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**A HYBRID COMPUTER STUDY  
OF A DYNAMIC SHIP  
POSITIONING SYSTEM**

Richard H. St. John, Jr.  
William P. Schneider

**RE 8-70**

**August, 1970**

**CULLEN COLLEGE OF ENGINEERING**

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DYNAMIC SHIP POSITIONING SYSTEM

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# ACKNOWLEDGMENT

Work reported herein was supported in part by  
NASA Grant NGL-44-005-084 and NSF Grant GK2436.

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## ABSTRACT

Dynamic positioning is a method of anchoring a vessel in deep areas of the ocean. The essential components of a dynamic positioning system are a vessel with positioning forces; a position measuring system; a comparator; and a controller. These components position a vessel by interacting with each other and with the environment.

Mathematical models define each component of the positioning system. The hybrid computer simulates the positioning system, and the aerodynamic and hydrodynamic forces present on the ocean's surface.

This report investigates the excitation/response characteristics of the model for a variety of environmental conditions. Optimum headings with respect to positioning thrust result for each environmental case. A vessel search algorithm is developed to locate an optimum heading.

## CHAPTER I

### INTRODUCTION

The hybrid computer simulates physical conditions for the efficient real-time analysis of physical systems. This simulation permits the study of the effects of parameter changes on the excitation-response characteristics of a system. To study a physical system in this manner, it is necessary to formulate a detailed model and then to tailor the model to that system. The model is a series of mathematical and logical equations. One important objective of such a study is the optimization of the system with respect to one or more criteria or performance functions.

The ocean is man's next frontier. Water covers more than seventy per cent of the earth. There are three main topographical divisions of the surface beneath the water: continental shelf, continental slope, and abyssal plain. The continental shelf is a shallow bank or gently sloping region which usually extends to a depth of no more than six hundred feet. The continental slope is a very steep area much like the side of a cliff and extends from the edge of the continental shelf to the ocean floor, or abyssal plain. Exploration and exploitation of this vast area of the earth's surface present major problems to the engineer and the scientist. The subject of this thesis is a hybrid study of a method to

solve some of these problems.

Scientists and engineers have developed mooring techniques to stabilize vessels in the ten per cent of the ocean area that is the continental shelf. Static, or normal, mooring techniques are impractical, however, for all the ocean areas beyond the continental shelf. Most of the oceans are one thousand to twenty thousand feet deep. The difficulties of mooring a vessel at this depth hamper work in the deep oceans.

Currently, vessels of the conventional ship-hull class are employed as stable working platforms for such deep water work as drilling into the sea floor, gathering oceanographic data, tracking satellites, and launching missiles. These operations require that the vessel be mobile for travel. Once the vessel reaches its location, it must also be capable of quick and easy anchorage for extended periods of time. Dynamic positioning is a method for anchoring which is comparable to the hovering action of a helicopter. This method uses the self-contained energy of the vessel to produce forces which counteract the adverse physical changes at the ocean surface. This process is the only known practical method of maintaining a given geographical position in water depths beyond the continental shelf.

The four essential subsystems required for dynamic positioning are:

1. a vessel with positioning forces;

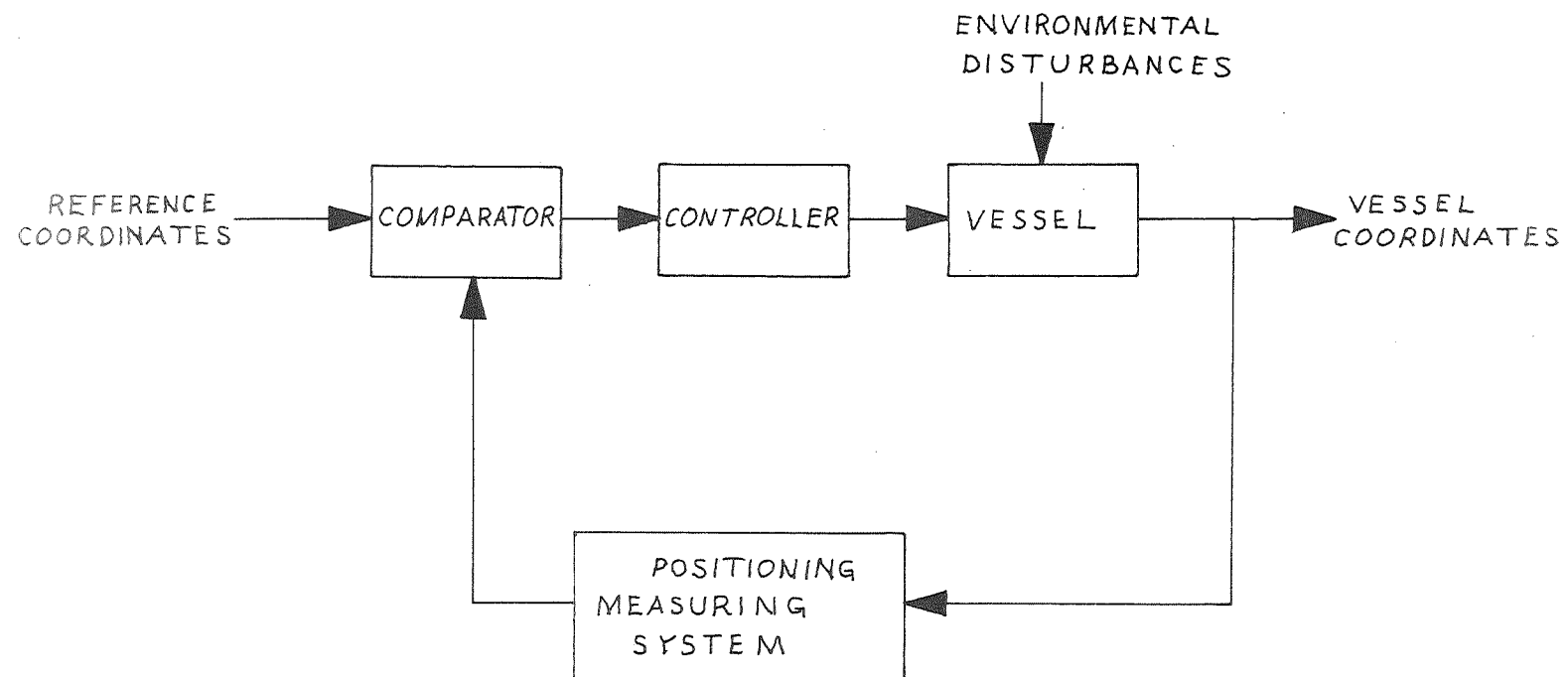
2. a position measuring system to define the actual vessel coordinates with respect to reference coordinates;
3. a comparator to indicate the vessel's deviation from the desired position; and
4. a controller to regulate the vessel's propulsion system in order to offset the deviation.

Figure 1.1 is a block diagram of the dynamic positioning system; Figure 1.2 is an illustration of that system.

Dynamic positioning is a closed-loop feedback control system. The comparator compares the input reference coordinates with the actual position of the ship. If there is deviation, the comparator generates an error signal. The controller processes the error signal and adjusts the thrust level of the vessel's propulsion system. This correction reduces the deviation so that when the deviation is zero, the measured position coincides with the reference position. If at any time the vessel moves as a result of physical changes such as winds, waves, or currents, the dynamic positioning process begins again.

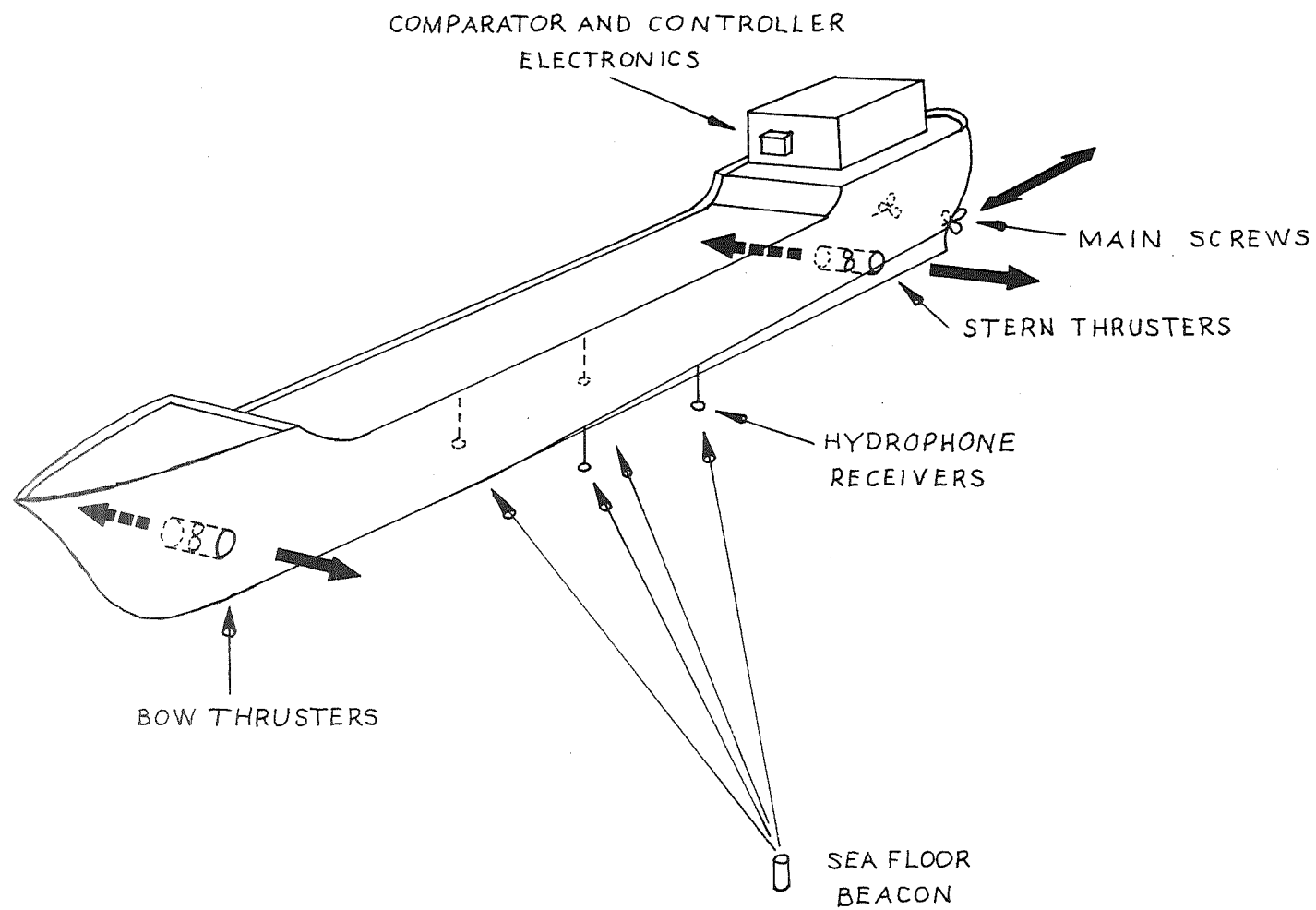
This type of dynamic positioning is presently in operation, but no one has attempted to optimize the system using any criteria. This thesis explores optimization with respect to required thrust. By this criterion, the ship holds position with a minimum amount of thrust.





DYNAMIC POSITIONING FEEDBACK SYSTEM

FIGURE 1.1



POSITIONING SYSTEM ILLUSTRATION

FIGURE 1.2

A hybrid study can provide general information on the overall station-keeping abilities of ship-hull vessels. The three specific questions of this study are:

1. Does an optimum vessel heading exist for specific environmental conditions?
2. If there is an optimum heading, is it a well-defined optimum that will provide a practical payout with respect to the necessary effort required to obtain it?
3. Can a practical vessel-search routine be formulated to find this optimum heading?

## CHAPTER II

### MATHEMATICAL MODEL

A mathematical model is a collection of equations which defines and delimits a physical system. This model is the link between the computer and the researcher in a hybrid study.

Figure 2.1 illustrates the coordinate system used for the simulation. X and Y form the inertial coordinate frame; x and y are the vessel coordinates;  $\psi$  is the heading angle. The model restricts the motion of the vessel to the X, Y plane with  $\psi$  the single angular degree of freedom.

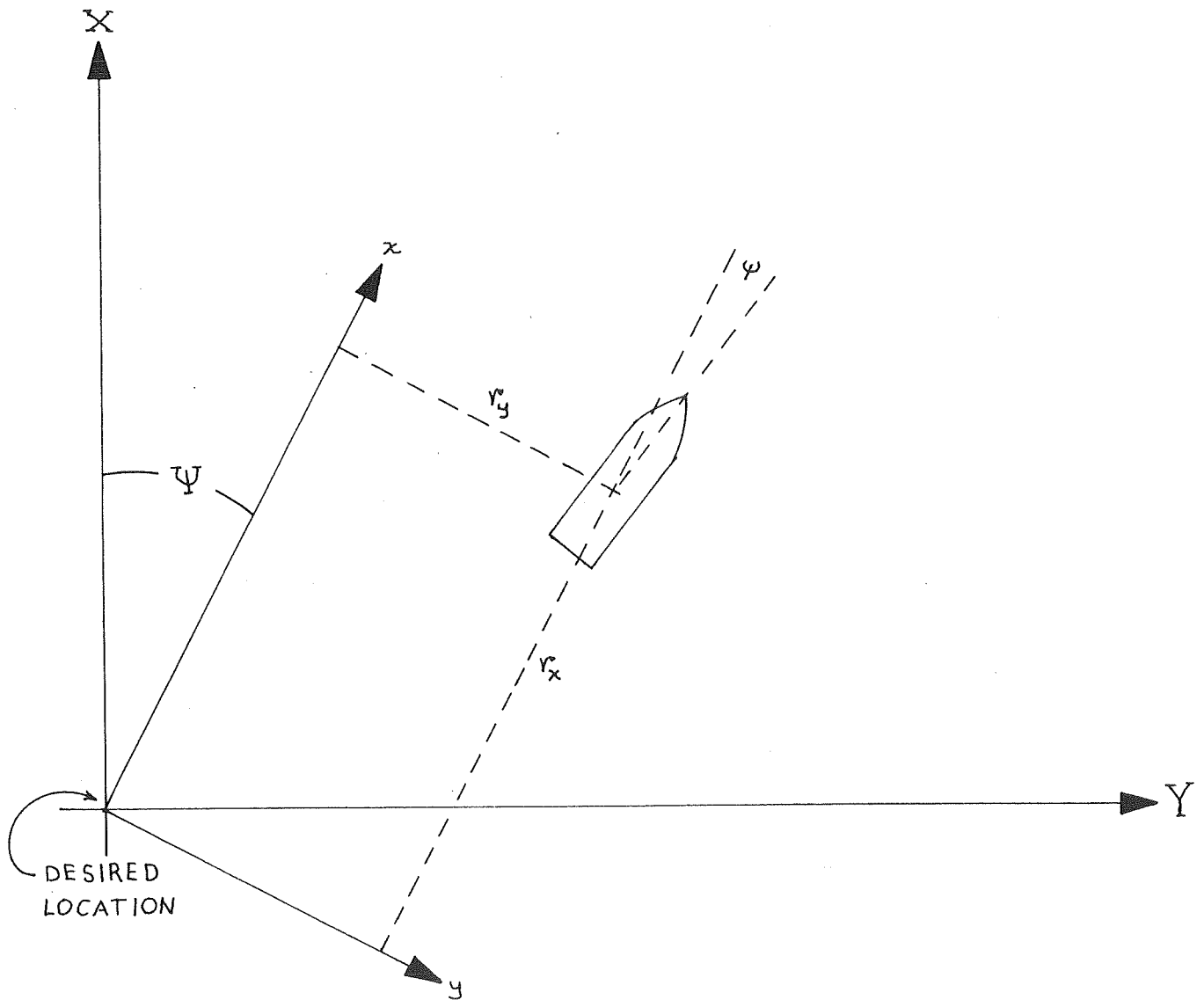
Newton's laws of motion govern the mathematical model of the vessel. The equations of acceleration in the vessel-coordinates are:

$$\frac{d}{dt}(V_x) = \frac{F_x}{m_x} + \omega V_y \quad (2.1)$$

$$\frac{d}{dt}(V_y) = \frac{F_y}{m_y} - \omega V_x \quad (2.2)$$

$$\frac{d}{dt}(\omega) = \frac{M_\psi}{I_\psi} \quad (2.3)$$

The integration of equations (2.1), (2.2), and (2.3) yields the x, y, and  $\psi$  velocities of the vessel. The velocity equations in the vessel coordinates are:



COORDINATE SYSTEM

FIGURE 2.1

$$\frac{d}{dt}(r_x) = V_x + \omega r_y \quad (2.4)$$

$$\frac{d}{dt}(r_y) = V_y - \omega r_x \quad (2.5)$$

$$\frac{d}{dt}(\psi) = \omega \quad (2.6)$$

The integration of equations (2.4), (2.5), and (2.6) yields the vessel position and heading.

Error functions representing the comparator output result from adding the conjugate value of the vessel position and heading to the reference position and heading. The error functions in the vessel coordinates are:

$$x_e = X - r_x \quad (2.7)$$

$$y_e = Y - r_y \quad (2.8)$$

$$\psi_e = \psi - \psi \quad (2.9)$$

The thrust demand is a function of the following variables:

1. the position and heading errors;
2. the velocity of the vessel; and
3. the steady-state environmental forces acting on

the vessel.

The control system, which is a function of these three variables; the physical system delays; and the noise filters regulate the vessel's propulsion system.

Laplace transforms are useful in understanding the mathematical model of the control system. Figure 2.2 illustrates a model of the control system. The model includes a second order filter for noise reduction; the control gains; and a first order time delay. Equations (2.1), (2.2), and (2.3) contain three functions,  $F_x$ ,  $F_y$ , and  $M_\psi$ . These functions are a summation of the thruster, the hydrodynamic, and the aerodynamic forces and moments.

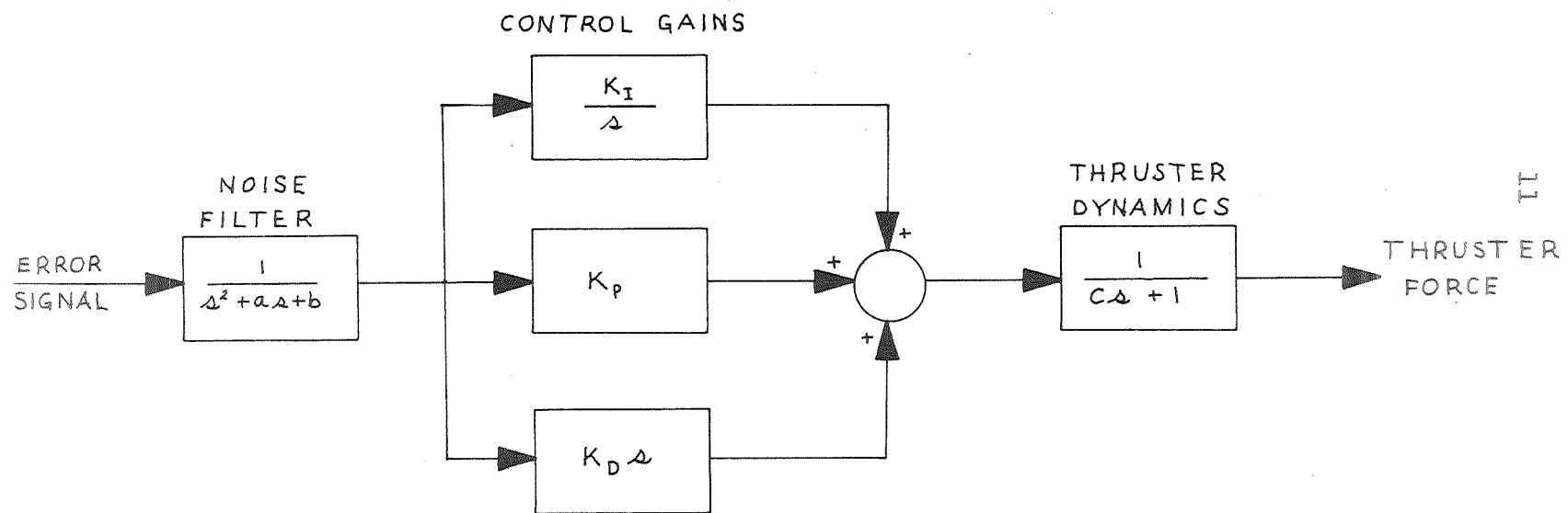
$$F_x = F_{xT} + F_{xH} + F_{xA} \quad (2.10)$$

$$F_y = F_{yT} + F_{yH} + F_{yA} \quad (2.11)$$

$$M_\psi = M_{\psi T} + M_{\psi H} + M_{\psi A} \quad (2.12)$$

The output of the controller subsystem indicated in Figure 2.2 is a thruster force or moment.

