-20.5, 9-27.0
    WA=10.0
C ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
    WE=0.4
C HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
    RHO=1.9876
    MASS=(.0044)*(5*RHO*L3)
    IZ=(0.00028)*(5*RHO*L5)
    YAWE=0.0
    X1=0.0
    X2=0.0
    X3=0.0
    X4=0.0
    X5=0.0
    YAW2=0.0
200 CONTINUE
    S=DSQRT(U**2 + V**2)
C INPUT YAW COMMAND
    YAWE=0.0
    IF (TIME.GE.0.0) YAWE=(1.0/57.296)
C ERROR SIGNAL TO DRIVE RUDDER (YAW ACTUAL - YAW COMMAND)
C FOR EQUATIONS OF MOTION.
    YAWE=YAW - YAWE
    D=YAWE
C
C NOMOTO 3RD ORDER PLANT
C
C ERROR SIGNAL TO DRIVE RUDDER (YAW COMMAND - YAW ACTUAL)
C FOR NOMOTO MODEL.
    D2=YAWC-YAW2
    X1=(D2-X2)/TP1
    X3=K*(Z*X1+X2)
    X4=(X3-X5)/TP2
C AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
    XUDOT=(-.0001)*(5*RHO*L3)
XUU = (-0.0003) * (0.5 * RHO * L2)
XU = (-0.0253) * (0.5 * RHO * L2 * S)
XVR = (0.0039) * (0.5 * RHO * L3)
XVV = (-0.0012) * (0.5 * RHO * L2)
XDD = (-0.0005) * (0.5 * RHO * L2 * S**2)

**C LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)**

YV = (-0.00758) * (0.5 * RHO * L2 * S)
YR = (0.0023) * (0.5 * RHO * L3 * S)
YD = (0.00145) * (0.5 * RHO * L2 * S**2)
YVVR = (0.01) * (0.5 * RHO * L3 / S)
YVRR = (-0.008) * (0.5 * RHO * L4 / S)
YVVV = (-0.03) * (0.5 * RHO * L2 / S)
YRRR = (0.003) * (0.5 * RHO * L5 / S)
YDDD = (-0.0005) * (0.5 * RHO * L2 * S**2)
YVDOT = -0.30908D+07
YV = -0.81271D+04
YVDOT = -0.36185D+07
YV = -0.24757D+06
YVDOT = -0.32890D+07
YV = -0.11775D+07
YVDOT = -0.23038D+07
YV = -0.18267D+07
YVDOT = -0.59800D+06
YV = -0.13260D+07

**C MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)**

NV = (-0.00213) * (0.5 * RHO * L3 * S)
NR = (-0.00105) * (0.5 * RHO * L4 * S)
ND = (-0.0007) * (0.5 * RHO * L3 * S**2)
NVVR = (-0.015) * (0.5 * RHO * L4 / S)
NVRR = (-0.008) * (0.5 * RHO * L5 / S)
NVVV = (0.01) * (0.5 * RHO * L3 / S)
NRRR = (-0.006) * (0.5 * RHO * L6 / S)
NDDD = (0.0001) * (0.5 * RHO * L3 * S**2)

**C NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED**

**C FOR DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY**
C SPEED=23 KNOTS, ENCOUNTER ANGLE = 60, ENCOUNTER FREQ = 0.75
C NRDOT = (-0.00027)*(.5*RHO*L5)
C
C sets sea state to zero
FX = 0.
FY = 0.
MZ = 0.
FX = WA*RX*DCOS(WE*TIME+TX)
FY = WA*RY*DCOS(WE*TIME+TY)
MZ = WA*RZ*DCOS(WE*TIME+TZ)
C actual speed
UC
C UC commanded speed
XP = propeller thrust
XP = -XUU*UC**2
C equations of motion
UDOT = ((XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C 1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
VDOT = (YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
1 + YVRR*V*R**2 + YVVV*V**3
2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
RDOT = (NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ )/(IZ-NRDOT)
C when to printout
IF (ICOUNT.EQ.11) GO TO 50
GO TO 300
C CONVERT RADIANS TO DEGREES
50 YAWDEG = YAW*57.296
    RDEG = R*57.296
    RDDEG = RDOT*57.296
    DDEG = D*57.296
    YAWC = YAWC*57.296
    ICOUNT = 1
C TEST IF WANT TO STOP
300 IF (TIME.GE.ETIME) GO TO 400
C INTEGRATION STEP SIZE DELT
    DELT = 1.0
C INTEGRATION
    X2 = X2 + X1*DELT
    X5 = X5 + X4*DELT
    YAW2 = YAW2 + X5*DELT
    U = U + UDOT*DELT
    V = V + VDOT*DELT
    R = R + RDOT*DELT
    YAW = YAW + R*DELT
C CONVERT SHIP TO FIXED COORDINATES ON EARTH
    XDOT = U*DCOS(YAW) - V*DSIN(YAW)
    YDOT = U*DSIN(YAW) + V*DCOS(YAW)
    X = X - XDOT*DELT
    Y = Y + YDOT*DELT
    TIME = TIME + DELT
    ICOUNT = ICOUNT + 1
C COST FUNCTION
    TDIFF = TDIFF + (YAW - YAW2)**2
GO TO 200
400 CONTINUE
C WRITE(6,500) TDIFF,K,Z,TP1,TP2
500 FORMAT(' ',IX,' COST=',F12.7,2X,' K=',F10.7,1 ' Z=',F15.7,' TP1=',F15.7,2X,' TP2=',F15.7)
RETURN
END
APPENDIX B

REGULAR SEASTATE FORMULATION

// REGUGAINS JOB (XXXX,XXXX), 'RESEARCH', CLASS=C
// * MAIN ORG=NPGVM1.XXXXP
// EXEC FORTXCG, PARM.FORT='OPT(2)', IMSL=DP, REGION=1024K
// FORT.SYSIN DD *

C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*), AND XL(*)

DIMENSION XS(3), XU(3), XL(3)
XS(1)=0.9650610
XS(2)=0.4500911
XS(3)=5.6194260

C XS(I) IS THE STARTING GUESS
C XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE

XL(1)=0.1
XU(1)=4.0
XL(2)=0.1
XU(2)=15.0
XL(3)=1.0
XU(3)=25.0

C A DESCRIPTION OF THE FOLLOWING PARAMETERS
C IS DISCUSSED IN BOXPLX
R=9./13.
NTA=1000
NPR=100
NAV=0
NV=3
IP=0

C THE FOLLOWING STATEMENT MUST BE CHANGED TO
C CALL PLANT(X)
C IF ONLY SIMULATION IS WANTED
CALL BOXPLX(NV, NAV, NPR, NTA, R, XS, IP, XU, XL, YMN, IER)
WRITE (6, 25)
25 FORMAT(1X, 'OPTIMAL GAINS',//)
DO 30 I=1, 3
30 WRITE(6, 40)I, XS(I)
40 FORMAT(1X,'X(',I2,'')=',F14.7)
STOP
END