The hydrodynamic and aerodynamic force components of equations (2.10) through (2.12) are drag forces. Equations (2.13) through (2.18) are empirical representations of the drag forces resulting from the flow of a fluid about an



CONTROLLER SUBSYSTEM

FIGURE 2.2



object.<sup>1</sup>

Equations (2.13), (2.14), and (2.15) formulate the hydrodynamic components of equations (2.10), (2.11), and (2.12).

$$F_{xH} = K_{xH} V_R |V_R| \quad (2.13)$$

$$F_{yH} = K_{yH} V_R |V_R| \quad (2.14)$$

$$M_{\psi H} = K_{\psi H} V_R |V_R| \quad (2.15)$$

An analysis of hydrodynamic drag force data taken in wave tank model studies for ship-hull vessels yields the values of  $K_{xH}$ ,  $K_{yH}$ , and  $K_{\psi H}$ . The relative velocity  $V_R$  in the ship's coordinates is the velocity of the ship with respect to the water.  $V_R$  is a function of the ship's velocity; the steady-state current velocity; and the instantaneous horizontal particle velocity of the ocean waves.

Simplifying equations of the small amplitude wave theory yields the instantaneous horizontal particle velocity. These wave equations are an approximation of the complete theoretical description of wave behavior. The errors resulting from practical assumptions and simplifications of the theory

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<sup>1</sup>R. G. Dean and D. R. F. Harleman, "Interaction of Structures and Waves," A. T. Ippen (ed.), Estuary and Coastline Hydrodynamics (New York: McGraw-Hill, 1966), 341-403.

are negligible in this hybrid computer study. Appendix A contains a complete derivation of the hydrodynamic wave equations used for this model. Appendix B contains graphs of typical hydrodynamic and aerodynamic drag force functions for ship-hull vessels.

Equations (2.16), (2.17), and (2.18) formulate the aerodynamic components of equations (2.10), (2.11), and (2.12).

$$F_{XA} = K_{XA} V_A |V_A| \quad (2.16)$$

$$F_{YA} = K_{YA} V_A |V_A| \quad (2.17)$$

$$M_{\psi A} = K_{\psi A} V_A |V_A| \quad (2.18)$$

An analysis of aerodynamic drag force data taken in wind tunnel tests on ship-hull vessels produces the values of  $K_{XA}$ ,  $K_{YA}$ , and  $K_{\psi A}$ .  $V_A$  is a function of the steady-state wind velocity and the instantaneous wind gust velocity.

The equations presented in this chapter are the mathematical model of a typical dynamic ship positioning system.



## CHAPTER III

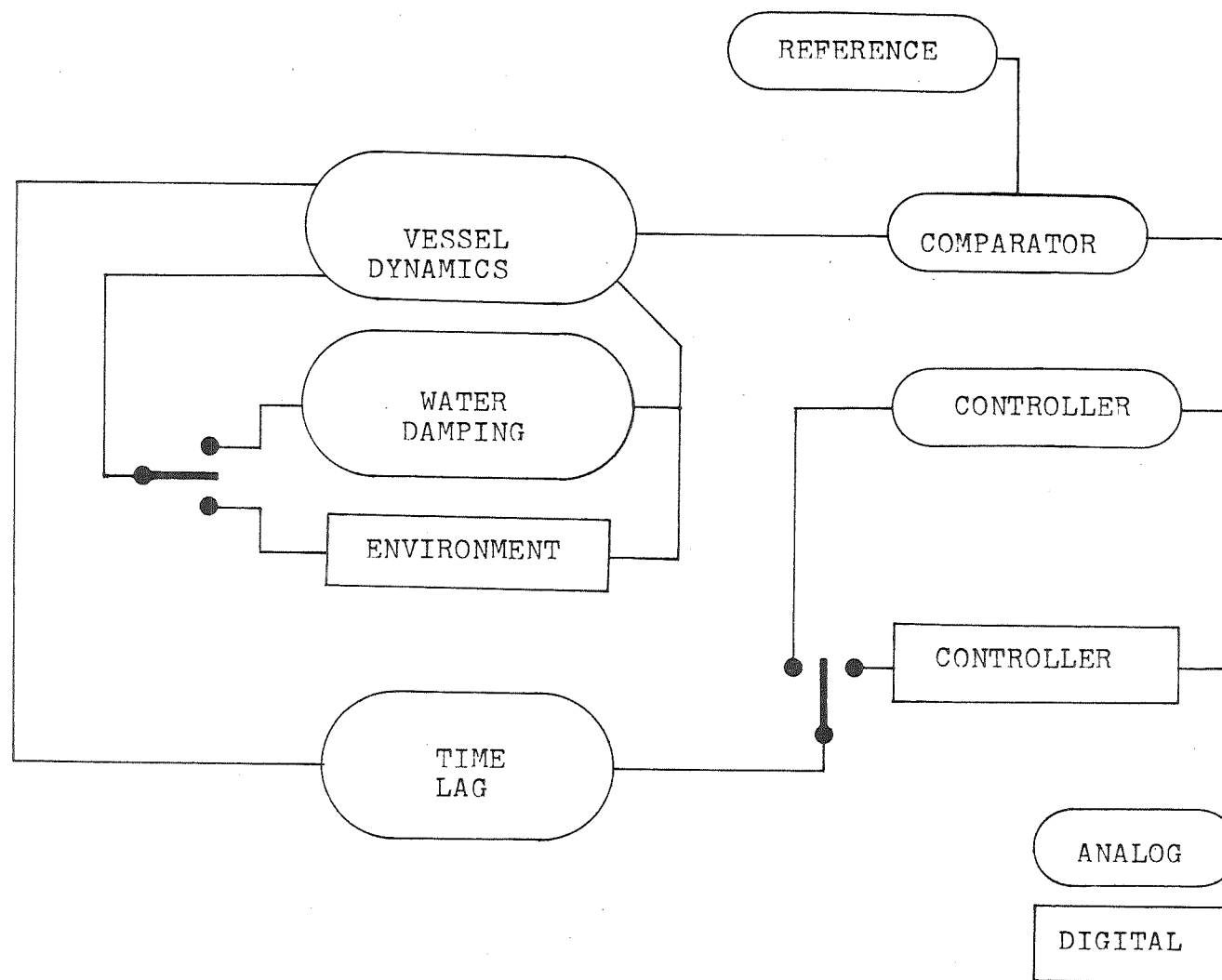
### COMPUTER MODE ASSIGNMENTS

The hybrid system used for this study is an IBM System/360 Model 44 general purpose digital computer with 32,000 words of core memory; an HSI SS-100 Analog/Hybrid computer with one hundred analog amplifiers; and an HSI Model 1044 Hybrid Linkage unit with multichannel communication paths. For this study one or both computers simulate the functions of each component of the dynamic positioning system. Figure 3.1 illustrates the computer mode assignments.

This study assigns the vessel simulation to the analog computer. The basic ship dynamics--acceleration, velocity, and position--are the central elements of the analog model. The process of integration is a primary task of analog computers. The integration of the vessel's acceleration gives the velocity; the integration of the velocity gives the position.

An analog summer-amplifier simulates the vessel's comparator subsystem. Either manual or servo-set potentiometers simulate the reference coordinates.

The controller subsystem filters noise from the comparator's error signal; modifies the signal by applying control gains; and sets the thrust demand level. Analog computing elements simulate the control system and filtering techniques of this model because the integral operator in the analog



COMPUTER MODE ASSIGNMENTS

FIGURE 3.1

computer can linearly replace the Laplace operator, " $1/s$ ".

Simulation of the controller on the analog computer is efficient for research purposes, but in actual practice, the controller subsystem of a dynamically positioned vessel would probably be a digital computer. For this reason, both computers simulate the control system. Digitally controlled signal switching places either control system into the feedback loops.

Generally, there is a time lag associated with the response of electromechanical systems. In this system, the time lag occurs between the demand for thrust and the response of the thrusters. The time lag is simulated by the analog computer by a first order lag function.

On the other hand, the digital computer primarily simulates the complex environmental forces at the ocean's surface. However, an option in the digital program allows an analog computer simulation of the steady state environmental forces and the hydrodynamic damping.

This discussion describes the design of the model. Chapter IV and Chapter V describe the fabrication of the hybrid model.



## CHAPTER IV

### ANALOG MODEL

The analog model of the vessel and control system results from constructing three separate closed loops: X-position loop, Y-position loop, and  $\psi$ -heading loop. These loops simulate vessel dynamics in the three degrees of freedom which this study allows. The analog representation of equations (2.1) through (2.6) forms the model of the vessel.

Dynamic range is one of the limitations of an analog computer. The analog computer for this study has a maximum dynamic range of plus and minus one hundred volts. Since the variables and constants of most models are not within this range, magnitude scaling is necessary. The steps in magnitude scaling are:

1. obtain the unscaled equations for each amplifier;
2. substitute an equivalent scaled program variable for each problem variable. For example, if the problem contains a variable,  $x$ , whose maximum value can be as high as 500, this variable is replaced in the equation with the computer variable,  $500[x/500]$ , without unbalancing the equation;
3. solve the equations for the scaled outputs in terms of the scaled inputs;



4. adjust the amplifier gains so that all potentiometer settings are less than unity.

In order to perform magnitude scaling of equations (2.1) through (2.6), it is necessary to define the maximum value of each variable and constant. Table I lists the parameters and their maximum values used in this study.

Substitution of the maximum parameter values from Table I into equations (2.1) through (2.6) yields the scaled model of the vessel. The scaled variables are bracketed and the potentiometer settings are shown in parentheses.

$$\begin{aligned} \frac{d}{dt} 20 \left[ \frac{V_x}{2.0} \right] &= \frac{5.0 \times 10^4}{7.5 \times 10^5} \left[ \frac{F_x}{5.0 \times 10^4} \right] / \left[ \frac{M_x}{7.5 \times 10^5} \right] + 0.1 \left[ \frac{\omega}{0.1} \right] 2.0 \left[ \frac{V_y}{2.0} \right] \\ \frac{d}{dt} \left[ \frac{V_x}{2.0} \right] &= (0.0033) \left[ \frac{F_x}{5.0 \times 10^4} \right] / \left[ \frac{M_x}{7.5 \times 10^5} \right] + (0.0100) \left[ \frac{\omega}{0.1} \right] \left[ \frac{V_y}{2.0} \right] \end{aligned} \quad (4.1)$$

$$\begin{aligned} \frac{d}{dt} 500 \left[ \frac{r_x}{500} \right] &= 20 \left[ \frac{V_x}{2.0} \right] + 0.1 \left[ \frac{\omega}{0.1} \right] 500 \left[ \frac{r_y}{500} \right] \\ \frac{d}{dt} \left[ \frac{r_x}{500} \right] &= (0.0400) \left[ \frac{V_x}{2.0} \right] + (0.1000) \left[ \frac{\omega}{0.1} \right] \left[ \frac{r_y}{500} \right] \end{aligned} \quad (4.2)$$

$$\begin{aligned} \frac{d}{dt} 2.0 \left[ \frac{V_y}{2.0} \right] &= \frac{5.0 \times 10^4}{1.1 \times 10^6} \left[ \frac{F_y}{5.0 \times 10^4} \right] / \left[ \frac{M_y}{1.1 \times 10^6} \right] - 0.1 \left[ \frac{\omega}{0.1} \right] 2.0 \left[ \frac{V_x}{2.0} \right] \\ \frac{d}{dt} \left[ \frac{V_y}{2.0} \right] &= (0.0227) \left[ \frac{F_y}{5.0 \times 10^4} \right] / \left[ \frac{M_y}{1.1 \times 10^6} \right] - (0.9999) \left[ \frac{\omega}{0.1} \right] \left[ \frac{V_x}{2.0} \right] \end{aligned} \quad (4.3)$$

$$\begin{aligned} \frac{d}{dt} 500 \left[ \frac{r_y}{500} \right] &= 2.0 \left[ \frac{V_y}{2.0} \right] - 0.1 \left[ \frac{\omega}{0.1} \right] 500 \left[ \frac{r_x}{500} \right] \\ \frac{d}{dt} \left[ \frac{r_y}{500} \right] &= (0.0040) \left[ \frac{V_y}{2.0} \right] - (0.1000) \left[ \frac{\omega}{0.1} \right] \left[ \frac{r_x}{500} \right] \end{aligned} \quad (4.4)$$

$$\begin{aligned} \frac{d}{dt} 0.1 \left[ \frac{\omega}{0.1} \right] &= \frac{1.0 \times 10^7}{1.375 \times 10^{10}} \left[ \frac{M_\psi}{1.0 \times 10^7} \right] / \left[ \frac{I_z}{1.375 \times 10^{10}} \right] \\ \frac{d}{dt} \left[ \frac{\omega}{0.1} \right] &= (0.0072) \left[ \frac{M_\psi}{1.0 \times 10^7} \right] / \left[ \frac{I_z}{1.375 \times 10^{10}} \right] \end{aligned} \quad (4.5)$$

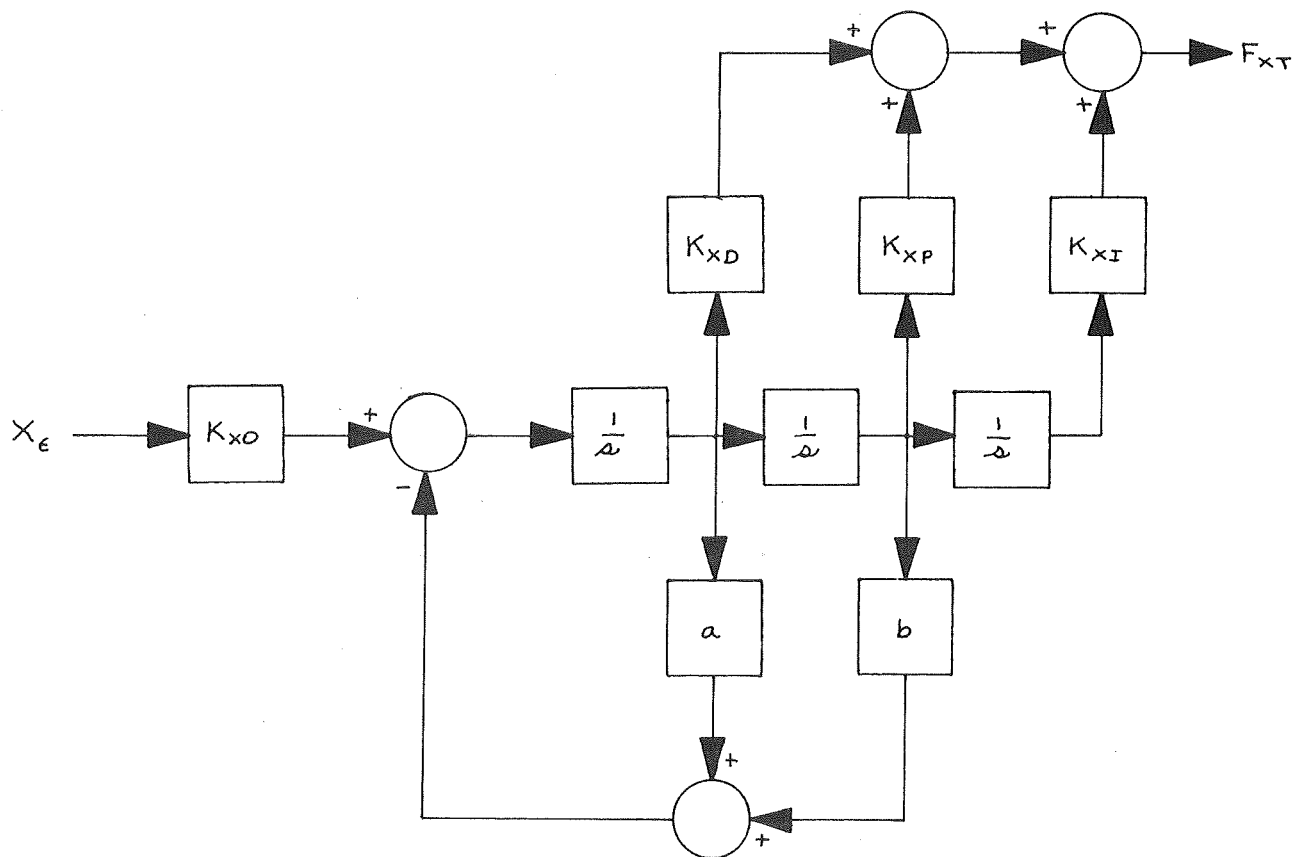
$$\frac{d}{dt} 3.14 \left[ \frac{\psi}{3.14} \right] = 0.1 \left[ \frac{\omega}{0.1} \right] \quad (4.6)$$

$$\frac{d}{dt} \left[ \frac{\psi}{3.14} \right] = (0.0318) \left[ \frac{\omega}{0.1} \right]$$

Three summer amplifiers, one in each loop, represent the vessel's position and heading comparator subsystem. The sum of the vessel position (heading) and the conjugate of the reference coordinate is the vessel position (heading) error signal.

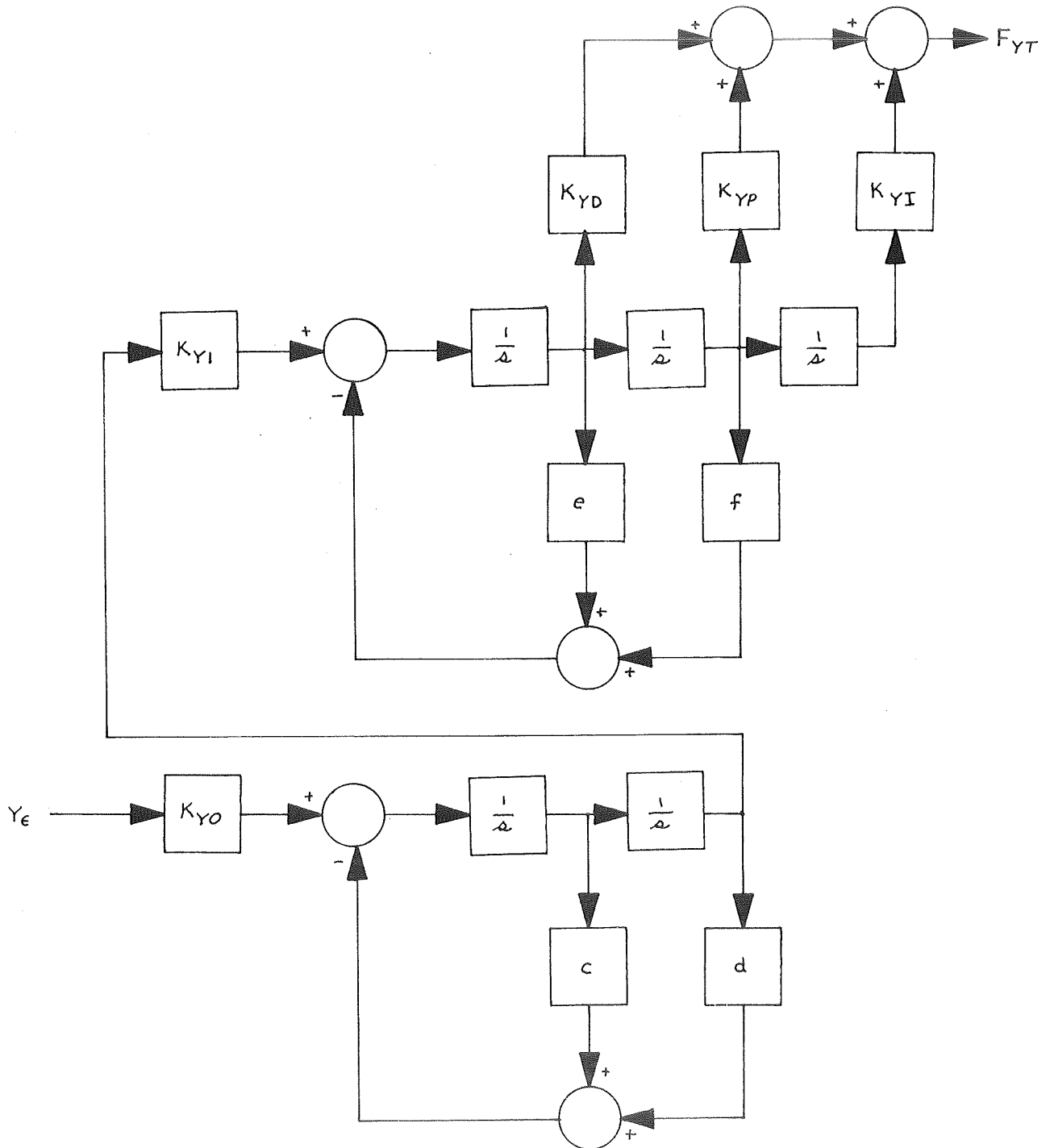
The control system operates on the error signal from the comparator which in turn receives its information from the position measuring system located remotely from the vessel. Because of the high ambient noise level, filtering at the input to the control system is necessary. This filtering is simulated by modeling a second order polynomial for the X-position loop and the heading loop, and a fourth order polynomial for the Y-position loop. Figures 4.1, 4.2, and 4.3 are block diagrams of these position and heading control loops.