SUBROUTINE PLANT(XX)
C SUBROUTINE PLANT(XX) SIMULATES THE SHIP
COMMON TDIFF
REAL*8 L, L2, L3, L4, L5, L6
REAL*8 X, XDOT, Y, YDOT, U, UDOT, V, VDOT, YAW, R, RDOT
REAL*8 TIME, ETIME, XUDOT, XUX, XVR, XVV, XDD
REAL*8 YV, YR, YD, YVVR, YVRR, YVRR, YYDD, YVDOT
REAL*8 NV, NR, ND, NVVR, NVRR, NVV, NRRR, NDDD, NRD
REAL*8 RHO, IZ, FX, FY, MZ, XP, MASS, DELT, MZI, WA, WE
REAL*8 DYAW, YAWE, YAWC, ISE, ISR, LAMDA, D, RYR, RYI, MZR
REAL*8 K1, T1, T2, D, X2, DX2, S, RX, RY, RZ, TX, TY, TZ, RXR, RXI
DIMENSION XX(3)
C
C CLOSE LOOP ANALYSIS WITH FILTER
C
C INITIAL CONDITIONS FOR INTEGRATION
C SIMULATION END TIME IN SECONDS
ETIME = 600.0
TIME = 0.0
ICOUNT = 1
C INITIALIZE THE COST FUNCTION
ISE = 0.0
ISR = 0.0
TDIFF = 0.0
LAMDA = 8.128
C GAIN COEFFICIENTS TO BE OPTIMIZED
K1 = XX(1)
T1=XX(2)
T2=XX(3)
C WRITE(6,1010) K1,T1,T2
C1010 FORMAT(1X,'K1 = ',F15.7,' T1 = ',F15.7,' T2 = ',F15.7)
C X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
  X=0.0
  Y=0.0
  XDOT=0.0
  YDOT=0.0
C U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
  V=0.0
  UDOT=0.0
  VDOT=0.0
  YAW=0.0
  R=0.0
  RDOT=0.0
C ORDERED SPEED IN FEET/SEC
C 38.81 FT/SEC=23 KNOTS
UC=38.81
C AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
  U=UC
C D = RUDDER ANGLE
  D=0.0
  L=880.5
  L2=L**2
  L3=L*L*L
  L4=L*L3
  L5=L*L4
  L6=L*L5
C SEA DISTURBANCE
C FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C MOMENTS IN Z
  FX=0.
  FY=0.
  MZ=0.
C RXR=-0.91037D+03
C RXI=0.50869D-05
C RYR=-0.20256D-04
C RYI=0.18077D+06
C MZR=-.14310D-08
C MZI=-.16903D+07
C RXR=-0.99047D-04
C RXI=.15994D+06
C RYR=-.64455D+05
C RYI=0.61873D+06
C MZR=.120180+08
C MZI=-.49204D+07
C RXR=-0.32876D+05
C RXI=0.25844D+06
C RYR=-.27053D+06
C RYI=.90191D+06
C MZR=0.11964D+09
C MZI=0.24103D+08
C RXR=-.54639D+05
C RXI=.28236D+06
C RYR=-.28668D+06
C RYI=0.79670D+06
C MZR=0.19925D+09
C MZI=0.77746D+08
RX=DSQRT(RXR*2+RXI**2)
RY=DSQRT(RYR**2+RYI**2)
RZ=DSQRT(MZR**2+MZI**2)
TX=DATAN2(RXI,RXR)
TY=DATAN2(RYI,RYR)
TZ=DATAN2(MZI,MZR)
C SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32, 2-0.75, 3-2.5,
C 4-5.0, 5-7.0, 6-10.0, 7-17.5, 8-20.5, 9-27.0
WA=10.0
C ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,.1.0,.1.5,.2.5
WE=1.5
C HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
RHO=1.9876
MASS=(0.0044)*(.5*RHO*L3)
IZ=(0.00028)*(.5*RHO*L5)
YAWE=0.0
X2=0.0
D:2=0.0
200 CONTINUE
S=DSQRT(U**2+V**2)
C INPUT YAW COMMAND
YAWE=0.0
IF (TIME.GE.0.0) YAWE=0.0
C ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C ( COMPENSATOR FILTER )
YAWE=YAW - YAWE
DX2=(YAWE-X2)/T2
D=K1*(TI*DX2+X2)
C AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C XUDOT IS THE ADDDED MASS TERM WHICH MUST BE CHANGED FOR
C DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
XUDOT=(-.0001)*(.5*RHO*L3)
XU=(-0.0253)*(.5*RHO*L2*S)
XUU=(-0.0003)*(.5*RHO*L2)
XVR=(0.0039)*(.5*RHO*L3)
XVV=(-0.0012)*(.5*RHO*L2)
XDD=(-0.0005)*(.5*RHO*L2*S**2)
C LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C
YV=(-0.00758)*(.5*RHO*L2*S)
77
\[
\begin{align*}
Y_R &= (0.0023) \times (0.5 \cdot \rho \cdot L^3 \cdot S) \\
Y_V &= (0.00145) \times (0.5 \cdot \rho \cdot L^2 \cdot S \times 2) \\
Y_{VV} &= (0.01) \times (0.5 \cdot \rho \cdot L^3 / S) \\
Y_{VR} &= (-0.008) \times (0.5 \cdot \rho \cdot L^4 / S) \\
Y_{V} &= (-0.03) \times (0.5 \cdot \rho \cdot L^2 / S) \\
Y_{RR} &= (0.003) \times (0.5 \cdot \rho \cdot L^5 / S) \\
Y_{DD} &= (-0.0005) \times (0.5 \cdot \rho \cdot L^2 \cdot S \times 2) \\
Y_{VDD} &= (-0.0039) \times (0.5 \cdot \rho \cdot L^3) \\
\end{align*}
\]

C YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
C YVDOT = (-0.0039) \times (0.5 \cdot \rho \cdot L^3)
C SPEED = 23 KNOTS, ENCOUNTER ANGLE = 60°, ENCOUNTER FREQ = 0.75
C
\begin{align*}
Y_{VDOT} &= -0.30908D-07 \\
Y_{V} &= -0.81271D+04 \\
Y_{VDOT} &= -0.36185D+07 \\
Y_{V} &= -0.24757D-06 \\
Y_{VDOT} &= -0.32890D+07 \\
Y_{V} &= -0.11775D-07 \\
Y_{VDOT} &= -0.23038D+07 \\
Y_{V} &= -0.18267D+07 \\
Y_{VDOT} &= -0.59800D+06 \\
Y_{V} &= -0.13260D+07 \\
\end{align*}

C MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)

\begin{align*}
N_V &= (-0.00213) \times (0.5 \cdot \rho \cdot L^3 \cdot S) \\
N_R &= (-0.00105) \times (0.5 \cdot \rho \cdot L^4 \cdot S) \\
N_D &= (-0.0007) \times (0.5 \cdot \rho \cdot L^3 \cdot S \times 2) \\
N_{VV} &= (-0.015) \times (0.5 \cdot \rho \cdot L^4 / S) \\
N_{VR} &= (-0.008) \times (0.5 \cdot \rho \cdot L^5 / S) \\
N_{VVV} &= (0.01) \times (0.5 \cdot \rho \cdot L^3 / S) \\
N_{RR} &= (-0.006) \times (0.5 \cdot \rho \cdot L^6 / S) \\
N_{DDD} &= (0.0001) \times (0.5 \cdot \rho \cdot L^3 \cdot S \times 2) \\
\end{align*}

C NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C FOR DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
C NRDOT = (-0.00027) \times (0.5 \cdot \rho \cdot L^5)
C SPEED=23 KNOTS, ENCOUNTER ANGLE=60, ENCOUNTER FREQ=0.75
C NRDOT=- .26251D-12
C NR= .53637D+09
C NRDOT=- .20125D-12
C NR= .94970D+10
C NRDOT=- .18671D+12
C NR= .46860D+11
C NRDOT=- .14518D-12
C NR= .87538D+11
C NRDOT= .37261D+11
C NR= .69856D+11
C REGULAR WAVE SEA STATE
FX=WA*RX*DCOS (WE*TIME+TX)
FY=WA*RY*DCOS (WE*TIME+TY)
MZ=WA*RZ*DCOS (WE*TIME+TZ)
C U ACTUAL SPEED
C UC COMMANDED SPEED
C XP = PROPELLER THRUST
   XP= -XUU*UC**2
C EQUATIONS OF MOTION
C UDOT= ((XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C 1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
   VDOT= (YV*V + (YR-MASS*U)*R + YD*D + YYVR*V**2*R
   1 + YYRR*V**3 + YYV*V**3
   2 + YYRRR**3 + YDDDD**3 + FY )/(MASS-YVDOT)
   RDOT= (NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V**3
   1 + NVVV*V**3 + NRRR*R**3 + NDDDD*D**3 + MZ)/(IZ-NRDOT)
C WHEN TO PRINTOUT
   IF (ICOUNT.EQ.11) GO TO 50
   GO TO 300
C CONVERT RADIANS TO DEGREES
50 YAWDEG= YAW*57.296
   RDEG=R*57.296
   RDDEG=RDOT*57.296
   DDEG=D*57.296
79
```
YAWC=YAWC*57.29
ICOUNT=1
C TEST IF WANT TO STOP
300 IF (TIME.GE.ETIME) GO TO 400
C INTEGRATION STEP SIZE DELT
DELT=1.0
C INTEGRATION
U=U+UDOT*DELT
V=V+VDOT*DELT
R=R+RDOT*DELT
YAW=YAW+R*DELT
X2=X2+DX2*DELT
C CONVERT SHIP TO FIXED COORDINATES ON EARTH
C XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C X=X+XDOT*DELT
C Y=Y+YDOT*DELT
TIME=TIME+DELT
ICOUNT=ICOUNT+1
ISE=ISE + LAMDA*YAW**2
ISR=ISR + D**2
GO TO 200
C J=TDIFF= COST FUNCTION
400 TDIFF=ISE+ISR
WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2
500 FORMAT(' ',1XISE=','ISR=','TOTAL=','
,1F15.7,2X,'K1=','F15.7,2X,'T1=','F15.7,2X,'T2=','F15.7)
RETURN
END
The function minimization subroutine BOXPLX follows.
Then the following two cards must be placed.
//GO.SYSIN DD *
/*
```
APPENDIX C
SYSTEM'S RESPONSE FOR REGULAR SEAS

//REGURESP JOB (XXXX,XXXX), 'RESEARCH', CLASS=A
//*MAIN ORG=NPGVM1.XXXP
// EXEC FORTXCG, PARM.FORT='OPT(2)', IMSL=DP, REGION=1024K
//FORT.SYSIN DD *
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*), AND XL(*)

COMMON J
DIMENSION X(3)
X(1) = 1.5420017
X(2) = 141.2350922
X(3) = 23.8943634

C CALL PLANT(X)
C IF ONLY SIMULATION IS WANTED
CALL PLANT(X)
WRITE (6,25)
25 FORMAT(1X, 'OPTIMAL GAINS', /)
DO 30 I = 1, 3
30 WRITE (6,40) I, X(I)
40 FORMAT (1X, 'X(', I2, ')=', F14.7)
WRITE (6,50) J
50 FORMAT (1X, 'J = ', E15.10)
STOP
END

SUBROUTINE PLANT(XX)
C SUBROUTINE PLANT(XX) SIMULATES THE SHIP
COMMON TDIFF
REAL*8 L, L2, L3, L4, L5, L6
REAL*8 X, XDOT, Y, YDOT, U, UDOT, V, VDOT, YAW, R, RDOT
REAL*8 TIME, ETIME, XUDOT, XUU, XV, XVV, XDD
REAL*8 YV, YR, YD, YYVR, YYRR, YVVV, YYRRR, YDDD, YVDOT

81
REAL*8 NV, NR, ND, NVVR, NVRR, NVVV, NRRR, NDDD, NRDOT
REAL*8 RHO, IZ, FX, FY, MZ, XP, MASS, DELT, MZI, WA, WE
REAL*8 DYawe, Yawe, YAWE, ISE, ISR, LAMDA, D, RYR, RYI, MZR
REAL*8 K1, T1, T2, D, X2, DX2, S, RX, RY, RZ, TX, TY, TZ, RXR, RXI
DIMENSION XX(3)

C
C CLOSE LOOP ANALYSIS WITH FILTER
C
C INITIAL CONDITIONS FOR INTEGRATION
C SIMULATION END TIME IN SECONDS
ETIME = 600.
TIME = 0.0
ICOUNT = 1
C INITIALIZE THE COST FUNCTION
ISE = 0.0
ISR = 0.0
TDIFF = 0.0
LAMDA = 8.128
C GAIN COEFFICIENTS TO BE OPTIMIZED
K1 = XX(1)
T1 = XX(2)
T2 = XX(3)
C WRITE(6,1010) K1, T1, T2
C1010 FORMAT(1X,'K1 = ',F15.7, ' T1 = ',F15.7, ' T2 = ',F15.7)
C X, XDOT, Y, YDOT ARE FIX COORDINATES ON EARTH
X = 0.0
Y = 0.0
XDOT = 0.0
YDOT = 0.0
C U, UDOT, V, VDOT ARE FIX COORDINATES ON SHIP
V = 0.0
UDOT = 0.0
VDOT = 0.0
YAW = 0.0
R = 0.0
RDOT=0.0

C ORDERED SPEED IN FEET SEC

C 38.82 FT/SEC = 23 KNOTS

UC=38.82

C AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)

U=UC

C D = RUDDER ANGLE

D=0.0

L=880.5

L2=L**2

L3=L*L

L4=L*L3

L5=L*L4

L6=L*L5

C SEA DISTURBANCE

C FORCES IN X,Y DIRECTION COMPUTED IN FORCES

C MOMENTS IN Z

FX=0.
FY=0.
MZ=0.

RXR=-.91037D+03
RXI=0.50896D+05
RYR=-.20256D+04
RYI=.18077D+06
MZR=-.14310D+08
MZI=-.16903D+07

RX=DSQRT(RXR**2+RXI**2)
RY=DSQRT(RYR**2+RYI**2)
RZ=DSQRT(MZR**2+MZI**2)

TX=DATAN2(RXI,RXR)
TY=DATAN2(RYI,RYR)
TZ=DATAN2(MZI,MZR)

C SIGNIFICANT WAVE HEIGHT; SEA STATE 1-0.32,2-0.75,3-2.5,
C 4-5.0,5-7.5,6-10.0,7-17.5,8-20.5,9-27.0

WA=27.0

83
ENCOUNTER FREQUENCY .1, .2, .3, .4, .5, .6, .75, 1.0, 1.5, 2.5
WE=0.2

HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
RHO=1.9876
MASS= (.0044)*(.5*RHO*L3)
IZ=(0.00028)*(.5*RHO*L5)
YAVE=0.0
X2=0.0
DX2=0.0

200 CONTINUE
S=DSQRT(U**2+V**2)

INPUT YAW COMMAND
YAWC=0.0

IF (TIME.GE.0.0) YAWC=0.0

ERROR SIGNAL TO DRIVE RUDDER (YAW ACTUAL - YAW ORDERED)

COMPENSATOR FILTER
YAWE=YAW - YAWC
DX2=(YAWE-X2)/T2
D=K1*(T1*DX2+X2)

AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)

XUDOT=(-.0001)*(.5*RHO*L3)
XU=(-0.0253)*(.5*RHO*L2*S)
XUU=(-0.0003)*(.5*RHO*L2)
XVR=(0.0039)*(.5*RHO*L3)
XVV=(-0.0012)*(.5*RHO*L2)
XDD=(-0.0005)*(.5*RHO*L2*S**2)

LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)