The outputs of these control loops are the thrust demand signals. Since there is a time lag associated with the response of the vessel to the thrust demands, simulation of a time delay is necessary. The models of these delays are first order analog lags and the outputs of the lags are the vessel thruster forces. The sum of the environmental forces and the thruster forces is the input to the vessel's dynamic model which closes the loop.



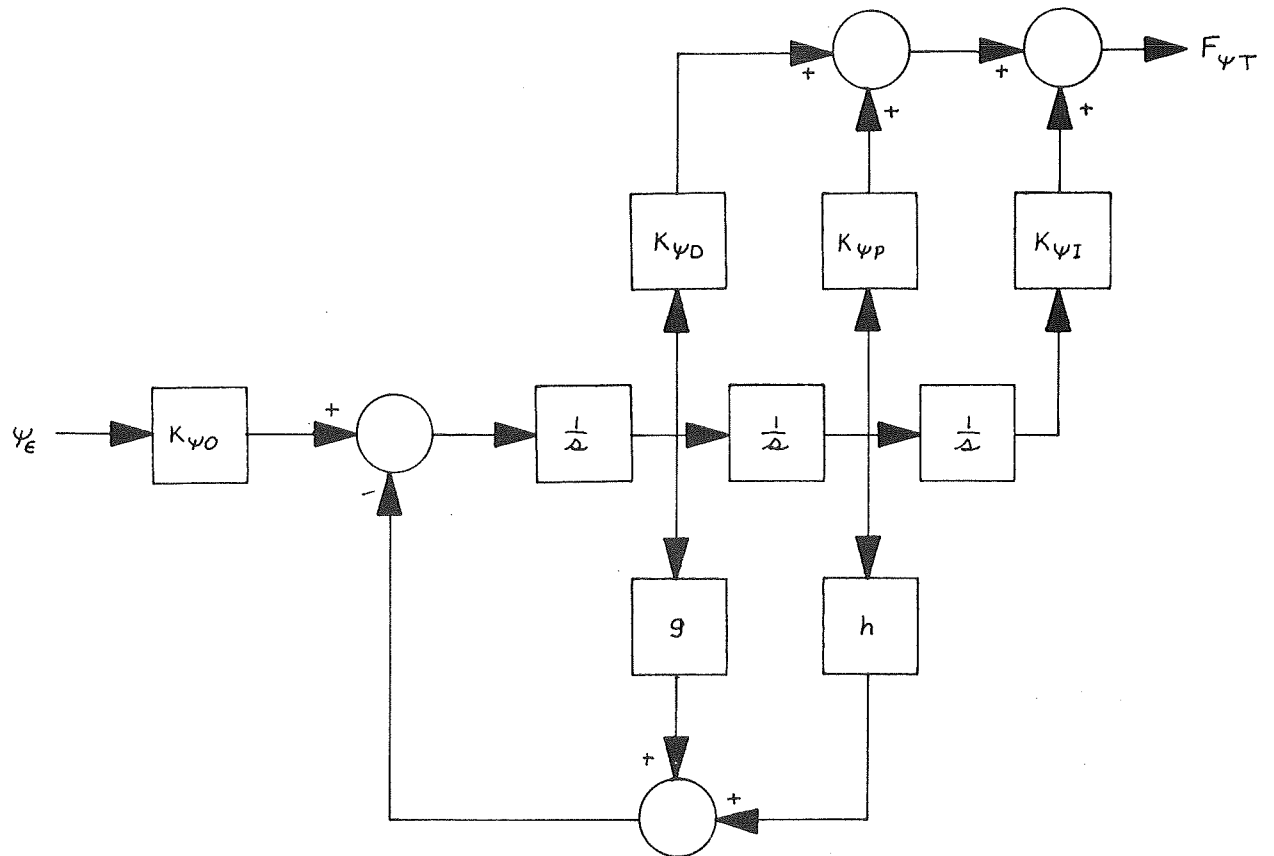
BLOCK DIAGRAM OF  
X-LOOP CONTROL SYSTEM

FIGURE 4.1



BLOCK DIAGRAM OF  
Y-LOOP CONTROL SYSTEM

FIGURE 4.2



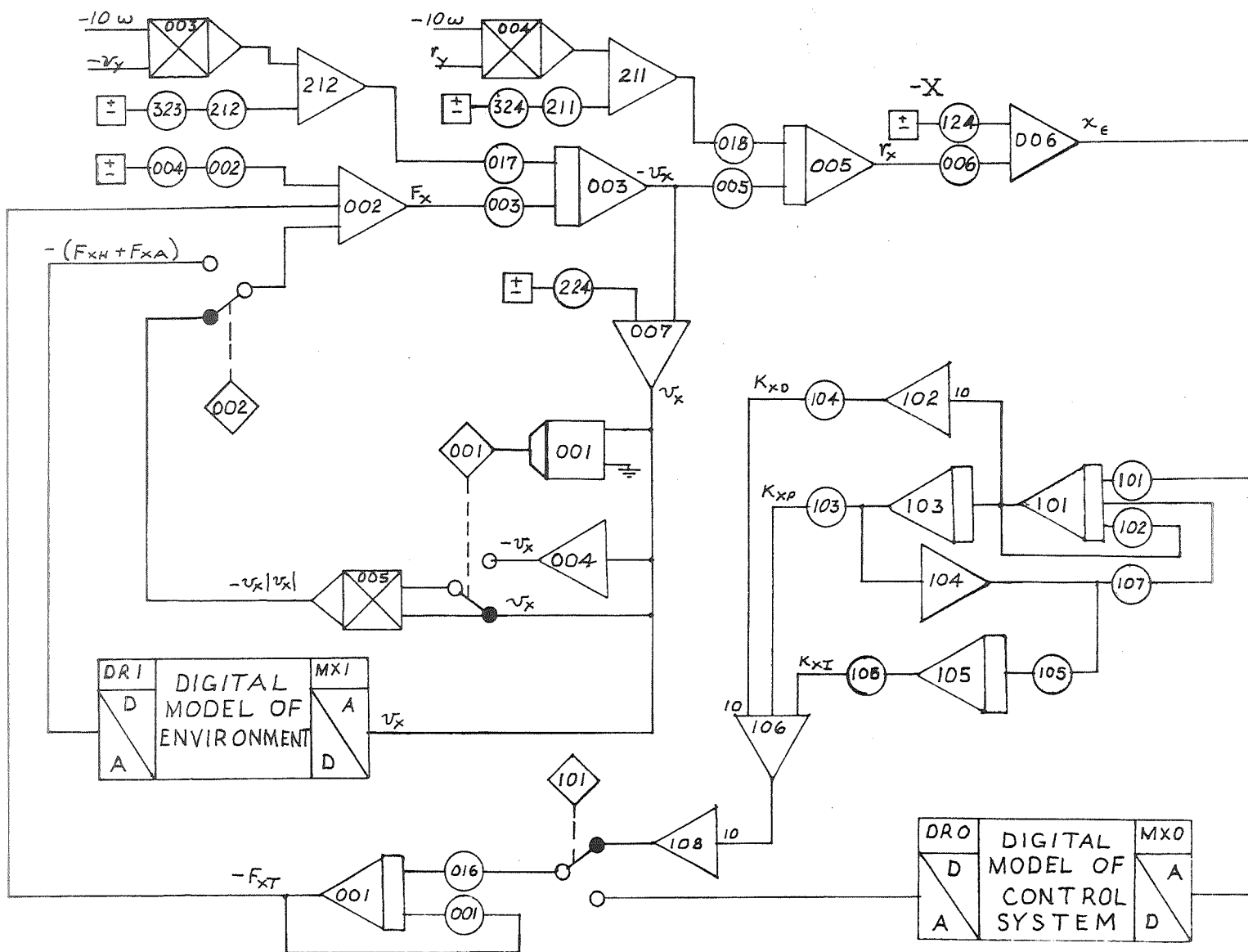
BLOCK DIAGRAM OF  
 $\Psi$ -LOOP CONTROL SYSTEM

FIGURE 4.3

Equations (2.13) through (2.15) represent the hydrodynamic damping force caused by the motion of the vessel with respect to the water. The velocity functions of these equations are simulated by using analog comparators and multipliers. The analog comparator senses the sign of the relative vessel velocity and the output of this comparator controls a function switch. If the sign of the relative velocity is negative, the function switch changes state and the multiplier receives both the positive signal and the negative signal. The product of the multiplier is the square of the velocity. However, the product retains the algebraic sign of the relative vessel velocity.

The multipliers used in the analog section have a small D. C. offset voltage at their outputs. To compensate for this offset, the multiplier outputs are summed with the conjugate of the offset value.

Figures 4.4, 4.5, and 4.6 illustrate the complete analog computer model for this study. Figure 4.7 is the key for the analog symbols shown. Table II lists the potentiometer settings.



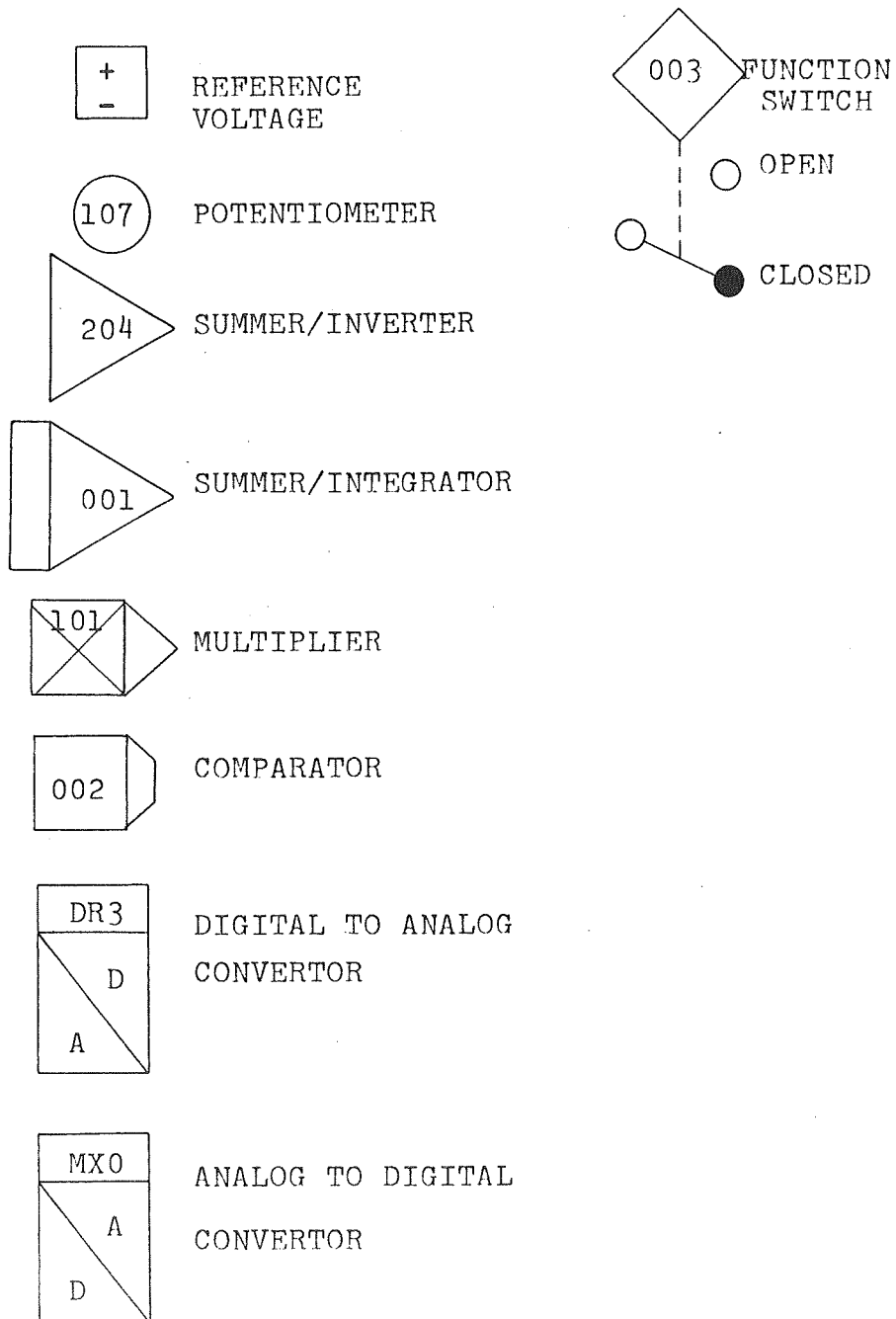
X-POSITION LOOP

FIGURE 4.4









ANALOG KEY

FIGURE 4.7



## CHAPTER V

### DIGITAL MODEL

The digital model is a FORTRAN computer program which performs three functions:

1. it controls the transfer of information or data between the digital computer and the analog computer;
2. it simulates the controller subsystem; and
3. it generates the hydrodynamic and aerodynamic forces in the case studies.

To simplify the FORTRAN programming, available system subroutines are incorporated in the digital program. A subroutine is a digital computer subprogram which, when called upon by the main program, performs a predefined task. Subroutines from both the Data Acquisition Multiprogramming System (DAMPS) and the Hybrid Executive control the transfer of information between the analog and the digital computer. DAMPS and the Hybrid Executive are collections of subroutines designed for use on the IBM System/360 Model 44--HSI SS-100 Analog/Hybrid computer. Table III lists the subroutines for this study.

The main program begins by calling on various subroutines to establish memory control blocks for each hybrid input/output channel in the simulation. The hybrid I/O channels in this study are:

1. analog to digital input;
2. digital to analog output;
3. sense line input;
4. control line input; and
5. mode control output.

Before each hybrid computer run, the digital line printer lists operating instructions and program options. These instructions and options are:

\*\*\*\*\*

INFORMATION CONCERNING REAL TIME OPERATION OF MAIN PROGRAM

THE FOLLOWING INFORMATION IS REQUESTED BY THE TYPEWRITER TERMINAL

N IS THE NUMBER OF PRINTED OUTPUT SAMPLES

A SAMPLE IS TAKEN EVERY FIFTH TIME THROUGH THE TIMED  
CONTROL LOOP

IF N=0 EXIT IS CALLED AND THE PROGRAM CONCLUDED

ISCALE IS THE TIME SCALE FACTOR

LOGIC IS AN INPUT THAT ENABLES PROGRAM OPTIONS

LOGIC=0 EXISTING GAINS ARE USED AND OPERATION BEGINS

LOGIC=1 NEW GAINS MAY BE INPUT FOR X-CHANNEL

LOGIC=2 NEW GAINS MAY BE INPUT FOR Y-CHANNEL

LOGIC=3 NEW GAINS MAY BE INPUT FOR PSI-CHANNEL

LOGIC=4 NEW GAINS INPUT FOR X, Y, & PSI-CHANNELS

LOGIC=5 INPUT CURRENT--POLAR COORDINATES

LOGIC=6 INPUT SEA STATE (0, 4, 6, OR 8) AND DIRECTION

LOGIC=7 INPUT WIND--POLAR COORDINATES

LOGIC=8 INPUT GUST MAGNITUDE, PERIOD, & VARIATION ANGLE

LOGIC=9 ANALOG CONTROL SYSTEM IS USED--NO GAINS INPUT

THE FOLLOWING RUN OPTIONS ARE AVAILABLE

ENABLE SENSE LINE "1" TO MAKE A PARAMETER CHANGE DURING  
A RUN

ENABLE SENSE LINE "0" TO MAKE A CONTINUOUS RUN

\*\*\*\*\*

After the line printer lists the instructions and options, the digital computer typewriter terminal requests the run time (N) and the time scale (ISCALE). The values of N and ISCALE enter the program through the typewriter terminal.

The programmer types the value for LOGIC into the computer; the computer then requests the corresponding program option. A case study begins only when LOGIC=0 or LOGIC=9. For LOGIC=0, the digital computer enables control line "0". Control line "0" in the enable position causes function switches in the analog computer to place the digital control system in the feedback loops. For LOGIC=9, the digital computer disables control line "0", placing the function switches in position for the analog control system.

When a case study begins, the parameters of the digital control system receive their initial values. The digital computer places the analog computer in the operate mode; starts the digital timer; and then reads the analog to digital input

lines. Velocity, position, heading, and error information are assigned to these input lines.

The program now directs the error information to the digital model of the control system. This model is a Z-transform representation of the analog control system. From this information the program calculates the level of thrust required to reduce the position and heading errors.

The y-coordinate thrusters supply both the thrust to maintain proper heading and the thrust to maintain proper y-position. The heading thrust requirements have priority on one half of the value of the y-coordinate, or translational thrust. The y-position thrust is at least one half of the translational thrust, plus the difference between one half of the translational thrust and the demanded heading thrust.

The next phase of the program is the simulation of the environmental forces. Sea States are a convenient method of classifying particular combinations of steady wind and wave conditions. The selection of an appropriate Sea State number, gust condition, and ocean current determines the complexity of the environmental model for a particular case study.

The program generates complex ocean waves by adding four sinusoidal wave components. Table V lists the wave components for the simulation of Sea States 4, 6, and 8 used in these case studies. The instantaneous wind velocity corresponding to the selected Sea State is, however, more com-

plicated. It is the sum of the steady state wind velocity and the gust velocity. The latter is simulated in the program by modulating both the magnitude and the direction of the wind as a function of the sine of the gust frequency.

In order to determine the x and y relative velocities of the vessel, the program transforms the water velocity and the wind velocity obtained above from the inertial coordinates to the vessel coordinates. The program then calculates the hydrodynamic and aerodynamic drag forces using Fourier series components of the drag force curves shown in Appendix B. Tables VI and VII list their major Fourier series components.

To normalize the thrust forces and the environmental forces to levels compatible with the analog model, magnitude scaling is performed. These normalized forces are then transferred from the digital computer to the analog computer.

The final phase of the program is the interrogation of the sense lines for an interrupt message from the analog computer. If there is no interrupt message, the program checks the status of run time. If the run time is not yet exceeded, the program begins again by reading analog to digital values of velocity, position, heading, and error.

Figure 5.1 is a block diagram flow chart of the digital computer program. Appendix C is a listing of the program.



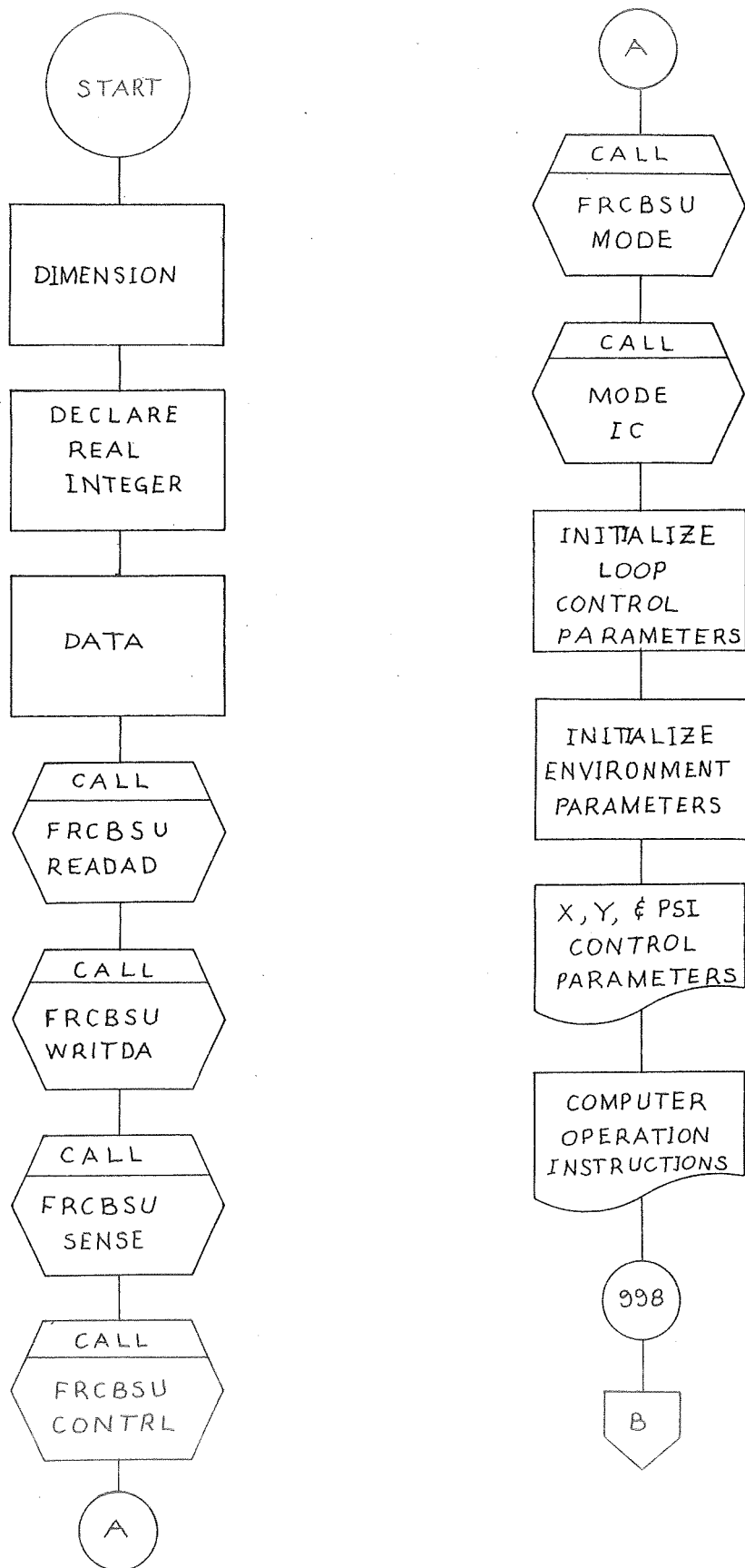


FIGURE 5.1a

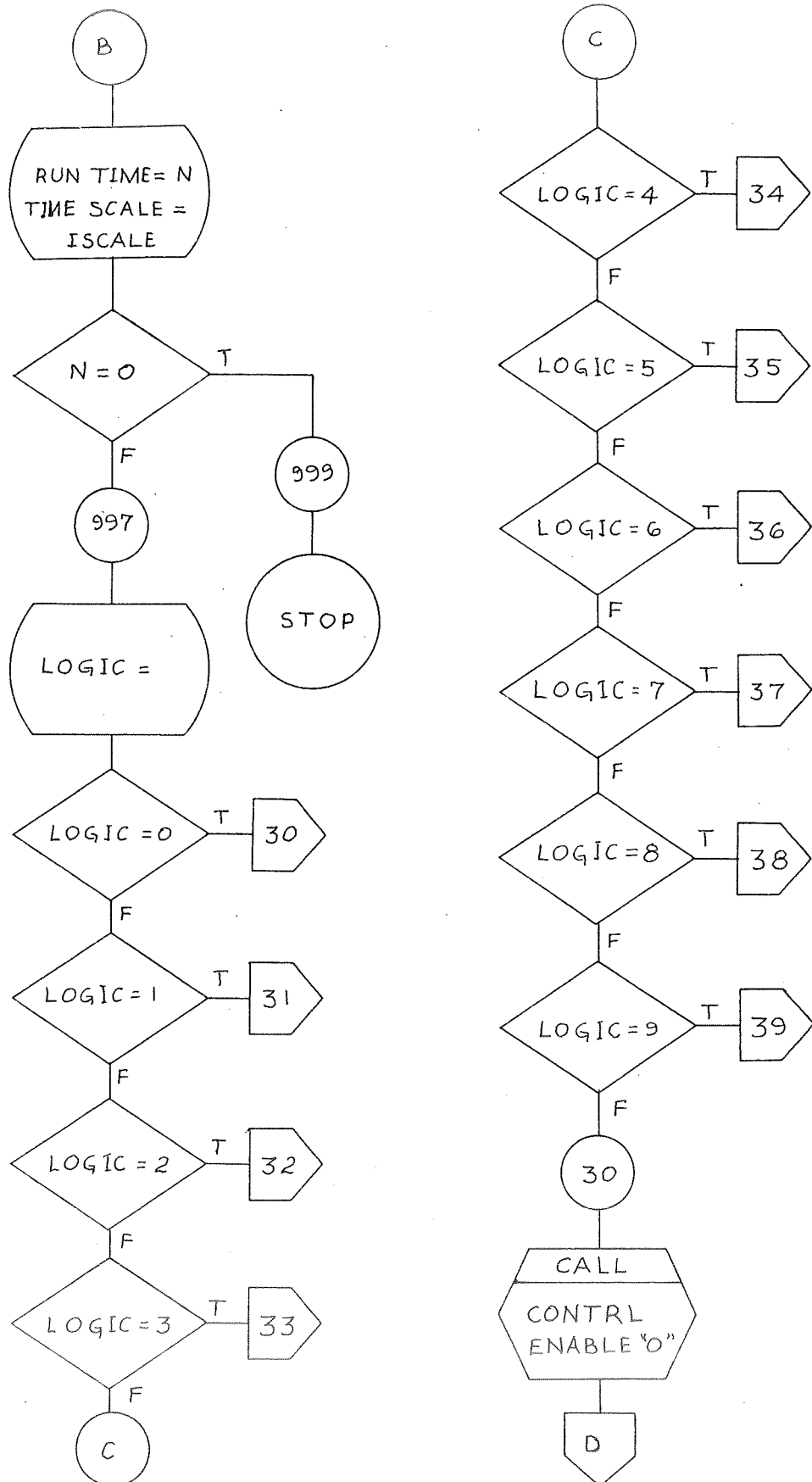


FIGURE 5.1b

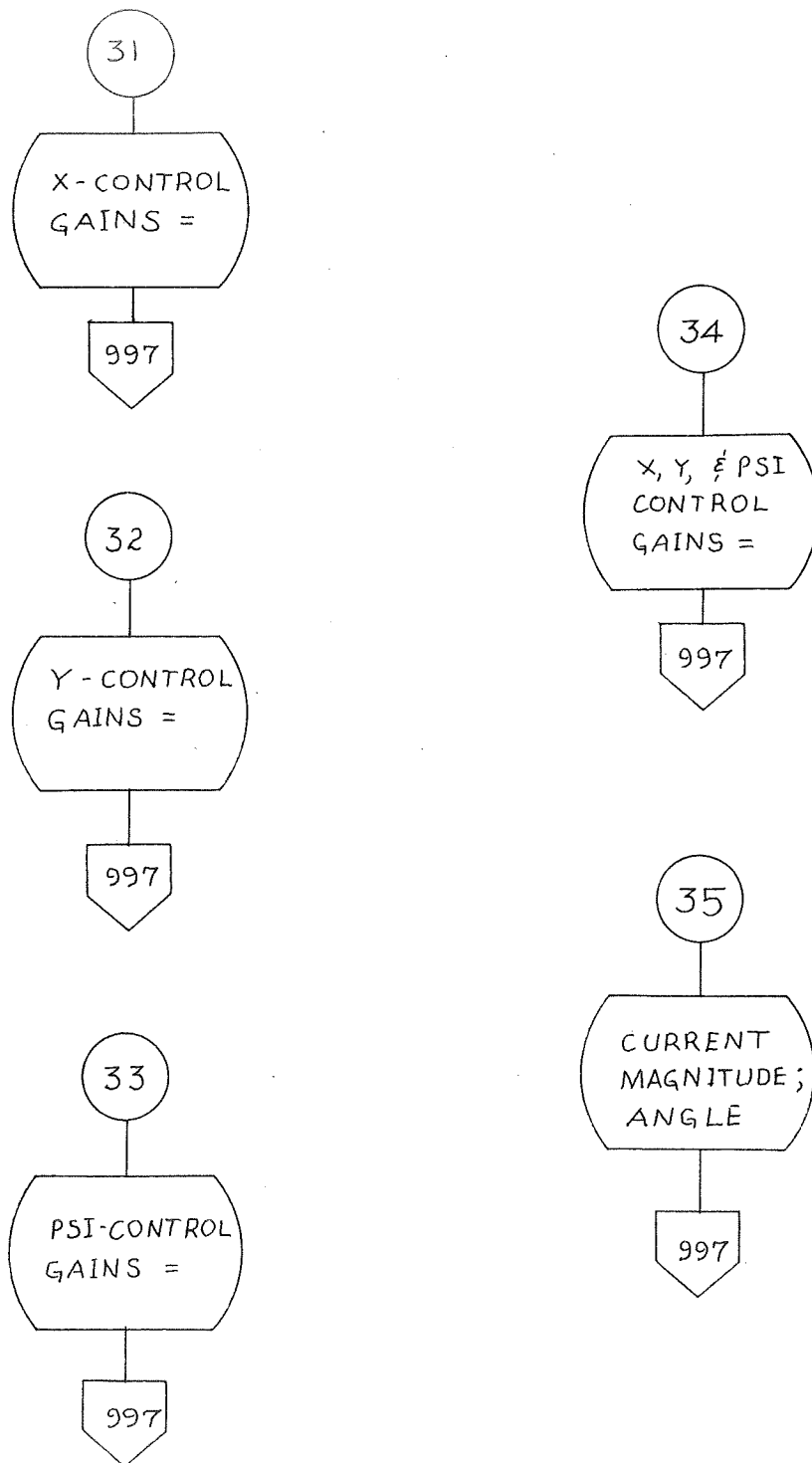


FIGURE 5.1c

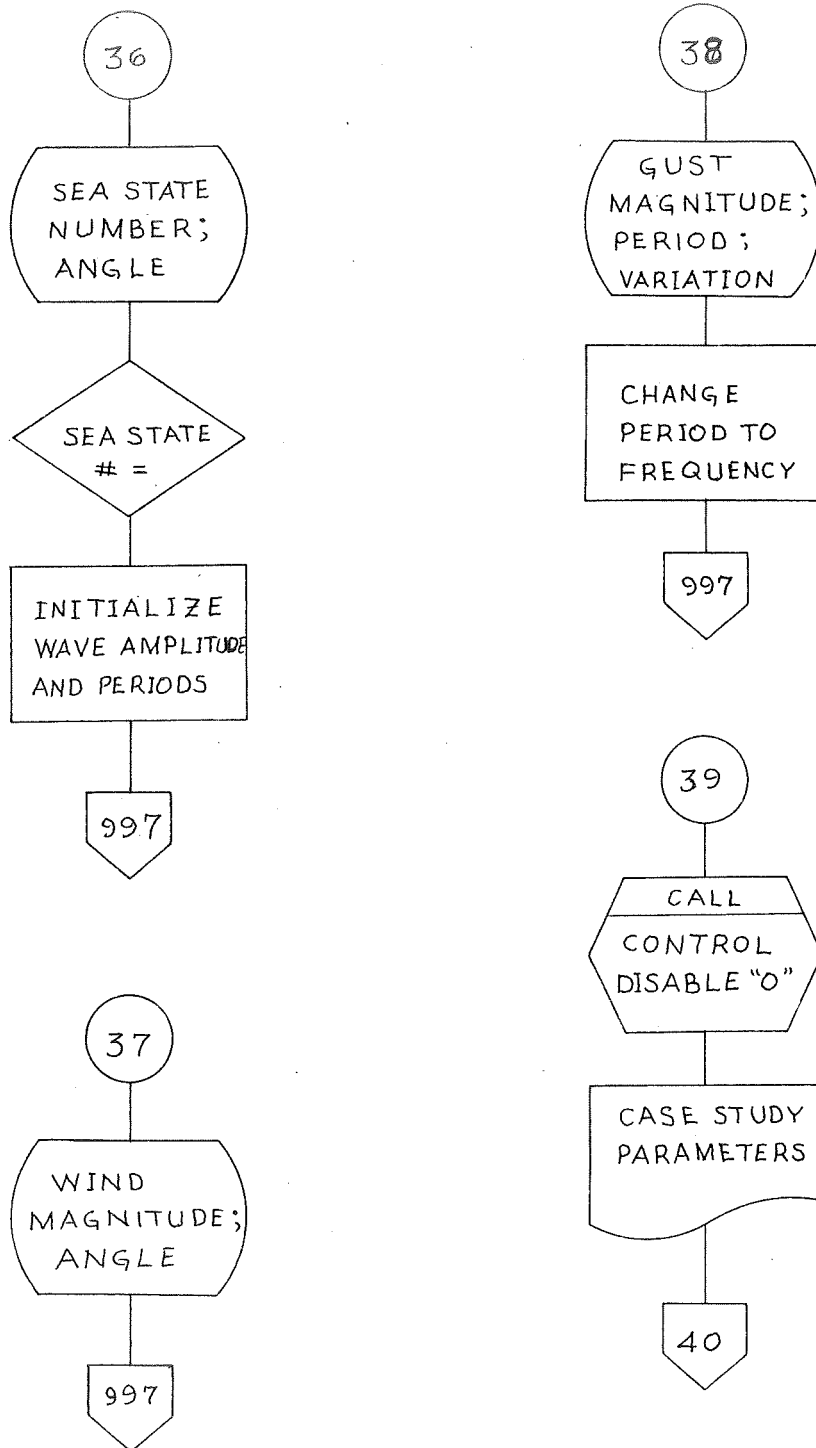


FIGURE 5.1d

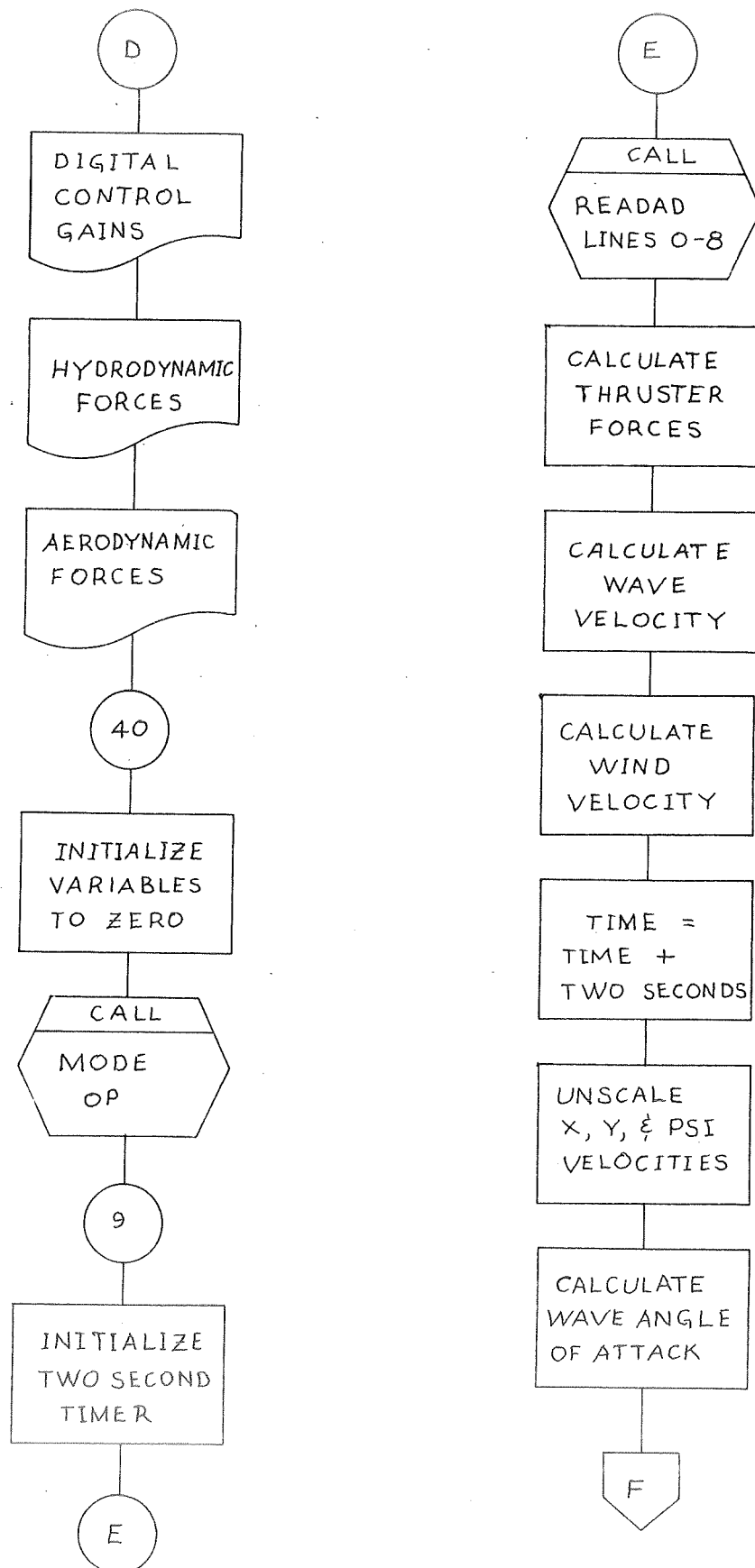


FIGURE 5.1e

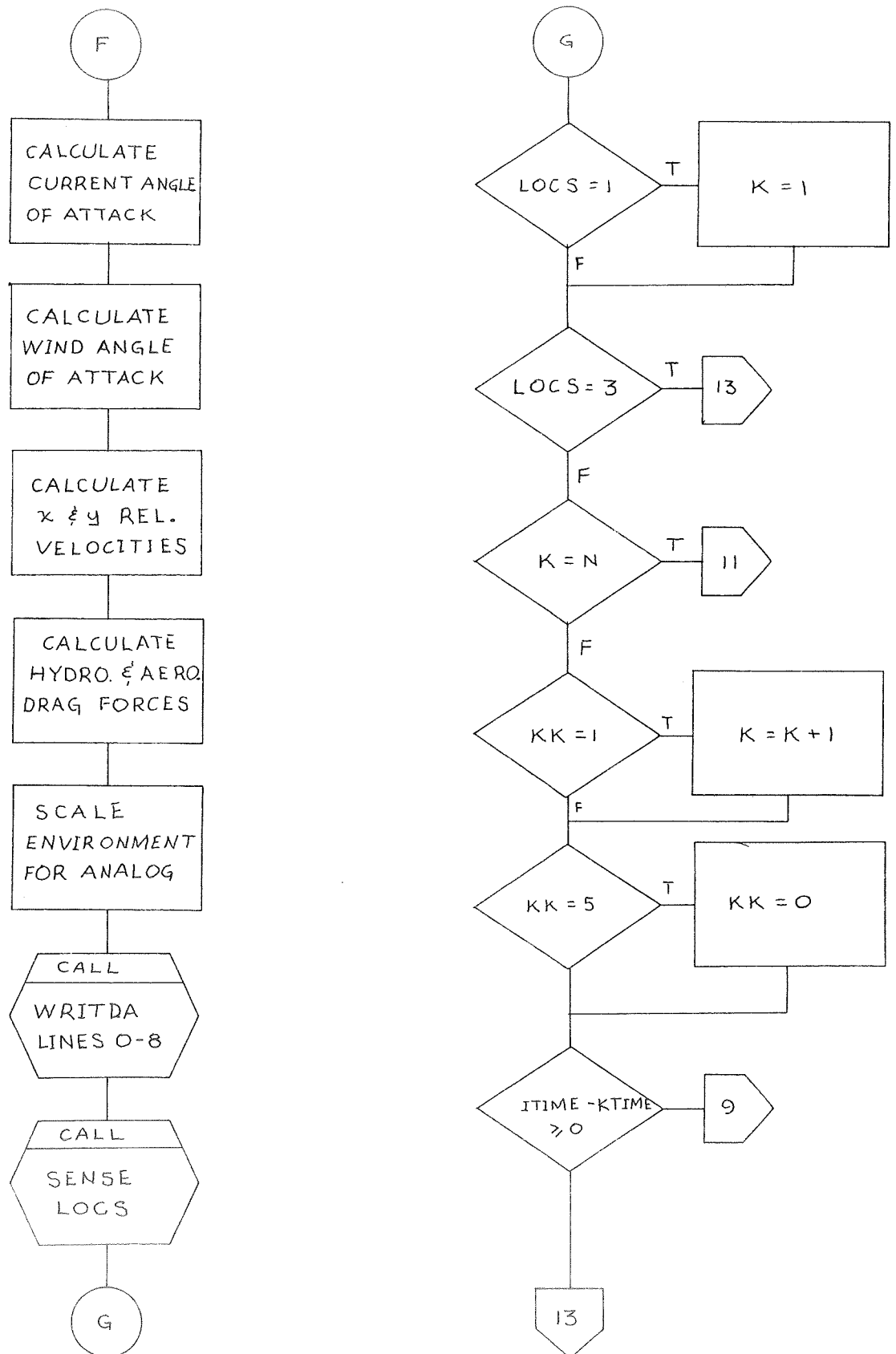


FIGURE 5.1f

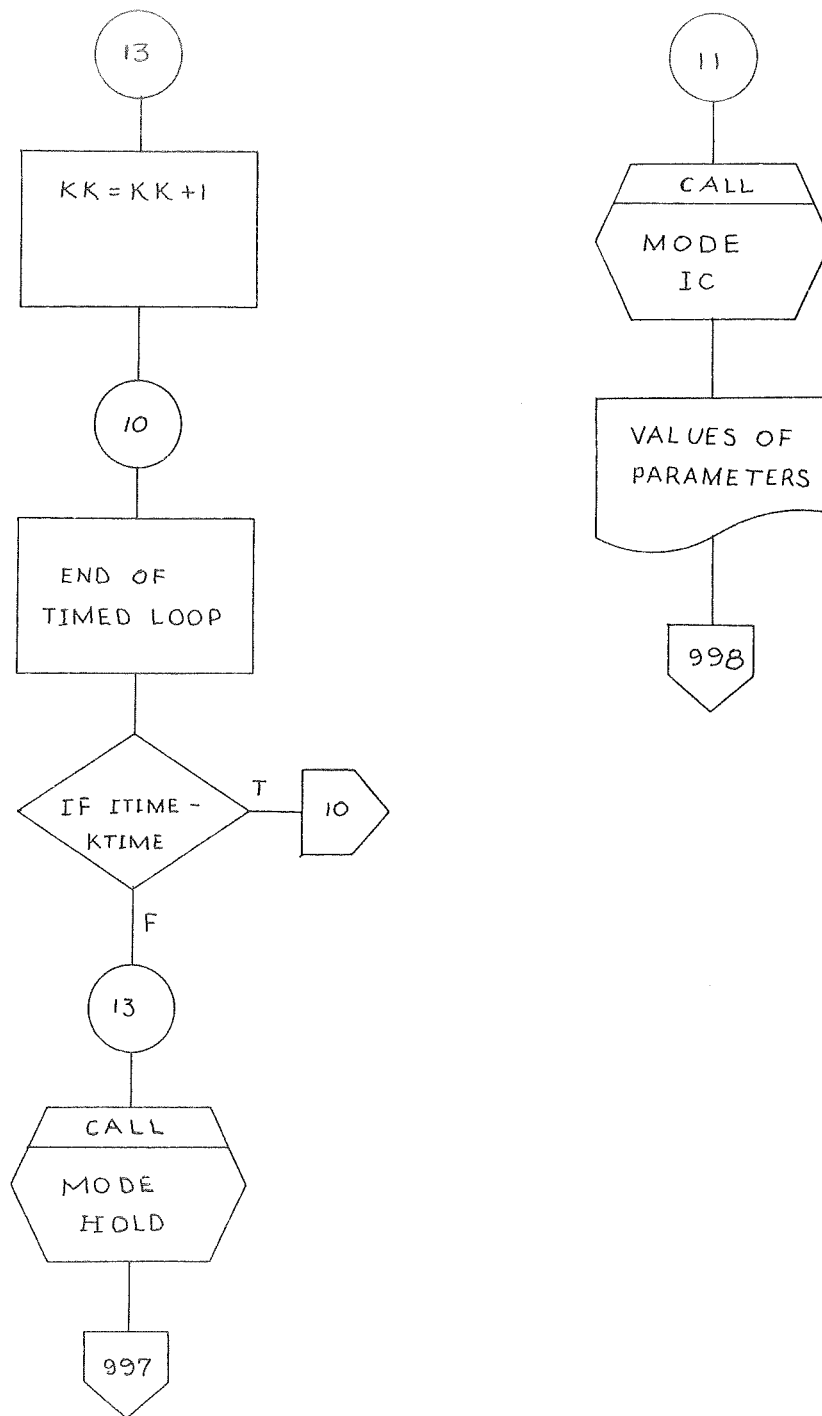


FIGURE 5.1g

## CHAPTER VI

### CASE STUDIES

This thesis investigates one control gain optimization study and three case studies for the response of a dynamic positioning system. There are an infinite combination of environmental variations on the ocean surface. Three representative variations--Sea States 4, 6, and 8--simulate probable operating conditions for the vessel.

Before a case study begins, it is necessary to select the computer time scale. Time can be compressed or expanded, much like an accordion, by altering the time scale. Generally one wants to compute either as quickly as possible, or, in certain applications, in real time. For either case, the upper limit is dictated by the computation cycle time required by the digital computer program (receive information from the analog computer, process this information, and transfer results back to the analog computer). In this case, computation cycle time is slightly less than twenty milliseconds and therefore time is compressed by a factor of one hundred so that twenty milliseconds computer time simulates two seconds actual time.

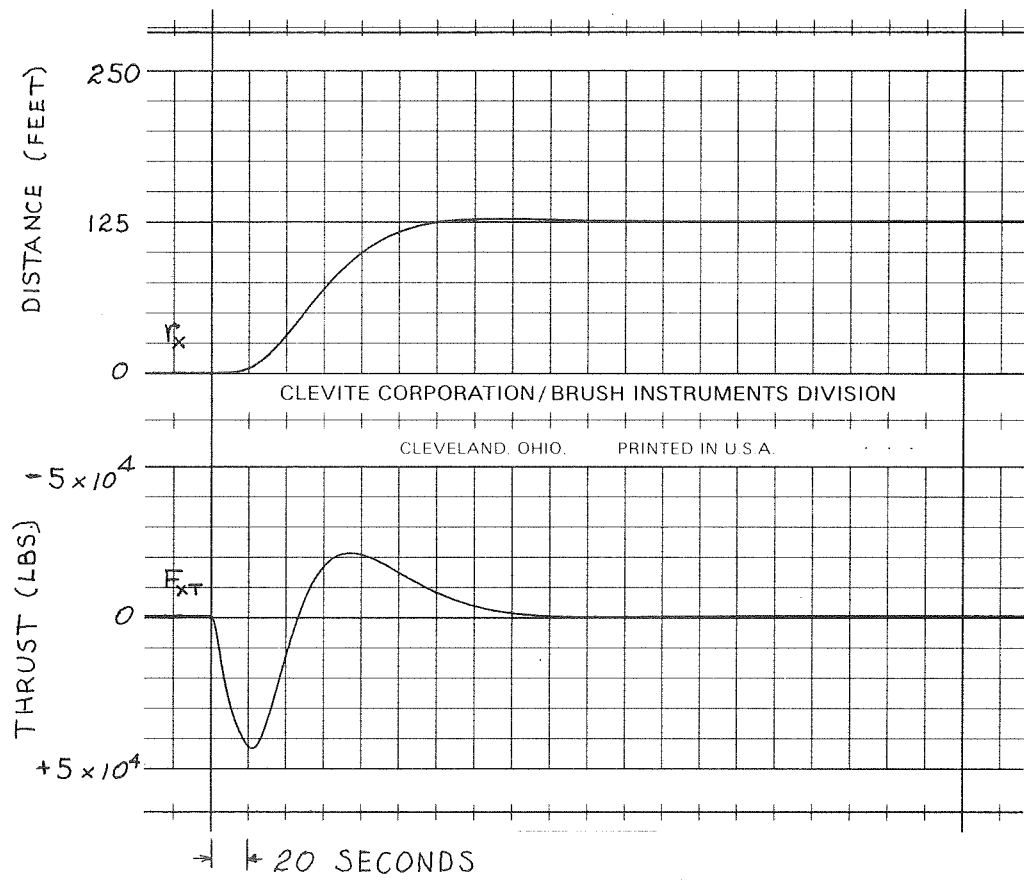
The first investigation is the vessel response to step changes in position and heading. A trial and error technique is used to optimize the control gains. Initial conditions for the vessel are offsets of 125 feet in the X and Y reference