YV=(-0.00758)*(.5*RHO*L2*S)
YR=(0.0023)*(.5*RHO*L3*S)
YD=(0.00145)*(.5*RHO*L2*S**2)
YVVR=(0.01)*(.5*RHO*L3/S)
YVRR=(-0.008)*(.5*RHO*L4/S)
YVVV = (-0.03) * (0.5 * RHO * L2 / S)
YRRR = (0.003) * (0.5 * RHO * L5 / S)
YDDD = (-0.0005) * (0.5 * RHO * L2 * S ** 2)

C YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
C YVDOT = (-0.0039) * (0.5 * RHO * L3)
C SPEED = 23 KNOTS, ENCOUNTER ANGLE = 60, ENCOUNTER FREQ = 0.75
C YVDOT = -0.30908 -07
C YV = -0.81271D-04

C MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
NV = (-0.00213) * (0.5 * RHO * L3 * S)
C NR = (-0.00105) * (0.5 * RHO * L4 * S)
ND = (-0.0007) * (0.5 * RHO * L3 * S ** 2)
NVVR = (-0.015) * (0.5 * RHO * L4 / S)
NVRR = (-0.008) * (0.5 * RHO * L5 / S)
NVVV = (0.01) * (0.5 * RHO * L3 / S)
NRRR = (-0.006) * (0.5 * RHO * L6 / S)
NDDD = (0.0001) * (0.5 * RHO * L3 * S ** 2)

C NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C FOR DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
C NRDOT = (-0.00027) * (0.5 * RHO * L5)
C SPEED = 32 KNOTS, ENCOUNTER ANGLE = 60, ENCOUNTER FREQ = 0.75
C NRDOT = -0.26251D+12
C NR = -0.53637D+09

C REGULAR WAVE SEA STATE
FX = WA * RX * DCOS (WE * TIME - TX)
FY = WA * RY * DCOS (WE * TIME + TY)
MZ = WA * RZ * DCOS (WE * TIME + TZ)

C U ACTUAL SPEED
C UC COMMENDED SPEED
C XP = PROPELLER THRUST
XP = -XUU * UC ** 2

C EQUATIONS OF MOTION
C UDOT = \((XVR - MASS)*V^*R + XUU*U^*2 - XVV*V^*2\)
C 1 + XDD*D*D - FX - XP )/(MASS-XUDOT)
VDOT = \((YV^*V - (YR - MASS)*V^*R - YD^*D - YVVR*V^*2*R^*2\)
1 + YVRR*V^*R^*2 - YYVV*V^*3
2 + YRRR*R^*3 + YDDD*D^*3 - FY )/(MASS-YVDOT)
RDOT = \((NV^*V - NR*R^* + ND*D - NVVR*V^*2*R^* + NVRR*V^*R^*2\)
1 + NVVV*V^*3 + NRRR*R^*3 + NDDD*D^*3 + MZ)/(IZ-NRDOT)
C WHEN TO PRINTOUT
  IF (ICOUNT.EQ. 2) GO TO 50
  GO TO 300
C CONVERT RADIANS TO DEGREES
50 YAWDEG = YAW*57.296
RDEG = R*57.296
RDDEG = RDOT*57.296
DDEG = D*57.296
YAWC = YAWC*57.296
WRITE (6,101) TIME,YAWDEG
101 FORMAT(1X,F12.8,1X,F12.8)
ICOUNT = 1
C TEST IF WANT TO STOP
300 IF (TIME.GE.ETIME) GO TO 400
C INTEGRATION STEP SIZE DELT
DELT = 1.0
C INTEGRATION
U = U + UDOT*DELT
V = V + VDOT*DELT
R = R + RDOT*DELT
YAW = YAW + R*DELT
X2 = X2 + DX2*DELT
C CONVERT SHIP TO FIXED COORDINATES ON EARTH
C XDOT = U*DCOS(YAW) - V*DSIN(YAW)
C YDOT = U*DSIN(YAW) + V*DCOS(YAW)
C X = X + XDOT*DELT
C Y = Y + YDOT*DELT
TIME = TIME + DELT

86
ICOUNT = ICOUNT - 1
ISE = ISE - LAMDA * YAKE * 2
ISR = ISR + D**2
GO TO 200

C J = TDIFF = COST FUNCTION

400 TDIFF = ISE - ISR
WRITE (6, 500) ISE, ISR, TDIFF, K1, T1, T2
500 FORMAT (' ', 1X, 'ISE=', F15.7, ' ISR=', F15.7, ' TOTAL=',
          1 F15.7, 2X, 'K1=', F15.7, 2X, 'T1=', F15.7, 2X, 'T2=', F15.7)
RETURN
END

//GO.SYSIN DD *
APPENDIX D
IRREGULAR SEASTATE FORMULATION

//IRREGAINS JOB (XXXX,XXXX), 'RESEARCH', CLASS=C
//*MAIN ORG=NPGVM1.XXXX
// EXEC FORTXCG, PARM.FORT='OPT(2)', IMSL=DP, REGION=1024K
// FORT.SYSIN DD *

C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*), AND XL(*)

DIMENSION XS(3), XU(3), XL(3)
XS(1)=0.655751
XS(2)=90.5483
XS(3)=36.74847

C XS(I) IS THE STARTING GUESS
C XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
XL(1)=0.01
XU(1)=2.0
XL(2)=20.0
XU(2)=180.0
XL(3)=5.0
XU(3)=180.0

C A DESCRIPTION OF THE FOLLOWING PARAMETERS
C IS DISCUSSED IN BOXPLX
R=9./13.
NTA=1000
NPR=100
NAV=0
NV=3
IP=0

C THE FOLLOWING STATEMENT MUST BE CHANGED TO
C CALL PLANT(X)
C IF ONLY SIMULATION IS WANTED
CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
WRITE (6,25)
25 FORMAT(1X,'OPTIMAL GAINS',/)
DO 30 I=1,3
30 WRITE(6,40)I,XS(I)
40 FORMAT(1X,'X(',I2,')=',F14.7)
STOP
END
SUBROUTINE PLANT(XX)
C SUBROUTINE PLANT(XX) SIMULATES THE SHIP
COMMON TDIFF
REAL*8 L,L2,L3,L4,L5,L6
REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XV,V,XDD
REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YRDD,YVDOT
REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NRDD,NRDDT
REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
REAL,8 DYAW,E,YAWE,YAWC,ISE,ISR,LAMDA,D
DIMENSION XX(3)