coordinates and 45 degrees in the heading coordinate. These offsets produce a 25 per cent error at the output of the position and heading error comparators. The step response characteristics of each loop are recorded for a chosen set of control gains. The gains are then varied, and the step response recorded again. This process is repeated until any further change in gain settings produces less desirable system response than the previous "best guess" setting. Figures 6.1, 6.2, and 6.3 are typical recordings of the vessel response to step changes. These recordings are representative of both the analog and the digital control system models.

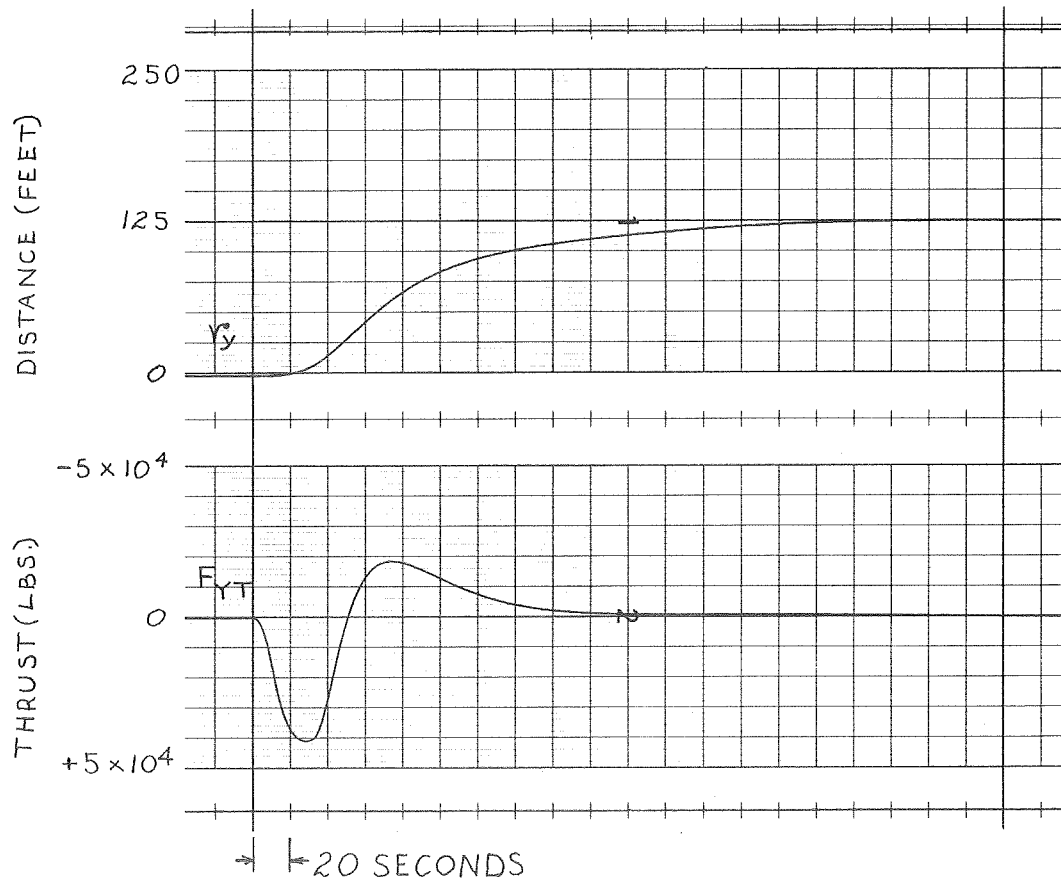
Case studies of Sea States 4, 6, and 8 demonstrate the effects of heading changes on the total magnitude of the thrust required to maintain a selected position. Table IV lists the wind and wave conditions associated with these Sea States. Figures 6.4, 6.5, and 6.6 are illustrations of the wind velocities and the wave profiles of these Sea States. The wave profile for Sea State 8 is a record of hurricane wave data in the Gulf of Mexico. Figures 6.7, 6.9, and 6.11 are illustrations of the environmental force orientation for these three case studies. Figures 6.8, 6.10, and 6.12 are recordings of the vessel heading and the total thruster force required to maintain heading and position.

An oscilloscope monitors the X-position and the Y-position of the vessel during a case study. The X-position provides vertical deflection and the Y-position provides