C CLOSE LOOP ANALYSIS WITH FILTER
C
C INITIAL CONDITIONS FOR INTEGRATION
C SIMULATION END TIME IN SECONDS
ETIME=600.
TIME=0.0
ICOUNT=1
C INITIALIZE THE COST FUNCTION
ISE=0.0
ISR=0.0
TDIFF=0.0
LAMDA=8.128
C GAIN COEFFICIENTS TO BE OPTIMIZED
K1=XX(1)
\text{T1}=\text{XX}(2) \\
\text{T2}=\text{XX}(3) \\
\text{WRITE}(6,1010) \text{KL,T1,T2} \\
\text{X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH} \\
\text{X}=0.0 \\
\text{Y}=0.0 \\
\text{XDOT}=0.0 \\
\text{YDOT}=0.0 \\
\text{U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP} \\
\text{V}=0.0 \\
\text{UDOT}=0.0 \\
\text{VDOT}=0.0 \\
\text{YAW}=0.0 \\
\text{R}=0.0 \\
\text{RDOT}=0.0 \\
\text{ORDERED SPEED IN FEET/SEC} \\
\text{38.82 FT/SEC}=23 \text{ KNOTS} \\
\text{UC}=38.82 \\
\text{AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)} \\
\text{U}=\text{UC} \\
\text{D = RUDDER ANGLE} \\
\text{D}=0.0 \\
\text{L}=880.5 \\
\text{L2}=L^2 \\
\text{L3}=L^3 \\
\text{L4}=L^4 \\
\text{L5}=L^5 \\
\text{L6}=L^6 \\
\text{SEA DISTURBANCE} \\
\text{FORCES IN X,Y DIRECTION COMPUTED IN FORCES} \\
\text{MOMENTS IN Z} \\
\text{FX}=0.0 \\
\text{FY}=0.0 \\
\text{MZ}=0.0 \\
\text{ISEA IS A SWITCH ; ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)}
ISEA=1
C HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS
RHO=1.9876
MASS=(.0044)*(.5*RHO*L3)
IZ=(.00028)*(.5*RHO*L5)
YAWE=0.0
X2=0.0
DX2=0.0
200 CONTINUE
S=DSQRT(U**2+V**2)
C INPUT YAW COMMAND
YAWC=0.0
IF (TIME.GE.0.0) YAWC=0.0
C ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C ( CONTROLLER FILTER )
YAWE=YAW - YAWC
DX2=(YAWE-X2)/T2
D=K1*(T1*DX2+X2)
C AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
XUDOT=(-.0001)*(.5*RHO*L3)
XU=(-.0253)*(.5*RHO*L2*S)
XUU=(-.0003)*(.5*RHO*L2)
XVR=(.0039)*(.5*RHO*L3)
XV=(-.0012)*(.5*RHO*L2)
XDD=(-.0005)*(.5*RHO*L2*S**2)
C LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
YV=(-.00758)*(.5*RHO*L2*S)
YR=(.0023)*(.5*RHO*L3*S)
YD=(.00145)*(.5*RHO*L2*S**2)
YVVR=(.01)*(.5*RHO*L3/S)
YVRR=(-.008)*(.5*RHO*L4/S)
YVVV=(-.03)*(.5*RHO*L2/S)
YRRR=(0.003)*(0.5*RHO*L5/S)
YDDD=(-0.0005)*(0.5*RHO*L2*S**2)
C YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
C DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
C YVDOT=(-0.0039)*(0.5*RHO*L3)
C SPEED=23 KNOTS, ENCOUNTER FREQUENCY =0.75
YVDOT=-2304300.0
C MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
   NV=(-0.00213)*(0.5*RHO*L3*S)
   NR=(-0.00105)*(0.5*RHO*L4*S)
   ND=(-0.0007)*(0.5*RHO*L3*S**2)
   NVVR=(-0.015)*(0.5*RHO*L4/S)
   NVRR=(-0.008)*(0.5*RHO*L5/S)
   NVVV=(0.01)*(0.5*RHO*L3/S)
   NRRR=(-0.006)*(0.5*RHO*L6/S)
   NDDD=(0.0001)*(0.5*RHO*L3*S**2)
C NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C FOR DIFFERENT ENCOUNTER ANGLE, SPEED, ENCOUNTER FREQUENCY
C
C NRDOT=(-0.00027)*(0.5*RHO*L5)
C SPEED=23 KNOTS, ENCOUNTER FREQUENCY =0.75
NRDOT=-1.4518E+11
C SETS SEA STATE TO ZERO
   IF (ISEA.EQ.1) GO TO 30
   FX=0.
   FY=0.
   MZ=0.
   GO TO 35
C UNIT 12 HAS THE SEA STATE DATA NAMED CH
C IT MUST BE SYNCHRONIZED BY TIME
30 READ (12) CH
   FX=CH(3)
   FY=CH(4)
   MZ=CH(8)
CONTINUE
C U ACTUAL SPEED
C UC COMMANDED SPEED
C XP = PROPELLER THRUST
   XP=-XUU*UC**2
C EQUATIONS OF MOTION
C UDOT=( (XVR + MASS)*V*R + XUU*U**2 - XVV*V**2
   1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
   VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
   1 + YVRR*V*R**2 + YVVV*V**3
   2 + YRRR*R**3 + YDDD*D**3 + FY )/(MASS-YVDOT)
   RDOT=(NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V**R**2
   1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ-NRDOT).
C WHEN TO PRINTOUT
   IF (ICOUNT.EQ.11) GO TO 50
   GO TO 300
C CONVERT RADIANS TO DEGREES
50  YAWDEG= YAW*57.296
    RDEG=R*57.296
    RDDEG=RDOT*57.296
    DDEG=D*57.296
    YAWC=YAWC*57.296
   ICOUNT=1
C TEST IF WANT TO STOP
300  IF (TIME.GE.ETIME) GO TO 400
C INTEGRATION STEP SIZE DELT
   DELT=1.0
C INTEGRATION
   U=U+UDOT*DELT
   V=V+VDOT*DELT
   R=R+RDOT*DELT
   YAW=YAW+R*DELT
   X2=X2+DX2*DELT
C CONVERT SHIP TO FIXED COORDINATES ON EARTH
C XDOT=U*DCOS(YAW)-V*D(*YAW)
C YDOT=U*DSIN(YAW)-V*DCOS(YAW)
C X=X+XDOT*DELT
C Y=Y+YDOT*DELT
TIME=TIME-DELT
ICOUNT=ICOUNT-1
ISE=ISE + LAMDA*YAVE**2
ISR=ISR + D**2
GO TO 200
C J=TDIFF= COST FUNCTION
400 TDIFF=ISE+ISR
   WRITE(6,500) TDIFF,K1,T1,T2
500 FORMAT( ' ',lX,'TOTAL =',F15.7,' K1 =',F15.7,
   1 ' T1 =',F15.7,2X,'T2=',F15.7)
REWIND 12
RETURN
END
The function minimization subroutine BOXPLX follows. Then the following three cards must be placed.
//GO.SYSIN DD *
/*
/ GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A241
APPENDIX E
SYSTEM'S RESPONSE FOR IRREGULAR SEAS

//IRRERESP JOB (XXXX,XXXX), 'RESEARCH', CLASS=B
//*MAIN ORG=NPGVM1.XXXXP
// EXEC FRTXCLGP, IMSL=DP, REGION=1024K
//FORT.SYSIN DD *
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED
DIMENSION XX(3)
C OPTIMAL GAINS FOR CONTROLLER
   XX(1)= .9192610
   XX(2)=18.5788116
   XX(3)=9.77668
C THE SUBROUTINE PLANT SIMULATES THE SL-7 CONTAINERSHIP
CALL PLANT(XX)
WRITE(6,25)
25 FORMAT(1X,'OPTIMAL GAINS',/) DO 30 I=1,3
30 WRITE(6,40)I,XX(I)
40 FORMAT(1X,'XX(',I2,')=',F14.7) STOP END
C
C SUBROUTINE PLANT(XX) SIMULATES THE SHIP
SUBROUTINE PLANT(XX)
COMMON TDIFF
REAL**8 L,L2,L3,L4,L5,L6
REAL**8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
REAL**8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
REAL**8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YYDD,YVDOT
REAL**8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
REAL**8 RHO,I2,FX,FY,MZ,XP,MASS,DELT
REAL*8 DYAWE,YAWE,YAWC,ISE,ISR,LAMDA,D
REAL*8 K1,T1,T2,D,X2,DX2,S,CH(II),DX3,X3,X4
DIMENSION XX(3)

C
C CLOSE LOOP ANALYSIS WITH FILTER
C
INITIAL CONDITIONS FOR INTEGRATION
C SIMULATION END TIME IN SECONDS
ETIME=600.
TIME=0.0
ICOUNT=1
C INITIALIZE THE COST FUNCTION
ISE=0.0
ISR=0.0
TDIFF=0.0
LAMDA=4.2
C GAIN COEFFICIENTS
K1=XX(1)
T1=XX(2)
T2=XX(3)
C X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
X=0.0
Y=0.0
XDOT=0.0
YDOT=0.0
C U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
V=0.0
UDOT=0.0
VDOT=0.0
YAW=0.0
R=0.0
RDOT=0.0
YAW=0.0
C ORDERED SPEED IN FEET/SEC
C 38.81 FT/SEC=23 KNOTS
UC=38.81

C AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)

U=UC

C D = RUDDER ANGLE

D=0.0

L=880.5

L2=L**2

L3=L*L*L

L4=L*L3

L5=L*L4

L6=L*L5

C SEA DISTURBANCE

C FORCES IN X,Y DIRECTION.COMPUTED IN FORCES

C MOMENTS IN Z

FX=0.