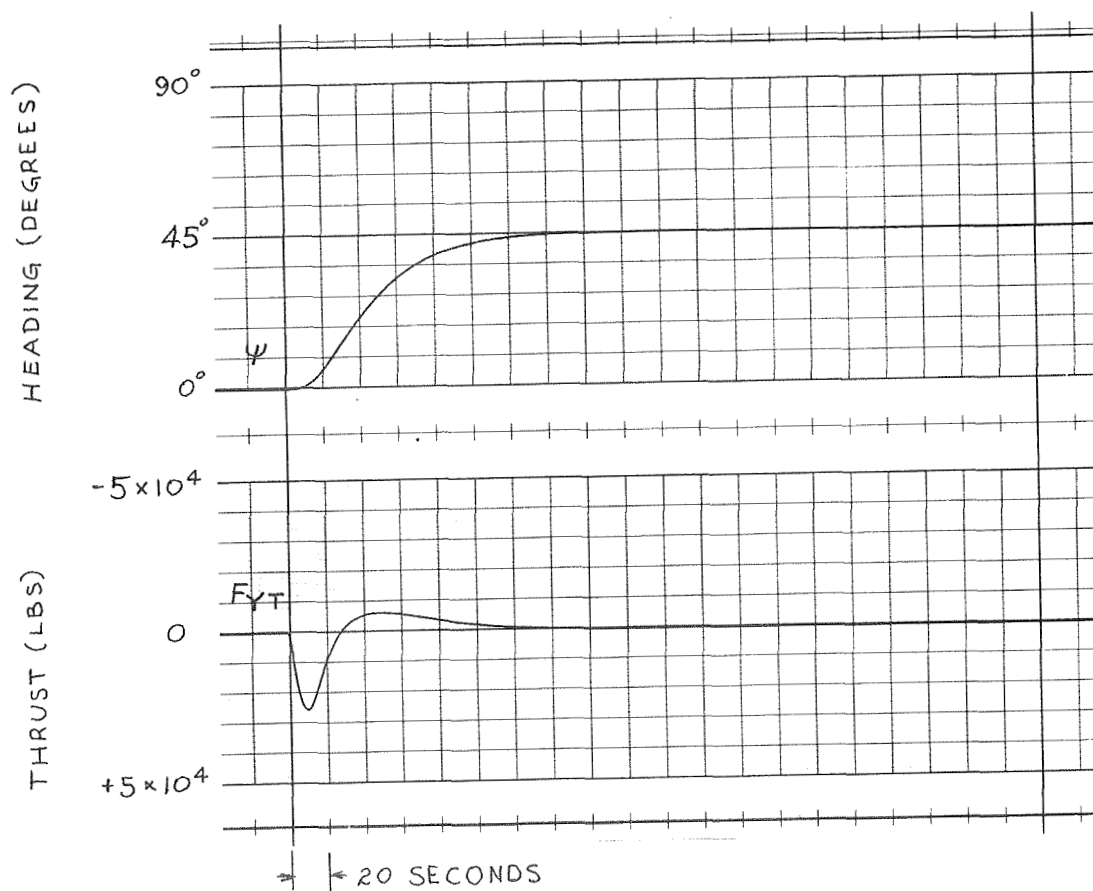
X-LOOP STEP RESPONSE

FIGURE 6.1



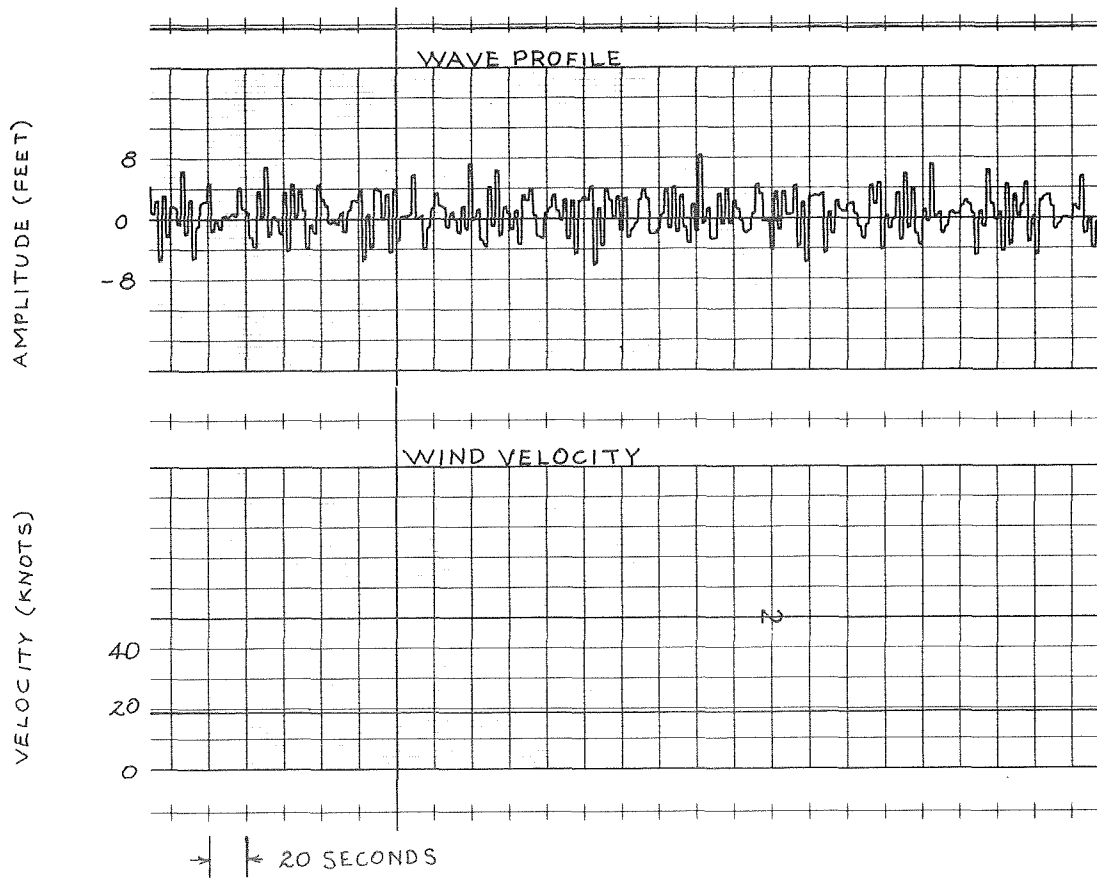
Y-LOOP STEP RESPONSE

FIGURE 6.2



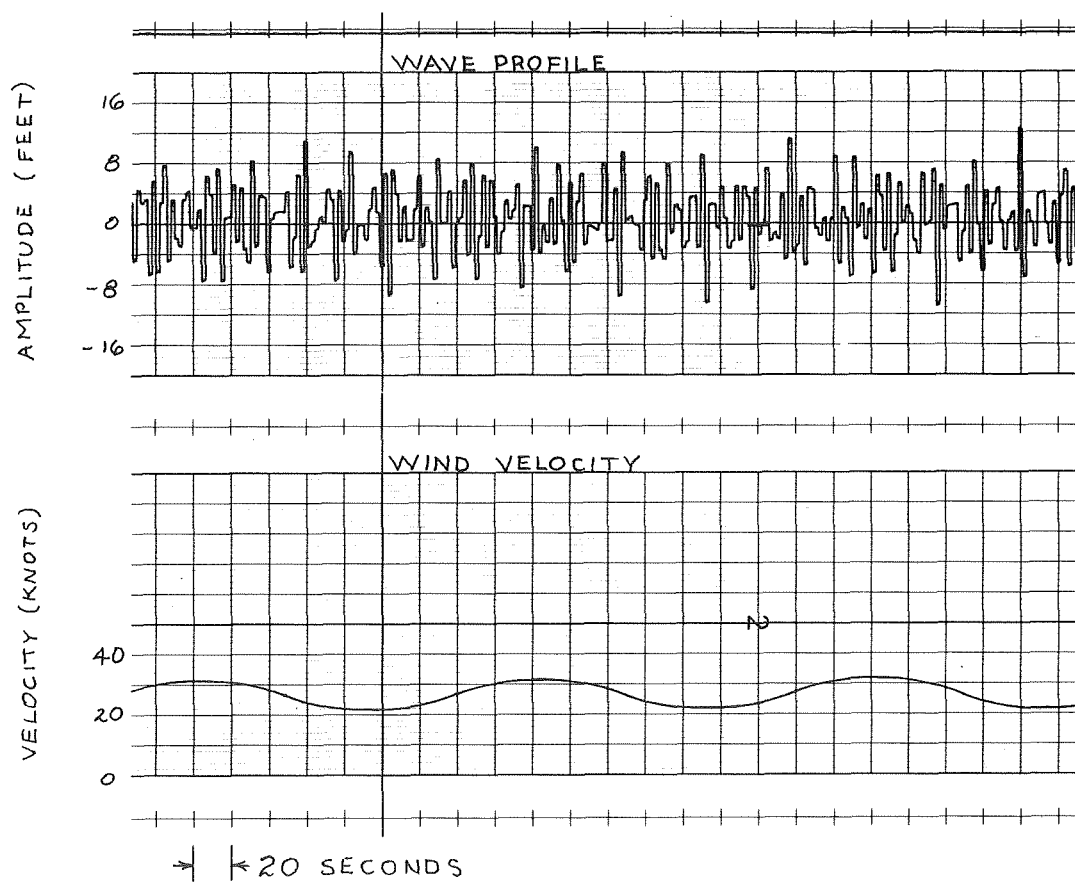
-LOOP STEP RESPONSE

FIGURE 6.3



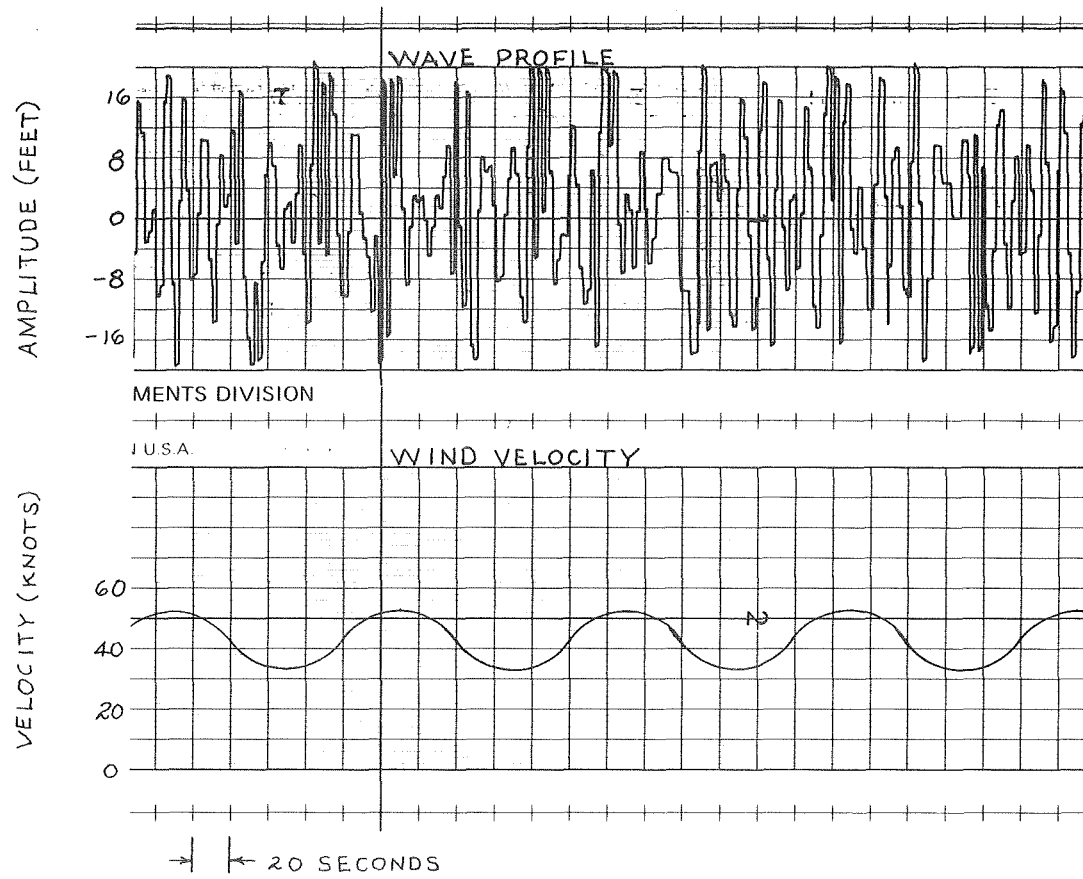
SEA STATE 4

FIGURE 6.4



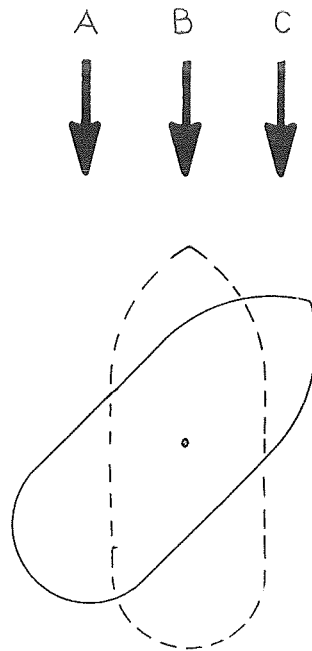
SEA STATE 6

FIGURE 6.5



SEA STATE 8

FIGURE 6.6

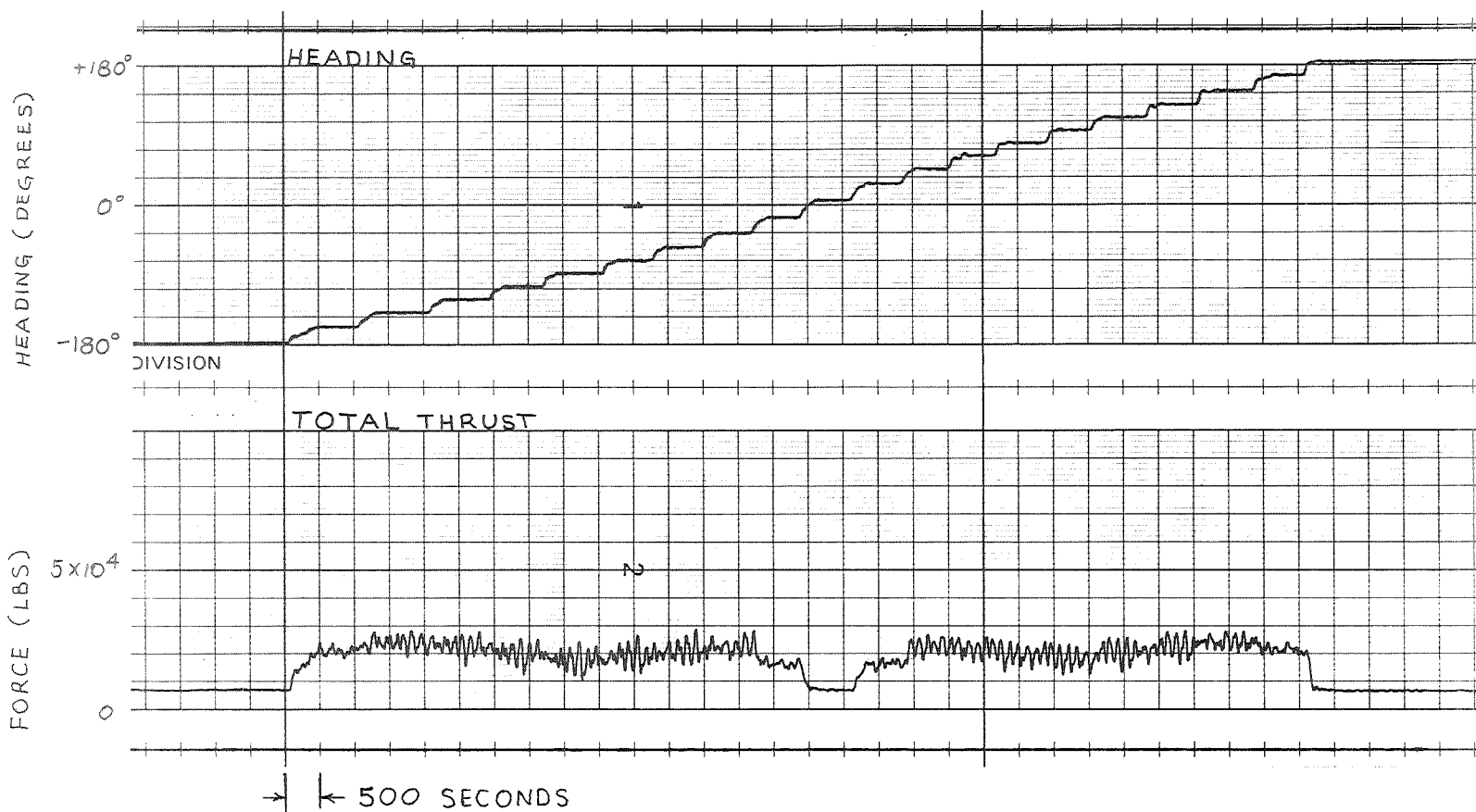


FORCE	DESCRIPTION	HEADING
A	WIND VELOCITY: 19 KNOTS	0 DEGREES
B	WAVES: SEA STATE 4	0 DEGREES
C	CURRENT: 0.5 KNOTS	0 DEGREES

CASE STUDY I

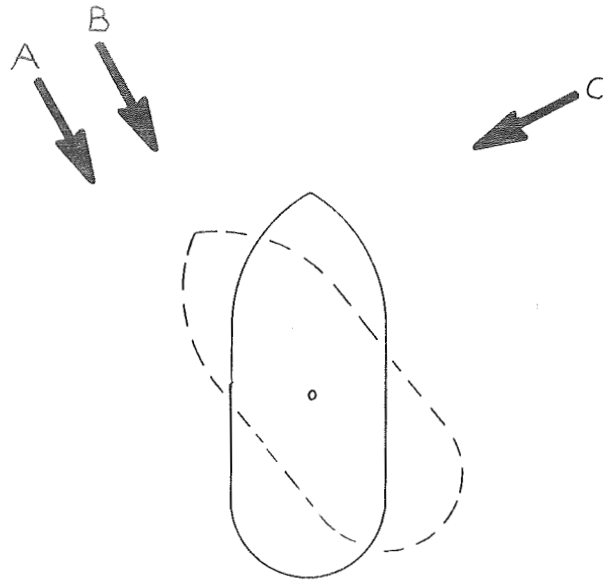
FIGURE 6.7





CASE STUDY I

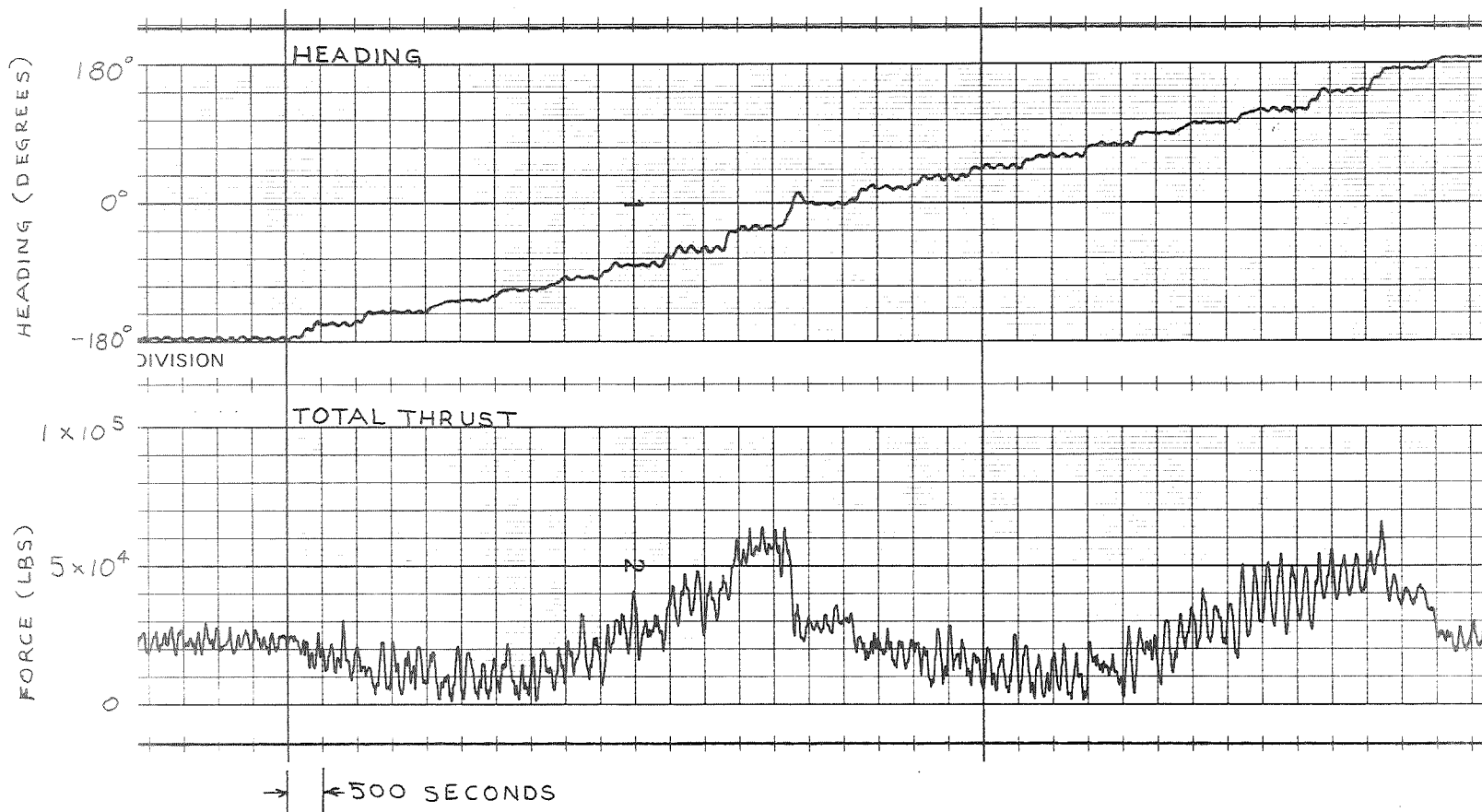
FIGURE 6.8



FORCE	DESCRIPTIONS	HEADING
A	WIND VELOCITY: 27 KNOTS GUST VELOCITY: $\pm 5$ KNOTS GUST PERIOD: 180 SECONDS	-30 DEGREES $\pm 5$ DEGREES
B	WAVES: SEA STATE 6	-30 DEGREES
C	CURRENT: 1 KNOT	+60 DEGREES

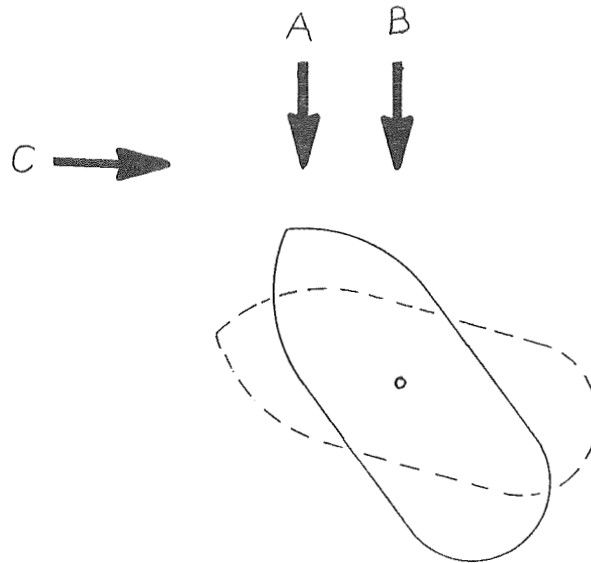
## CASE STUDY II

FIGURE 6.9



CASE STUDY II

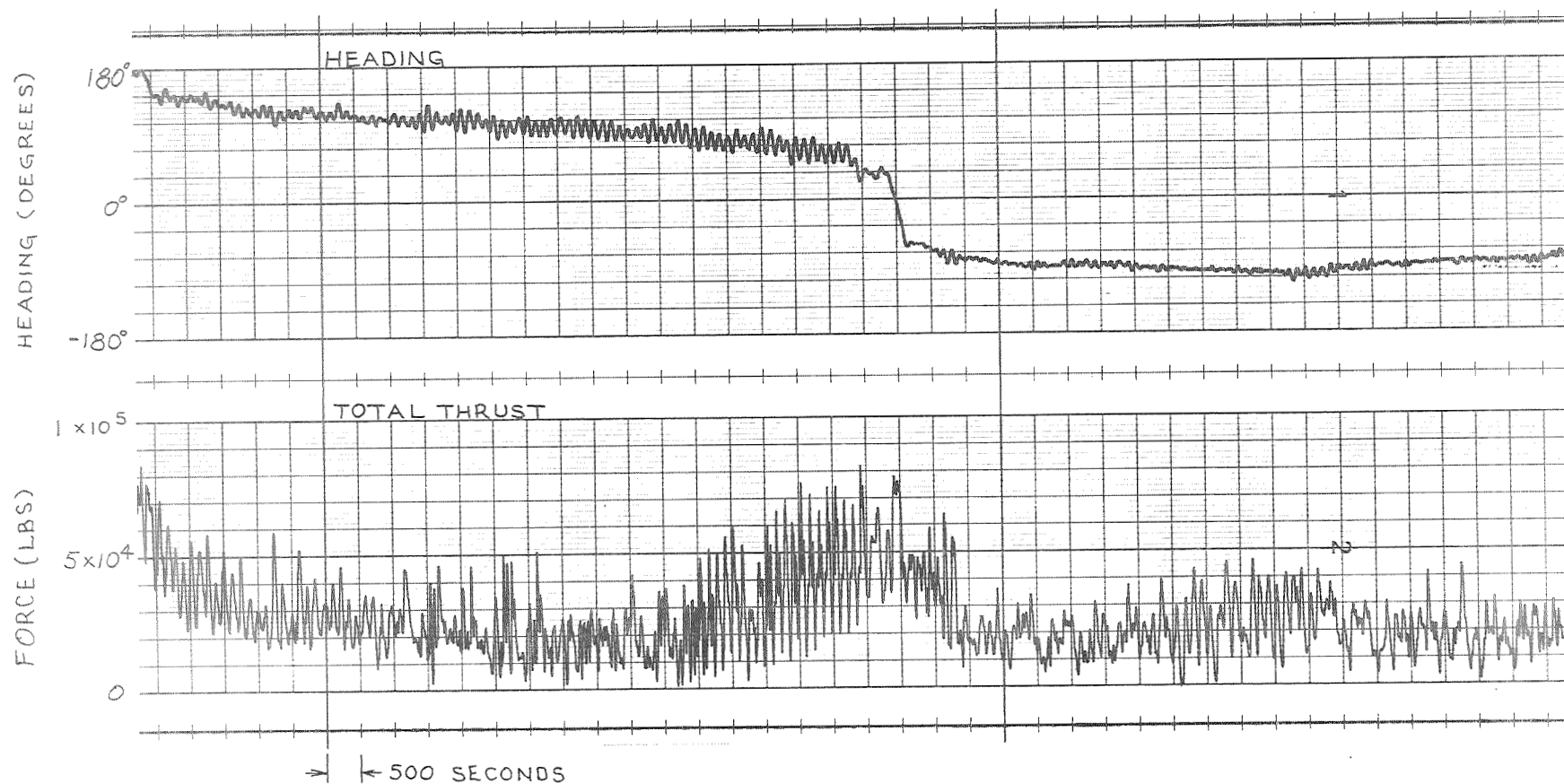
FIGURE 6.10



FORCE	DESCRIPTION	HEADING
A	WIND VELOCITY: 43 KNOTS GUST PERIOD: 120 SECONDS GUST VELOCITY: $\pm 10$ KNOTS	0 DEGREES $\pm 10$ DEGREES
B	WAVES: SEA STATE 8	0 DEGREES
C	CURRENT 2 KNOTS	-90 DEGREES

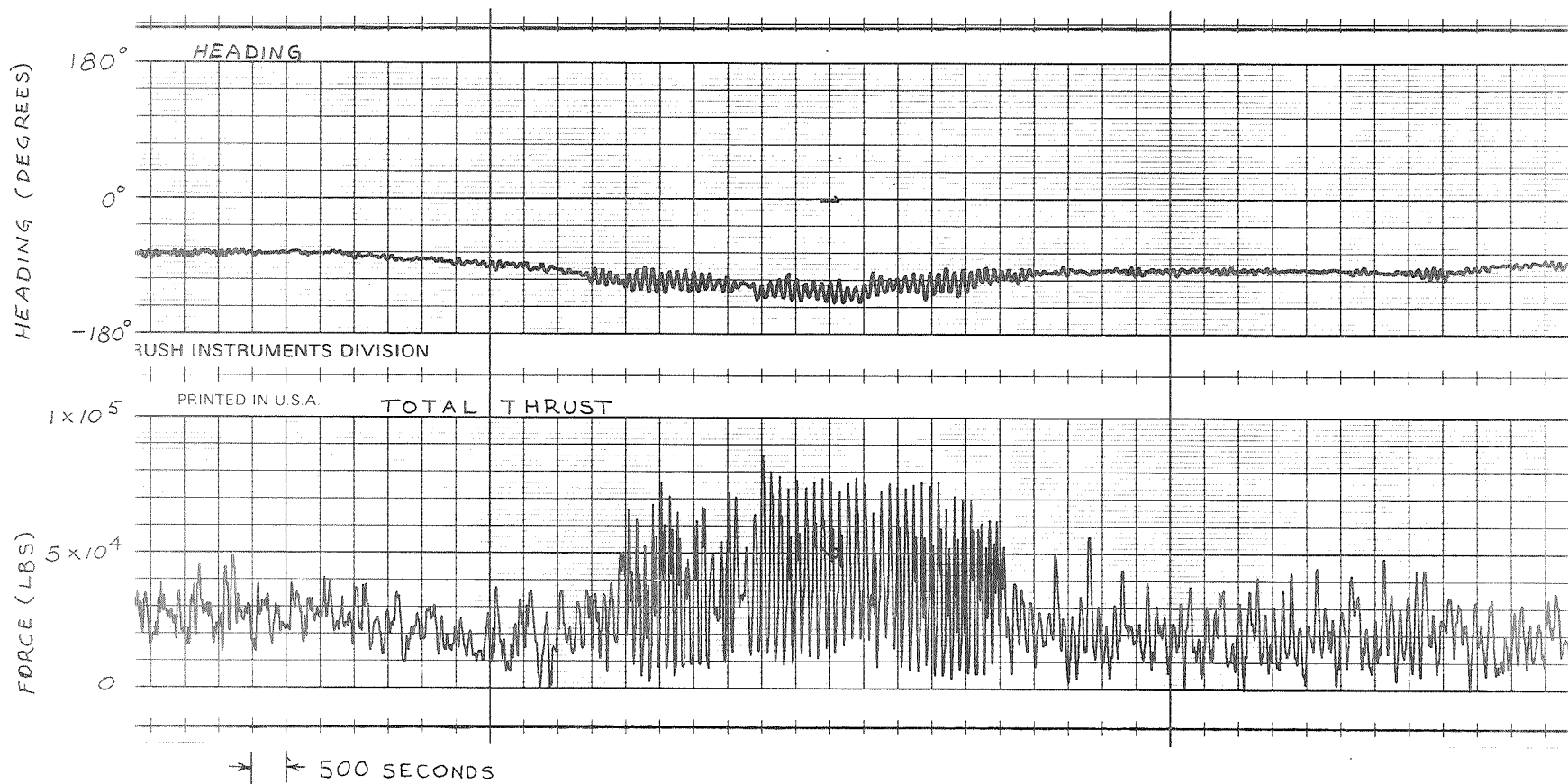
CASE STUDY III

FIGURE 6.11



CASE STUDY III

FIGURE 6.12a



CASE STUDY III

FIGURE 6.12b

horizontal deflection. This monitoring verifies the success of the dynamic positioning system in maintaining position.

For cases I and II, the dynamic positioning system holds the vessel position to within fifty feet of reference zero for all headings.

For case III, X-position errors reach peak values of one hundred feet and Y-position errors reach values as high as 250 feet. Heading errors of fifteen degrees occur in the regions of maximum thrust. The vessel cannot maintain a heading of zero degrees because there is insufficient thrust available to overcome the moment generated at this heading. Headings between -135 degrees and -180 degrees are not shown on the recordings for case III because of insufficient thrust available to maintain position at these angles of attack.

## CHAPTER VII

### CONCLUSIONS

The hybrid computer model developed for this study is an efficient research tool. The model permits detailed investigation of the excitation/response characteristics of a dynamic ship positioning system.

The results of each case study demonstrate the one-parameter optimization technique. A close investigation of the results shows two well-defined optimum headings. These optimum headings occur in approximately eighteen degree bands and are always 180 degrees apart. These studies indicate that for most environmental conditions, the vessel heading will never be more than ninety degrees away from an optimum.

A practical vessel-search algorithm can be formulated to locate this optimum. A possible algorithm is to compare the average thrust level for the present heading with the average thrust level for the immediate past heading. If the thrust level increases, the direction of heading change is reversed. If the thrust decreases, further changes in heading continue until the thrust is at a minimum level. When increments in heading change are ten degrees, an optimum heading results after twelve or fewer changes.

There are two specific problem areas of the present model. One is the selection of gains for the control system.



The optimum control gains are not obvious because the model is nonlinear. Future investigations should consider an adaptive control system which would self-adjust the control gains in order to minimize position error with minimum thrust.

The other problem area involves the generation of false position-error signals resulting from the cross product of  $r$  and  $\omega$ . Small changes in heading introduce large errors in  $x$  and  $y$  position which cause needless thruster reversals and fuel consumption. Future investigations using the present model should consider the possibility of modifying the control system to detect and ignore the false signals.

## TABLES



<u>Parameter</u>	<u>Description</u>	<u>Maximum Value</u>	
$F_x$	Effective component of X-thruster force	$5.0 \times 10^4$ lbs.	
$F_y$	Effective component of Y-thruster force	$5.0 \times 10^4$ lbs.	
$M_\psi$	Effective moment due to thruster force	$1.0 \times 10^7$ ft.lbs.	
$V_x$	X component of vessel velocity	20.0 ft./sec.	
$V_y$	Y component of vessel velocity	2.0 ft./sec.	
$\omega$	Vessel angular velocity	0.1 Rad./sec.	
$r_x$	X coordinate of vessel position	500.0 ft.	
$r_y$	Y coordinate of vessel position	500.0 ft.	
$\psi$	Vessel heading coordinate	$\pi$ degrees	
$m_x$	Effective longitudinal mass of vessel	$7.5 \times 10^5$ slugs	
$m_y$	Effective transverse mass of vessel	$1.1 \times 10^6$ slugs	
$I_\psi$	Effective moment of inertia in yaw	$1.375 \times 10^{10}$ slug-ft. <sup>2</sup>	

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# MODEL MAXIMUM VALUES

TABLE I

POT	SECT "0" VALUE	SECT "1" VALUE	SECT "2" VALUE	SECT "3" VALUE
P" "01	.1000	.0100	.1000	.0230
02	.0050	.1400	.0050	.1800
03	.0033	.0090	.0227	.1910
04	----	.1325	----	.1840
05	.0400	.0100	.0040	.0200
06	.9999	.0100	.9999	.1000
07	----	.0100	----	.0230
08	----	----	.0500	----
09	.1000	.3500	.0050	----
10	.0050	.2400	----	----
11	.0072	.1640	.0050	----
12	.9999	.1000	.0050	
13	.0318	.0240	.0100	
14	.9999	.0630	.1400	
15	----	----	.0100	
16	.1000	----	.1000	
17	.1000	----	.9999	
18	.9999	----	.9999	
19	----	----	----	
20	.1000	.0630	----	

POTENTIOMETER SETTINGS

TABLE II

## HYBRID EXECUTIVE

READAD -- Analog/Digital Conversion  
WRITDA -- Digital/Analog Conversion  
SENSE --- Read Sense Lines  
CONTRL -- Write to Control Lines  
MODE ---- Analog Computer Mode Control  
POTSS --- Set Potentiometers  
ANALOG -- Analog Element Readout

## DAMPS

FRCBSU -- Build a Request Control Block, Fortran  
FRTIO --- Fortran Real Time I/O  
FCHECK -- Check Status of Real Time I/O

## SYSTEM SUBROUTINES

## TABLE III

SEA STATE	DESCRIPTION	WIND KNOTS	WAVE HEIGHT FEET	WAVE PERIOD SECONDS
0	VERY CALM	0	0	---
4	MODERATE WAVES	17-21	4-6	2.5-10
6	LARGE WAVES	25-30	8-12	4-12
8	DISTURBED SEA	40-47	30-50	7-14

## SEA STATE CLASSIFICATION

TABLE IV

SEA STATE	AMPLITUDE				PERIOD			
	A1	A2	A3	A4	T1	T2	T3	T4
0	0	0	0	0	---	---	---	---
4	2.5	1.5	0.75	1.25	10.1	4.9	2.3	3.6
6	5.0	4.0	2.0	1.0	12.2	5.8	3.5	4.2
8	19.1	12.6	9.8	6.8	11.4	8.7	14.05	7.14

## WAVE COMPONENTS

TABLE V

	FOURIER COEFFICIENT	FUNCTION
$F_x$	46.0727	$-\cos(\omega t)$
	9.5869	$\cos(3\omega t)$
	2.2716	$-\cos(7\omega t)$
	2.2570	$\cos(5\omega t)$
	1.8287	$-\cos(9\omega t)$
$F_y$	100.8445	$-\sin(\omega t)$
	7.2288	$-\sin(3\omega t)$
	2.8212	$\sin(7\omega t)$
	2.4385	$\sin(5\omega t)$
	1.7634	$\sin(9\omega t)$
$M_\psi$	$50.6504 \times 10$	$-\sin(2\omega t)$
	$27.2316 \times 10$	$-\sin(\omega t)$
	$7.2552 \times 10$	$-\sin(4\omega t)$
	$1.2857 \times 10$	$\sin(5\omega t)$
	$1.2452 \times 10$	$\sin(8\omega t)$

AERODYNAMIC DRAG FORCE COEFFICIENTS

TABLE VI



	FOURIER COEFFICIENT	FUNCTION
$F_X$	-.1387	DC
	.6200	-COS( $\omega t$ )
	.1809	-COS( $3\omega t$ )
	.1457	COS( $4\omega t$ )
	.0562	-COS( $5\omega t$ )
	.0503	COS( $7\omega t$ )
	.0481	-COS( $2\omega t$ )
	.0372	-COS( $6\omega t$ )
$F_Y$	.7105	-SIN( $\omega t$ )
	.0710	SIN( $2\omega t$ )
	.0416	SIN( $3\omega t$ )
	.0376	SIN( $5\omega t$ )
	.0252	SIN( $7\omega t$ )
$M_\psi$	.5180	-SIN( $2\omega t$ )
	.2034	SIN( $\omega t$ )
	.0725	SIN( $3\omega t$ )
	.0625	-SIN( $5\omega t$ )
	.0565	SIN( $6\omega t$ )
	.0394	SIN( $7\omega t$ )

HYDRODYNAMIC DRAG FORCE COEFFICIENTS

TABLE VII

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APPENDIX A  
SMALL AMPLITUDE WAVE THEORY



## APPENDIX A

### SMALL AMPLITUDE WAVE THEORY

To model the ocean waves, one must understand the basic premise of the mathematical equations. Small amplitude wave theory is a particular case of Laplace's potential flow theory. Figure A.1 shows the coordinate system for this derivation.

The continuity equation for an incompressible fluid in steady or unsteady flow is

$$\frac{\partial u}{\partial t} + \frac{\partial v}{\partial t} + \frac{\partial w}{\partial t} = 0 \quad (\text{A.1})$$

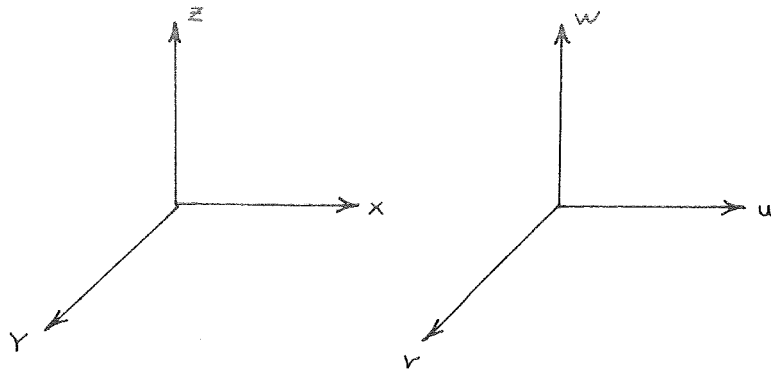
Two dimensional motion in the X, Y plane reduces equation (A.1) to

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \quad (\text{A.2})$$

$\Phi(x, y, t)$  define a scalar function. The following equations represent a velocity potential.

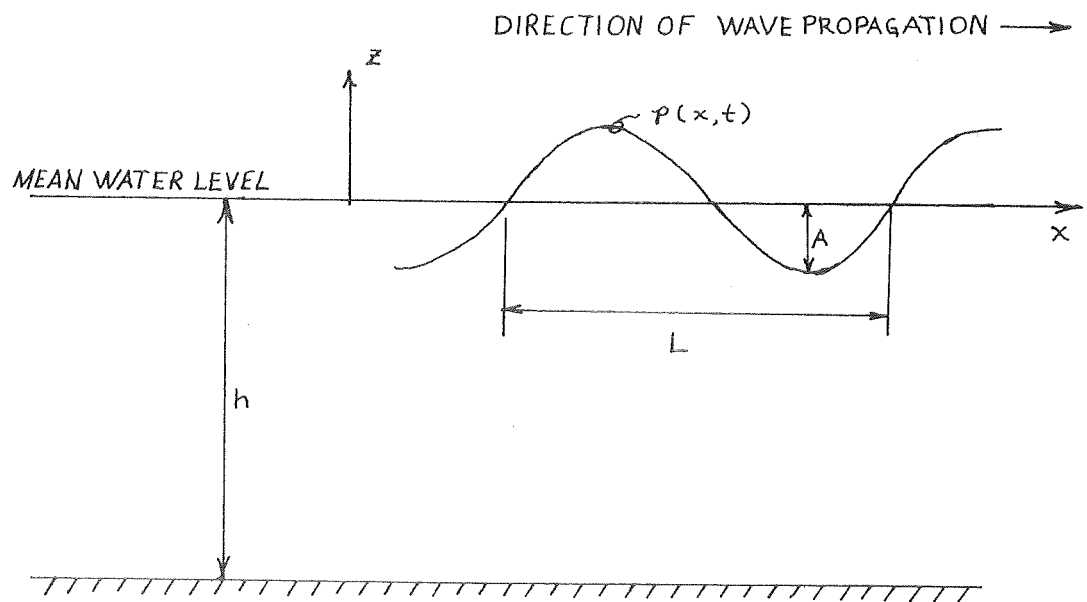
$$\begin{aligned} u &= -\frac{\partial \Phi}{\partial x} \\ w &= -\frac{\partial \Phi}{\partial z} \end{aligned} \quad (\text{A.3})$$

The combination of equations (A.2) and (A.3) yields



COORDINATE SYSTEM

FIGURE A.1



PROFILE OF A SMALL AMPLITUDE WAVE

FIGURE A.2

Laplace's equation.

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \quad (\text{A.4})$$

The appropriate boundary conditions of water waves are necessary to solve this partial differential equation. Figure A.2 presents a simple harmonic, progressive wave moving in the +x direction. In Figure A.2, h represents the depth of the water; A the amplitude of the wave;  $p(x,t)$  the wave profile; and l the wave length. Equation (A.4) must be satisfied in the region

$$-h \leq z \leq p$$

Determination of the boundary conditions at the surface and the ocean floor is a prerequisite for solving equation (A.4). If the bottom is a fixed impermeable horizontal boundary, the first boundary condition is

$$\begin{aligned} w &= - \frac{\partial \Phi}{\partial z} = 0 & (z = -h) \\ p(x,t) &= \frac{1}{g} \frac{\partial \Phi}{\partial t} & (z = 0) \end{aligned} \quad (\text{A.6})$$

The acceleration of gravity, g, is the restoring force for the vertical motion of the wave. It is necessary to solve equation (A.4) and satisfy the boundary conditions specified by (A.5) and (A.6) to obtain the mathematical model of an ocean wave.



$$\Phi = \alpha(x) \times \beta(z) \times \gamma(t) \quad (\text{A.7})$$

Substituting (A.7) in (A.4) yields

$$\alpha''(x)\beta(z)\gamma(t) + \alpha(x)\beta''(z)\gamma(t) = 0 \quad (\text{A.8})$$

Dividing (A.8) by (A.7) yields

$$\frac{\alpha''(x)}{\alpha(x)} + \frac{\beta''(z)}{\beta(z)} = 0 \quad (\text{A.9})$$

It follows that

$$\frac{\alpha''(x)}{\alpha(x)} = -\frac{\beta''(z)}{\beta(z)} = \text{CONSTANT} \quad (\text{A.10})$$

If the constant is  $-k^2$ , equation (A.10) becomes

$$\alpha''(x) + k^2 \alpha(x) = 0 \quad (\text{A.11})$$

$$\beta''(z) - k^2 \beta(z) = 0 \quad (\text{A.12})$$

The solution of (A.11) yields

$$\alpha(x) = C_1 \cos(kx) + C_2 \sin(kx) \quad (\text{A.13})$$

The solution of (A.12) yields

$$\beta(z) = c_3 e^{kz} + c_4 e^{-kz} \quad (\text{A.14})$$

$c_1, c_2, c_3$ , and  $c_4$  are arbitrary constants.

Equation (A.7) becomes

$$\Phi = (c_1 \cos(kx) + c_2 \sin(kx))(c_3 e^{kz} + c_4 e^{-kz}) \gamma(t) \quad (\text{A.15})$$

It is desirable that the solution of (A.15) be simple harmonic in time. Therefore, let  $\gamma(t)$  be either  $\sin(\omega t)$  or  $\cos(\omega t)$  where  $\omega$  represents the angular frequency of the wave. Evaluating (A.15) at the boundary values yields the wave equation. Because (A.15) is a linear equation, an elementary set of  $\Phi$  equations is

$$\Phi_1 = c_1 (c_3 e^{kz} + c_4 e^{-kz}) \cos(kx) \cos(\omega t) \quad (\text{A.16})$$

$$\Phi_2 = c_1 (c_3 e^{kz} + c_4 e^{-kz}) \cos(kx) \sin(\omega t) \quad (\text{A.17})$$

$$\Phi_3 = c_2 (c_3 e^{kz} + c_4 e^{-kz}) \sin(kx) \cos(\omega t) \quad (\text{A.18})$$

$$\Phi_4 = c_2 (c_3 e^{kz} + c_4 e^{-kz}) \sin(kx) \sin(\omega t) \quad (\text{A.19})$$

Applying (A.5) to (A.16)

$$\left[ \frac{\partial \Phi_1}{\partial z} \right]_{z=-h} = 0 = c_1 \cos(kx) \cos(\omega t) [c_3 k e^{-kh} - c_4 k e^{kh}] \quad (\text{A.20})$$

$$c_4 k e^{\kappa h} = c_3 k e^{-\kappa h}$$

$$c_4 = c_3 e^{-2\kappa h} \quad (\text{A.21})$$

Substituting (A.21) into (A.16) and rewriting the result yields

$$\Phi_1 = 2c_1 c_3 e^{\kappa h} \frac{[e^{\kappa(h+z)} + e^{-\kappa(h+z)}]}{2} \cos(kx) \cos(\omega t) \quad (\text{A.22})$$

$$\Phi_1 = 2c_1 c_3 e^{\kappa h} \cosh[\kappa(h+z)] \cos(kx) \cos(\omega t) \quad (\text{A.23})$$

Now applying (A.6) to (A.23) yields

$$\frac{1}{g} \left[ \frac{\partial \Phi_1}{\partial t} \right]_{z=0} = p(x,t) = \frac{-2\omega c_1 c_3}{g} e^{\kappa h} \cosh(\kappa h) \cos(kx) \sin(\omega t) \quad (\text{A.24})$$

The maximum value  $p(x,t)$  can have is  $A$ , the wave height.

The maximum for (A.24) occurs only when  $\cos(kx)\sin(\omega t)=1$ .