FY=0.

MZ=0.

C ISEA IS A SWITCH; ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)

ISEA=1

C HYDRODYNAMIC COEFFICIENTS ARE INSERTED AS PARAMETERS

RHO=1.9876

MASS=(.0044)*(RHO*L3)

IZ=(0.00028)*(RHO*L5)

YAWE=0.0

X2=0.0

DX2=0.0

X3=0.0

DX3=0.0

X4=0.0

200 CONTINUE

S=DSQRT(U**2 + V**2)

C INPUT YAW COMMAND

YAWC=0.0

IF (TIME.GE.0.0) YAWC=0.0

C ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)

97
C ( COMPENSATOR FILTER )

\[ \text{YAWE} = \text{YAW} - \text{YAWC} \]
\[ \text{DX2} = \frac{\text{YAWE} - \text{X2}}{\text{T2}} \]
\[ \text{X4} = k_1 \times (T_1 \times \text{DX2} + \text{X2}) \]
\[ \text{DX3} = \frac{\text{X4} - \text{X3}}{\text{T4}} \]
\[ \text{D} = \frac{\text{T3} \times \text{DX3} + \text{X3}}{} \]

C AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)

C

C XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
DIFFERENT ENCOUNTER ANGLE AND SPEED.

C

\[ \text{XUDOT} = (-0.0001) \times (0.5 \times \text{RHO} \times \text{L3}) \]
\[ \text{XUU} = (-0.0003) \times (0.5 \times \text{RHO} \times \text{L2}) \]
\[ \text{XVR} = (0.0039) \times (0.5 \times \text{RHO} \times \text{L3}) \]
\[ \text{XVV} = (-0.0012) \times (0.5 \times \text{RHO} \times \text{L2}) \]
\[ \text{XDD} = (-0.0005) \times (0.5 \times \text{RHO} \times \text{L2} \times \text{S} \times \text{S}) \]

C LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)

C

\[ \text{YV} = (-0.00758) \times (0.5 \times \text{RHO} \times \text{L2} \times \text{S}) \]
\[ \text{YR} = (0.0023) \times (0.5 \times \text{RHO} \times \text{L3} \times \text{S}) \]
\[ \text{YD} = (0.00145) \times (0.5 \times \text{RHO} \times \text{L2} \times \text{S} \times \text{S}) \]
\[ \text{YVVR} = (0.008) \times (0.5 \times \text{RHO} \times \text{L4} \times \text{S}) \]
\[ \text{YVRR} = (-0.008) \times (0.5 \times \text{RHO} \times \text{L5} \times \text{S}) \]
\[ \text{YVVV} = (-0.03) \times (0.5 \times \text{RHO} \times \text{L2} \times \text{S}) \]
\[ \text{YRRR} = (0.003) \times (0.5 \times \text{RHO} \times \text{L5} \times \text{S}) \]
\[ \text{YDDD} = (-0.0005) \times (0.5 \times \text{RHO} \times \text{L2} \times \text{S} \times \text{S}) \]

C YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED FOR
DIFFERENT ENCOUNTER ANGLE AND SPEED.

C

C

\[ \text{YVDOT} = (-0.0039) \times (0.5 \times \text{RHO} \times \text{L3}) \]
\[ \text{YVDOT} = -3654800.00 \]

C MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)

C

\[ \text{NV} = (-0.00213) \times (0.5 \times \text{RHO} \times \text{L3} \times \text{S}) \]
\[ \text{NR} = (-0.00105) \times (0.5 \times \text{RHO} \times \text{L4} \times \text{S}) \]
\[ \text{ND} = (-0.0007) \times (0.5 \times \text{RHO} \times \text{L3} \times \text{S} \times \text{S} \times \text{S}) \]
\[ \text{NVVR} = (-0.015) \times (0.5 \times \text{RHO} \times \text{L4} \times \text{S}) \]
\[ \text{NVRR} = (-0.008) \times (0.5 \times \text{RHO} \times \text{L5} \times \text{S}) \]
NVVV = (0.01) * (0.5/PR * L3/S)
NRRR = (-0.006) * (0.5/PR * L6/S)
NDDD = (0.0001) * (0.5/PR * L3*S)**2

C NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.

C NRDOT = (-0.00027) * (0.5/PR * L5)
NRDOT = -2.1815E-11

C SETS SEA STATE TO ZERO
IF (ISEA.EQ.1) GO TO 30
FX = 0.
FY = 0.
MZ = 0.
GO TO 35

C UNIT 12 HAS THE SEA STATE DATA NAMED CH
C IT MUST BE SYNCHRONIZED BY TIME

30 READ (12) CH
FX = CH(3)
FY = CH(4)
MZ = CH(8)

35 CONTINUE

C U ACTUAL SPEED
C UC COMMANDED SPEED
C XP = PROPELLER THRUST
XP = -XUU*UC**2

C EQUATIONS OF MOTION
C UDOT = ((XVR + MASS)*V*R + XUU*U**2 + XV*V**2
C 1 + XDD*D*D + FX + XP )/(MASS - XUDOT)
VDOT = (YV*V + (YR-MASS*S)*R + YD*D + YVVR*V**2*R
1 + YVRR*R**2 + YVVV*V**3
1 + YRRR*R**3 + YDDD*D**3 + FY)/(MASS - YVDOT)
RDOT = (NV*V + NR*R + ND*D + NVVR*V**2*R + NVRR*V*R**2
1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3 + MZ)/(IZ - NRDOT)

C WHEN TO PRINTOUT
IF (ICOUNT.EQ.2) GO TO 50

99
GO TO 300
C CONVERT RADIANS TO DEGREES
50 YAWDEG= YAW*57.296
    RDEG=R*57.296
    RDDEG=RDOT*57.296
    DDEG=D*57.296
    YAWC=YAWC*57.296
WRITE (6,100) TIME,YAWDEG
100 FORMAT(1X,F12.8,1X,F12.8)
    ICOUNT=1
C TEST IF WANT TO STOP
300 IF (TIME.GE.ETIME) GO TO 400
C INTEGRATION STEP SIZE DELT
    DELT=1.
C INTEGRATION
    U=U+UDOT*DELT
    V=V+VDOT*DELT
    R=R+RDOT*DELT
    YAW=YAW+R*DELT
    X2=X2+DX2*DELT
    X3=X3+DX3*DELT
C CONVERT SHIP TO FIXED COORDINATES ON EARTH
    XDOT=U*DCOS(YAW)-V*DSIN(YAW)
    YDOT=U*DSIN(YAW)+V*DCOS(YAW)
    X=X*XDOT*DELT
    Y=Y*YDOT*DELT
    TIME=TIME*DELT
    ICOUNT=ICOUNT+1
    ISE=ISE + LAMDA*YAW**2
    ISR=ISR + D**2
GO TO 200
C J=TDIFF= COST FUNCTION
400 TDIFF=ISE*ISR
    WRITE(6,500) ISE,ISR,TDIFF
500 FORMAT(1,T5,'ISE= ',F15.7,' ISR= ',F15.7,'  TDIFF= ',F15.7,')
1 ' TOTAL=',F15.7)
STOP
END
//GO.SYSIN DD *
/
//GO.FT12FO01 DD DISP=SHR,DSN=MSS.S2160.A211
APPENDIX F
MODIFIED MINIMIZATION SUBROUTINE

SUBROUTINE BOXPLX (NV, NAV, NPR, NTZ, RZ, XS, IP, BU, BL, YMN, IER)
C
DIMENSION V(50,50), FUN(50), SUM(25), CEN(25), XS(NV),
   1BU(NV), BL(NV)
C
   KV = 5
   EP = 1.E-4
   NTA = 2000
   IF (NTZ.GT.0) NTA = NTZ
   R = RZ
   IF (R.LE.0..OR.R.GE.1.) R=1./3.
   NVT = NV*NAV
C
   TOTAL VARS, EXPLICIT PLUS IMPLICIT
   NT = 0
   CURRENT TRIAL NO.
   NPT = 0
   CURRENT NO. OF PERMISSIBLE TRIALS
   NTFS = 0
C
   CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED
C
   CHECK FEASIBILITY OF START POINT
C
   DO 4 I=1,NV
   VT = XS(I)
   IF (BL(I).LE.VT) GO TO 1
   II = -I
   VT = BL(I)
   GO TO 2
1 IF (BU(I).GE.VT) GO TO 3
C
        102
II = I
VT = BU(I)

2 IF (NPR.GT.0) WRITE (6,49) II
3 V(I,1) = VT
   CEN(I) = VT
   IF (IP.EQ.1) GO TO 4
   BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))
   BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))
4 SUM(I) = VT

C
C
NCE = 1
C NUMBER OF CONSTRAINT EVALUATIONS
I = 1
IF (KE(V(1,1)).EQ.0) GO TO 5
IF (NPR.LE.0) GO TO 12
WRITE (6,50)
GO TO 12
5 NFE = 1
C
C NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.
   K = (2*NV)/3
C
C NUMBER OF DISPLACEMENTS ALLOWED.
   NLIM = 5*NV+10
C
C NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED FE TO
C TO TERMINATE
   NCT = NLIM*NV
   ALPHA = 1.3
   FK = K
   FKM = FK-1.
   BETA = ALPHA+1.
C
C INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.
IQR = R*1.E7
IF (MOD(IQR,2).EQ.0) IQR=IQR+101

C
C SET UP INITIAL VERTICES
FUN(1) = FE(V(1,1))
YMN = FUN(1)

6 FI = 1.
FUNOLD = FUN(1)
C
DO 15 I=2,K
FI = FI+1.
LIMT = 0
7 LIMT = LIMT+1
C
C END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.
IF (LIMT.GE.NLIM) GO TO 11
C
DO 8 J=1,NV
C
C RANDOM NUMBER GENERATOR (RANDU)
IQR = IQR*65539
IF (IQR.LT.0) IQR = IQR+2147483647+1
RQX = IQR
RQX = RQX*.4656613E-9
V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)
8 CONTINUE
C
DO 10 L=1,NLIM
NCE = NCE+1
IF (KE(V(1,I)).EQ.0) GO TO 13
C
DO 9 J=1,NV
VT = .5*(V(J,I)-CEN(J))
IF (IP.EQ.1) VT = AINT(VT+.5)
9 CONTINUE
104
V(J, I) = VT
9 CONTINUE
C
10 CONTINUE
C
11 IF (NPR.LE.0) GO TO 12
   WRITE (6,51) I
   CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
12 IER = -1
   GO TO 48
C
13 DO 14 J=1,NV
   SUM(J) = SUM(J)+V(J,I)
14 CEN(J) = SUM(J)/FI
C
C TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
   NCE = NCE+1
   IF (KE(CEN).EQ.0) GO TO 60
   SUM(J) = SUM(J) -V(J,I)
   GO TO 7
60 NFE = NFE+1
   FUN(I) = FE(V(1,I))
15 CONTINUE
C
C END OF LOOP SETTING OF INITIAL COMPLEX.
   IF (NPR.LE.0) GO TO 17
   CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
C FIND THE WORST VERTEX, THE 'J' TH.
J = 1
C
DO 16 I=2,K
   IF (FUN(J).GE.FUN(I)) GO TO 16
   J = I
16 CONTINUE
BASIC LOOP. ELIMINATE EACH WORST VERTEX IN TURN.
IT MUST BECOME NO LONGER WORST, NOT MERELY IMPROVED.
FIND NEXT-TO-WORST VERTEX, THE 'JN' TH ONE.

17 JN = 1
   IF (J.EQ.1) JN = 2

DO 18 I=1,K
   IF (I.EQ.J) GO TO 18
   IF (FUN(JN).GE.FUN(I)) GO TO 18
   JN = I
18 CONTINUE

LIMT = NUMBER OF MOVES DURING THIS TRIAL TOWARD THE CENTROID DUE TO FUNCTION VALUE.
LIMT = 1

COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.

DO 19 I=1,NV
   VT = V(I,J)
   SUM(I) = SUM(I)-VT
   CEN(I) = SUM(I)/FKM
   VT = BETA*CEN(I)-ALPHA*VT
   IF (IP.EQ.1) VT = AINT(VT+.5)

INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
19 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))

NT = NT+1

CHECK FOR IMPLICIT CONSTRAINT VIOLATION.

20 DO 25 N=1,NLIM
   NCE = NCE+1

106
IF (KE(V(I,J)).EQ.0) GO TO 26

C EVERY KV TH TIME, OVER-REFLECT THE OFFENDING VERTEX
C THROUGH THE BEST VERTEX.
IF (MOD(N,KV).NE.0) GO TO 22
CALL FBV (K,FUN,M)

DO 21 I=1,NV
VT = BETA*V(I,M)-ALPHA*V(I,J)
IF (IP.EQ.1) VT = AINT(VT-.5)
21 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))

GO TO 24

C CONSTRAINT VIOLATION: MOVF NEW POINT TOWARD CENTROID.

DO 23 I=1,NV
VT = .5*(CEN(I)+V(I,J))
IF (IP.EQ.1) VT = AINT(VT-.5)
V(I,J) = VT
23 CONTINUE

NT = NT+1
25 CONTINUE

IER = 1

C CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
C OR BY OVER-REFLECTING THRU THE BEST VERTEX.
IF (NPR.LE.0) GO TO 42
WRITE (6,52) NT,J
CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V.K,FUN,CEN,J)
GO TO 42

C FEASIBLE VERTEX FOUND, EVALUATE THE OBJECTIVE FUNCTION.
26 NFE = NFE-1  
FUNTRY = F(E(V(1,J)))

C  
C TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.  
AFO = ABS(FUNTRY-FUNOLD)  
AMX = AMAX1(ABS(FUN,J)-FUNOLD),EP)

C  
C ACTIVATE THE FOLLOWING TWO STATEMENTS  
C FOR DIAGNOSTIC PURPOSES ONLY.
C  
WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),FUN(JN),  
C  
1NTFS,N  
C  
99 FORMAT (1X,13,6E15.7,215)  
IF (AFO.GT.AMX) GO TO 27  
NTFS = NTFS+1  
IF (NTFS.LT.NCT) GO TO 28  
IER = 0  
IF (NPR.LE.0) GO TO 42  
WRITE (6,53) K  
CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)  
GO TO 42
27 NTFS = 0  
C  
C IS THE NEW VERTEX NO LONGER WORST?  
28 IF (FUNTRY.LT.FUN(JN)) GO TO 34  
C  
C TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.  
C EVERY 'KV' TH TIME, OVER-REFLECT THE OFFENDING VERTEX  
C THROUGH THE BEST VERTEX.  
LIMT = LIMT+1  
IF (MOD(LIMT,KV).NE.0) GO TO 30  
CALL FBV (K,FUN,M)
C  
DO 29 I=1,NV  
VT = BETA*V(I,M)-ALPHA*V(I,J)  
IF (IP.EQ.1) VT = AINT(VT+.5)

108
29 \( V(I,J) = \text{AMAX1}(\text{AMIN1}(VT,BU(I)),BL(I)) \)

C

GO TO 32

C

30 DO 31 I=1,NV
   VT = \( .5 \times (\text{CEN}(I) - V(I,J)) \)
   IF (IP.EQ.1) VT = \text{AINT}(VT+.5)
   V(I,J) = VT
31 CONTINUE

C

32 IF (LIMT.LT.NLIM) GO TO 33

C

CANNOT MAKE THE 'J' TH VERTEX NO LONGER WORST BY
C DISPLACING TOWARD THE CENTROID OR BY OVER-REFLECTING
C THRU THE BEST VERTEX.
   IER = 2
   IF (NPR .LE. 0) GO TO 42
   WRITE (6,52) NT, J
   CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
   GO TO 42
33 NT = NT+1
   GO TO 20

C

SUCCESS: WE HAVE A REPLACEMENT FOR VERTEX J.
34 FUN(J) = FUNTRY
   FUNOLD = FUNTRY
   NPT = NPT+1

C

STOP AT THE 100' TH PERMISSIBLE TRIAL
   IF (MOD(NPT,100).EQ.0) GO TO 48

C

DO 36 I=1,NV
   SUM(I) = 0.

C

DO 35 N=1,K

109
35  SUM(I) = SUM(I)*V(I,N)
C
     CEN(I) = SUM(I)/FK
36  CONTINUE
C
     LC = 0
     GO TO 39
C
37  DO 38 I=1,NV
38  SUM(I) = SUM(I)+V(I,J)
C
     LC = J
C
39  IF (NPR.LE.0) GO TO 40
     IF (MOD(NPT,NPR).NE.0) GO TO 40
C
     CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,LC)
C
C HAS THE MAX. NUMBER OF TRIALS BEEN REACHED WITHOUT
C CONVERGENCE ? IF NOT, GO TO NEW TRIAL.
40  IF (NT.GE.NTA) GO TO 41
C
C NEXT-TO-WORST VERTEX NOW BECOMES WORST.
    J = JN
    GO TO 17
41  IER = 3
     IF (NPR.GT.0) WRITE (6,54)
C
C COLLECTOR POINT FOR ALL ENDINGS.
C  1) CANNOT DEVELOP FEASIBLE VERTEX.          IER = 1
C  2) CANNOT DEVELOP A NO-LONGER-WORST VERTEX. IER = 2
C  3) FUNCTION VALUE UNCHANGED FOR K TRIALS.   IER = 0
C  4) LIMIT ON TRIALS REACHED.                 IER = 3
C  5) CANNOT FIND FEASIBLE VERTEX AT START.    IER = -1
42  CONTINUE

110
C
C FIND BEST VERTEX.
   CALL FBV (K,FUN,M)
   IF (IER.GE.3) GO TO 44
C RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER THAN
C THE PREVIOUS OR IF THIS IS THE FIRST TRY.
   IF (NPR.LE.0) GO TO 43
   WRITE (6,55) (M,YMN,FUN(M))
43 IF (FUN(M).GE.YMN) GO TO 47
   IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
44 YMN = FUN(M)
   FUN(1) = FUN(M)
C
   DO 45 I=1,NV
   CEN(I) = V(I,M)
   SUM(I) = V(I,M)
45 V(I,1) = V(I,M)
C
   DO 46 I=1,NVT
46 XS(I) = V(I,M)
C
   IF (IER.LT.3) GO TO 6
47 IF (NPR.LE.0) GO TO 48
   CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)
   WRITE (6,56) FUN(M)
48 RETURN
C
49 FORMAT (50HOINDEX AND DIRECTION OF OUTLYING
1VARIABLE AT STARTI5)
50 FORMAT (50HOIMPLICIT CONSTRAINT VIOLATED AT START.
1DEAD END.)
51 FORMAT ('OCANNOT FIND FEASIBLE',I4,'TH VERTEX OR
ICENTROID AT START.')
52 FORMAT (10HOAT TRIAL I4,54H CANNOT FIND FEASIBLE
IVERTEX WHICH IS NO LONGER WORST, I4, 15X, 'RESTART FROM BEST VERTEX. ' )

53 FORMAT (40HOFUNCTION HAS BEEN ALMOST UNCHANGED FOR I5,7H TRIALS)
54 FORMAT (27HOLIMIT ON TRIALS EXCEEDED. )
55 FORMAT ('OBEST VERTEX IS NO.', I3, ' OLD MIN WAS ', 1E15.7, ' NEW MIN IS ',E15.7)
56 FORMAT ('OMIN OBJECTIVE FUNCTION IS ',E15.7)

END

SUBROUTINE FBV (K, FUN, M)
DIMENSION FUN(50)
M = 1

DO 1 I = 2, K
IF (FUN(M) .LE. FUN(I)) GO TO 1
M = I
1 CONTINUE

RETURN
END

SUBROUTINE BOUT (NT, NPT, NFE, NCE, NV, NVT, V, K, FN, C, IK)
DIMENSION V(50,50), FN(50), C(25)
WRITE (6, 4) NT, NPT, NFE, NCE

DO 1 I = 1, K
WRITE (6, 5) FN(I), (V(J, I), J = 1, NV)
IF (NVT .LE. NV) GO TO 1
NVP = NV + 1
WRITE (6, 6) (V(J, I), J = NVP, NVT)
1 CONTINUE

IF (IK .NE. 0) GO TO 2

WRITE (6, 7) (C(I), I = 1, NV)
RETURN

112
2 IF (IK.GE.0) GO TO 3
   WRITE (6,8) (C(I),I=1,NV)
   RETURN
3 WRITE (6,9) IK,(C(I),I=1,NV)
   RETURN
4 FORMAT ('ONO. TOTAL TRIALS = ',I5,4X,'NO. FEASIBLE
1TRIALS = ',
2I5,4X,'NO. FUNCTION EVALUATIONS = ',I5,4X,'NO.
3CONSTRAINT EVALUATIONS
4= ',I5/'O FUNCTION VALUE',6X,'INDEPENDENT
5VARIABLES/DEPENDENT
6OR IMPLICIT CONSTRAINTS')
5 FORMAT (1H ,E18.7,2X,7E14.7/(21X,7E14.7))
6 FORMAT (21X,7E14.7)
7 FORMAT (10HOCENTROID 11X,7E14.7/(21X,7E14.7))
8 FORMAT ('0 BEST VERTEX',7X,7E14.7/(21X,7E14.7))
9 FORMAT ('OCENTROID LESS VX',I2,2X,7E14.7/(21X,7E14.7))
END
   FUNCTION FE(X)
   DIMENSION X(3),
   COMMON TDIFF
   CALL PLANT(X)
   FE=TDIFF
   RETURN
END
   FUNCTION KE(X)
   DIMENSION X(3)
   KE=0
   RETURN
END
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