Making these substitutions yields

$$c_1 c_3 e^{\kappa h} = - \frac{Ag}{2\omega \cosh(\kappa h)} \quad (\text{A.25})$$

The constants in the remaining elementary equations are obtained in a similar manner. The results are summarized below.

$$\Phi_1 = - \frac{Ag \cosh[\kappa(h+z)]}{\omega \cosh[\kappa h]} \cos(kx) \cos(\omega t) \quad (\text{A.26})$$

$$\Phi_2 = \frac{Ag \cosh[k(h+z)]}{\omega \cosh(kh)} \sin(kx) \sin(\omega t) \quad (\text{A.27})$$

$$\Phi_3 = - \frac{Ag \cosh[k(h+z)]}{\omega \cosh(kh)} \sin(kx) \cos(\omega t) \quad (\text{A.28})$$

$$\Phi_4 = \frac{Ag \cosh[k(h+z)]}{\omega \cosh(kh)} \cos(kx) \sin(\omega t) \quad (\text{A.29})$$

Since Laplace's equation is linear, we can linearly combine its solutions to form other solutions. By adding (A.28) and (A.29) and substituting the trigonometric identity,  $\sin(\omega t - kx) = \sin(\omega t)\cos(kx) - \cos(\omega t)\sin(kx)$ , the result is

$$\Phi = \Phi_3 + \Phi_4 = \frac{Ag \cosh[k(h+z)]}{\omega \cosh(kh)} \sin(\omega t - kx) \quad (\text{A.30})$$

From (A.6) we obtain the equation for the surface of a wave

$$p(x, t) = \frac{1}{g} \left[ \frac{\partial \Phi}{\partial t} \right]_{z=0} = A \cos(\omega t - kx) \quad (\text{A.31})$$

To solve for  $k$ , we make use of the fact that  $p$  is periodic in  $x$  and  $t$ . If we choose some constant position on the wave profile and travel with the wave keeping this same position, then equation (A.31) reduces to

$$p(x, t) = \text{CONSTANT} = A \cos(\omega t - kx) \\ \omega t - kx = \text{CONSTANT}$$

and the wave's propagational velocity is

$$\frac{L}{T} = \frac{dx}{dt} = \frac{\omega}{k} \quad (\text{A.32})$$

Solving for  $k$  yields

$$k = \frac{\omega T}{L} = \frac{2\pi}{L} \quad (\text{A.33})$$

Substituting (A.33) into (A.31) and (A.30) yields the wave profile equation

$$p(x, t) = A \cos \left( \omega t - \frac{2\pi x}{L} \right) \quad (\text{A.34})$$

and the velocity potential equation

$$\Phi(x, z, t) = \frac{Ag \cosh \left[ \frac{2\pi}{L} (h+z) \right]}{\omega \cosh \left[ \frac{2\pi h}{L} \right]} \sin \left( \omega t - \frac{2\pi x}{L} \right) \quad (\text{A.35})$$

From the velocity potential equation, the component particle velocities of the wave are found. First, the relationship between period, wave length, and propagational velocity must be determined. Equation (A.32) describes the propagational velocity. The vertical velocity component,  $w$ , is

$$w = \frac{\partial p}{\partial t} + \cancel{\frac{\partial p}{\partial x} \frac{\partial x}{\partial t}} \rightarrow 0 \quad (\text{A.36})$$

Because the wave amplitude is very small, equation (A.36) is approximated by

$$\omega = - \frac{\partial p}{\partial z} \quad (\text{A.37})$$

Because of the properties of the velocity potential equation,  $w$  also takes the form

$$\omega = - \frac{\partial \Phi}{\partial z} \quad (\text{A.38})$$

Equating (A.27) and (A.38) yields

$$- \frac{\partial \Phi}{\partial z} = \frac{\partial p}{\partial t} \quad (\text{A.39})$$

Substituting (A.6) yields

$$\frac{\partial \Phi}{\partial z} = \frac{1}{g} \frac{\partial^2 \Phi}{\partial t^2} \quad (z=0) \quad (\text{A.40})$$

Applying (A.35) yields

$$- \frac{\partial \Phi}{\partial z} = - \frac{A g 2\pi}{\omega L} \tanh \frac{2\pi h}{L} \sin \left( \omega t - \frac{2\pi x}{L} \right) \quad (\text{A.41})$$

$$\frac{1}{g} \left[ \frac{\partial^2 \Phi}{\partial t^2} \right]_{z=0} = -A \omega \sin \left( \omega t - \frac{2\pi x}{L} \right) \quad (\text{A.42})$$

Substituting (A.41) and (A.42) into (A.40) yields

$$\begin{aligned} \omega^2 &= \frac{2\pi}{L} g \tanh \frac{2\pi h}{L} \\ L &= \frac{2\pi}{\omega^2} g \tanh \frac{2\pi h}{L} \end{aligned} \quad (\text{A.43})$$

$$L = \frac{gT^2}{2\pi} \tanh \frac{2\pi h}{L} \quad (\text{A.43})$$

The horizontal velocity,  $u$ , is

$$u = -\frac{\partial \Phi}{\partial x}$$

$$u = \frac{2\pi A g}{\omega L} \frac{\cosh \left[ \frac{2\pi}{L} (h+z) \right]}{\cosh \left[ \frac{2\pi h}{L} \right]} \cos \left( \omega t - \frac{2\pi x}{L} \right) \quad (\text{A.44})$$

Substituting (A.43) into (A.44) yields

$$u = A \omega \cos \left( \omega t - \frac{2\pi x}{L} \right) \frac{\cosh \left[ \frac{2\pi}{L} (h+z) \right]}{\sinh \left[ \frac{2\pi h}{L} \right]} \quad (\text{A.45})$$

Evaluating  $u$  at the surface, ( $z=0$ ); in deep water with small amplitude waves

$$\frac{h}{L} \gg \frac{1}{2}$$

Equation (A.45) becomes

$$u = A \omega \cos \left( \omega t - \frac{2\pi x}{L} \right) \cancel{\tanh \frac{2\pi h}{L}}^{\approx 1} \quad (\text{A.46})$$

$$u = A \omega \cos \left( \omega t - \frac{2\pi x}{L} \right)$$

Using ( $x=0$ ) as the reference point, equation (A.46) becomes

$$u = A \omega \cos (\omega t) \quad (\text{A.47})$$

Differentiating equation (A.47) yields the horizontal particle

acceleration.

$$\frac{\partial u}{\partial t} = -A \omega^2 \sin(\omega t) \quad (\text{A.48})$$

Equations (A.47) and (A.48) represent a simple one component wave. Because Laplace's equation is linear, a linear superposition of simple one component waves produces a multicomponent complex wave. The complex wave equations are

$$u(x, t) = \sum_{i=1}^n A_i \omega_i \cos\left(\omega_i t - \frac{2\pi x_i}{L_i}\right) \frac{\cosh\left[\frac{2\pi(h+z)}{L_i}\right]}{\sinh\left[\frac{2\pi h}{L_i}\right]} \quad (\text{A.49})$$

$$\frac{\partial u}{\partial t} = \sum_{i=1}^n -A_i \omega_i^2 \sin\left(\omega_i t - \frac{2\pi x_i}{L_i}\right) \frac{\cosh\left[\frac{2\pi(h+z)}{L_i}\right]}{\sinh\left[\frac{2\pi h}{L_i}\right]} \quad (\text{A.50})$$

Applying the same small amplitude, deep water relationships used to reduce equations (A.45) to (A.47), the reduced complex wave equations are

$$u(t) = \sum_{i=1}^n A_i \omega_i \cos(\omega_i t) \quad (\text{A.51})$$

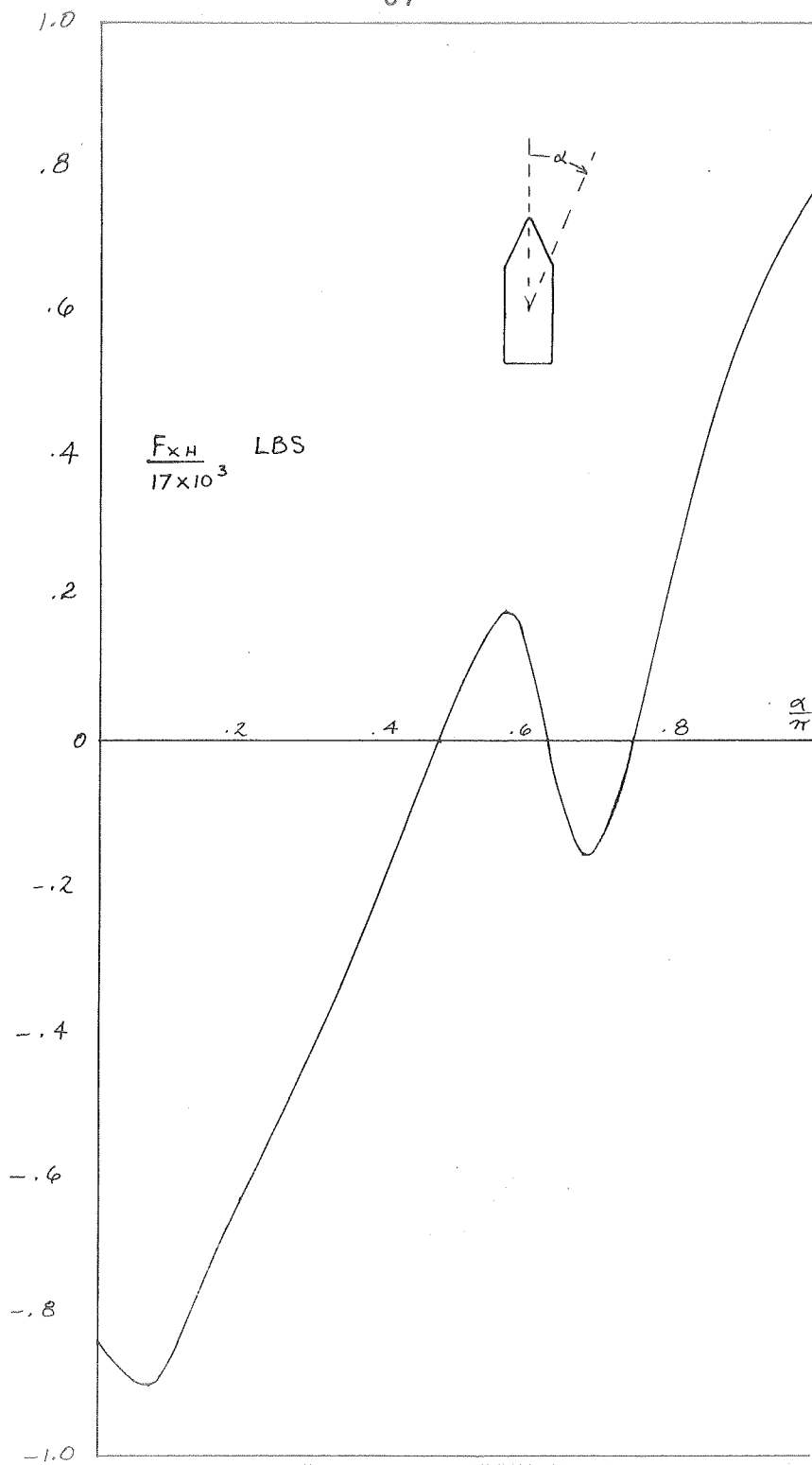
$$\frac{\partial u}{\partial t} = \sum_{i=1}^n -A_i \omega_i^2 \sin(\omega_i t) \quad (\text{A.52})$$





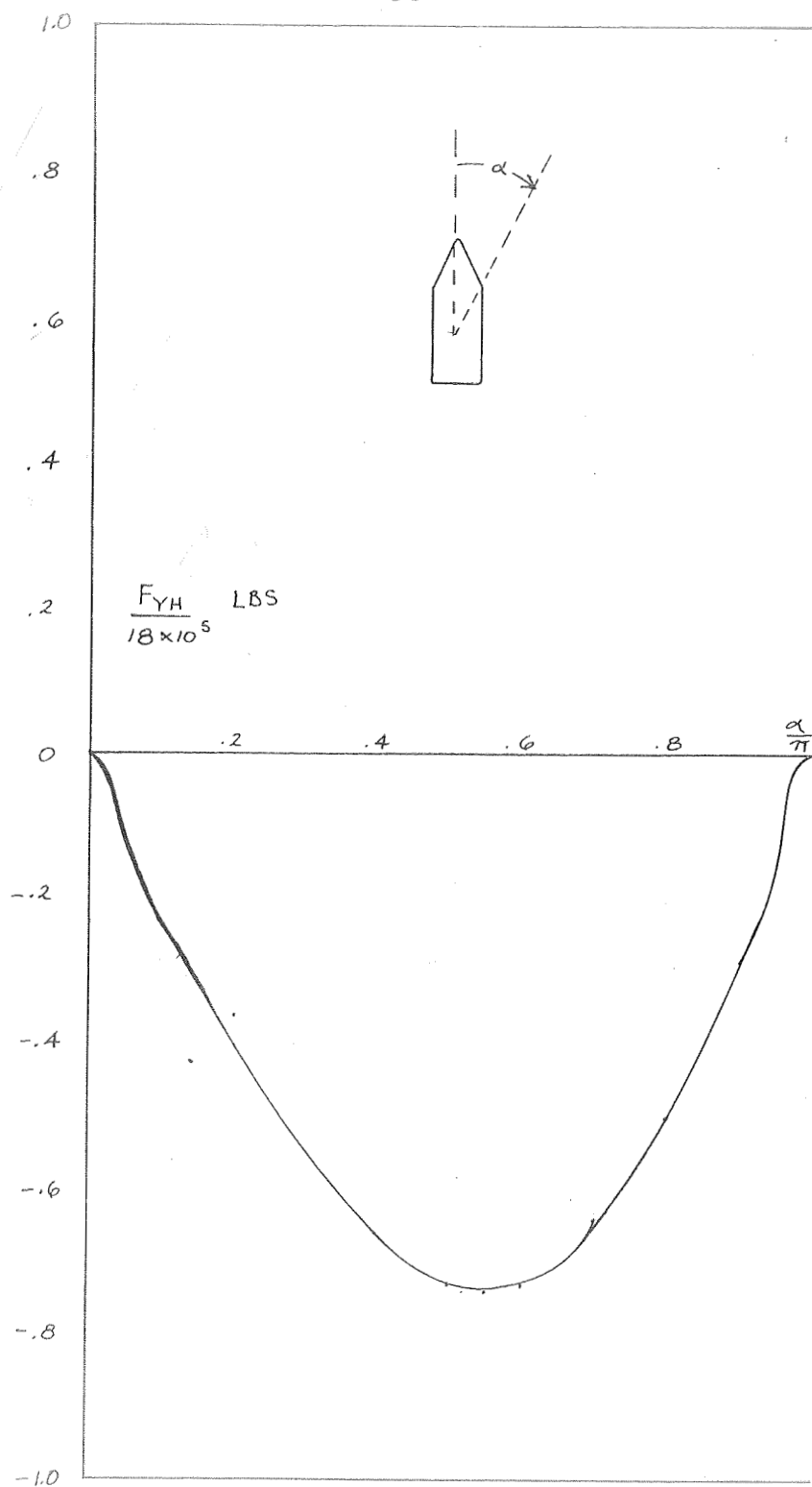
APPENDIX B  
HYDRODYNAMIC AND AERODYNAMIC  
DRAG FORCE DATA





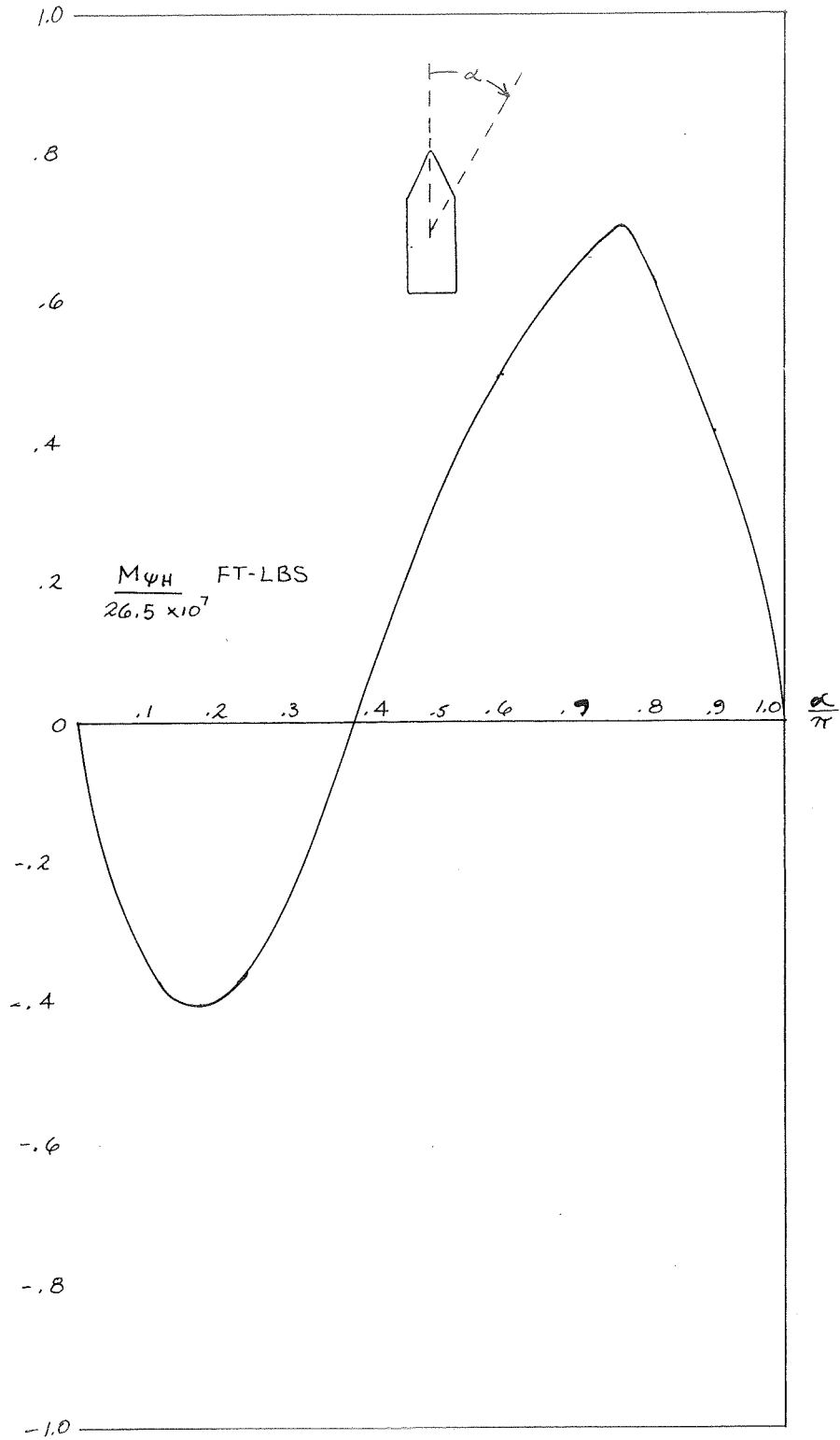
X-HYDRODYNAMIC DRAG FORCE

FIGURE B.1



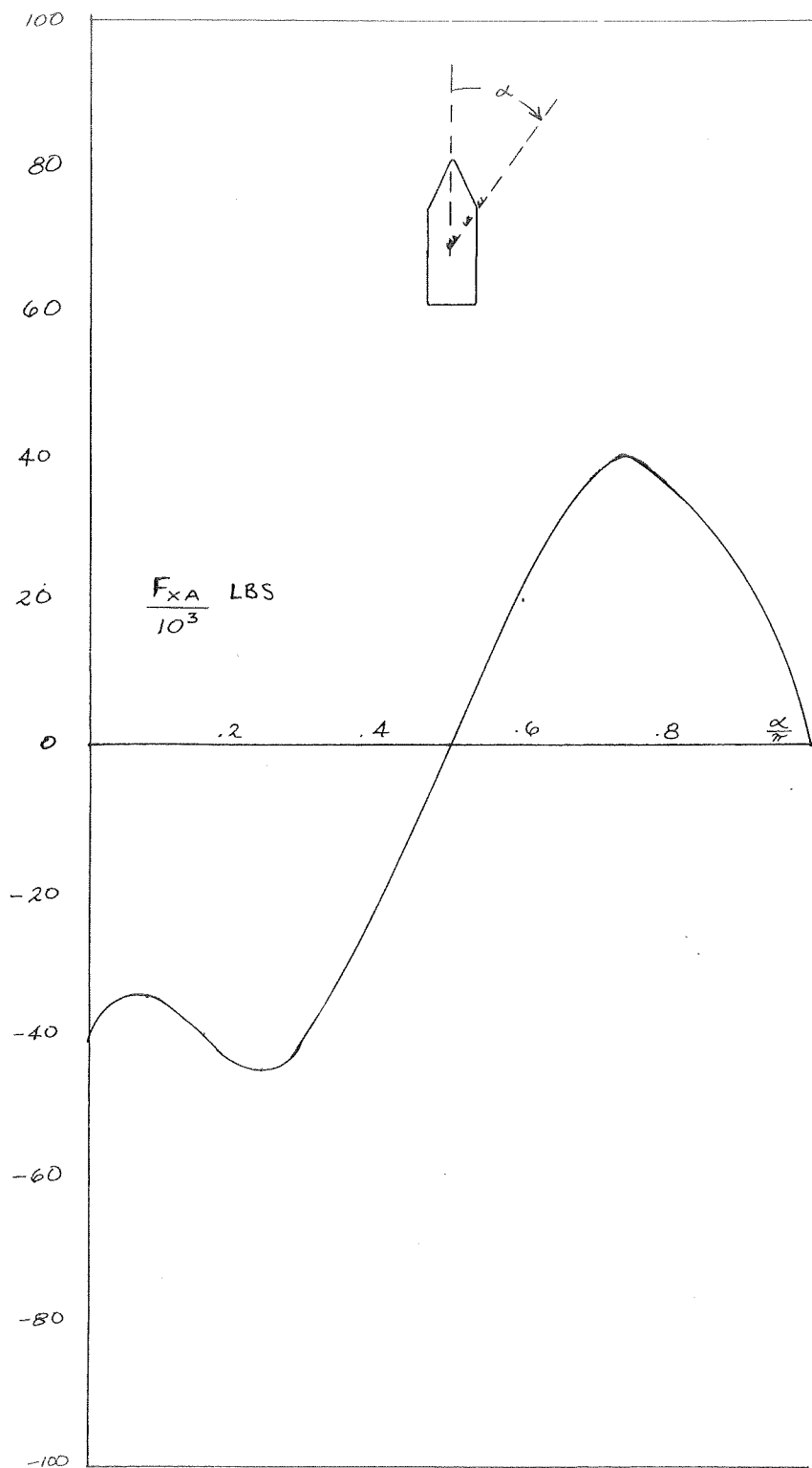
Y-HYDRODYNAMIC DRAG FORCE

FIGURE B.2



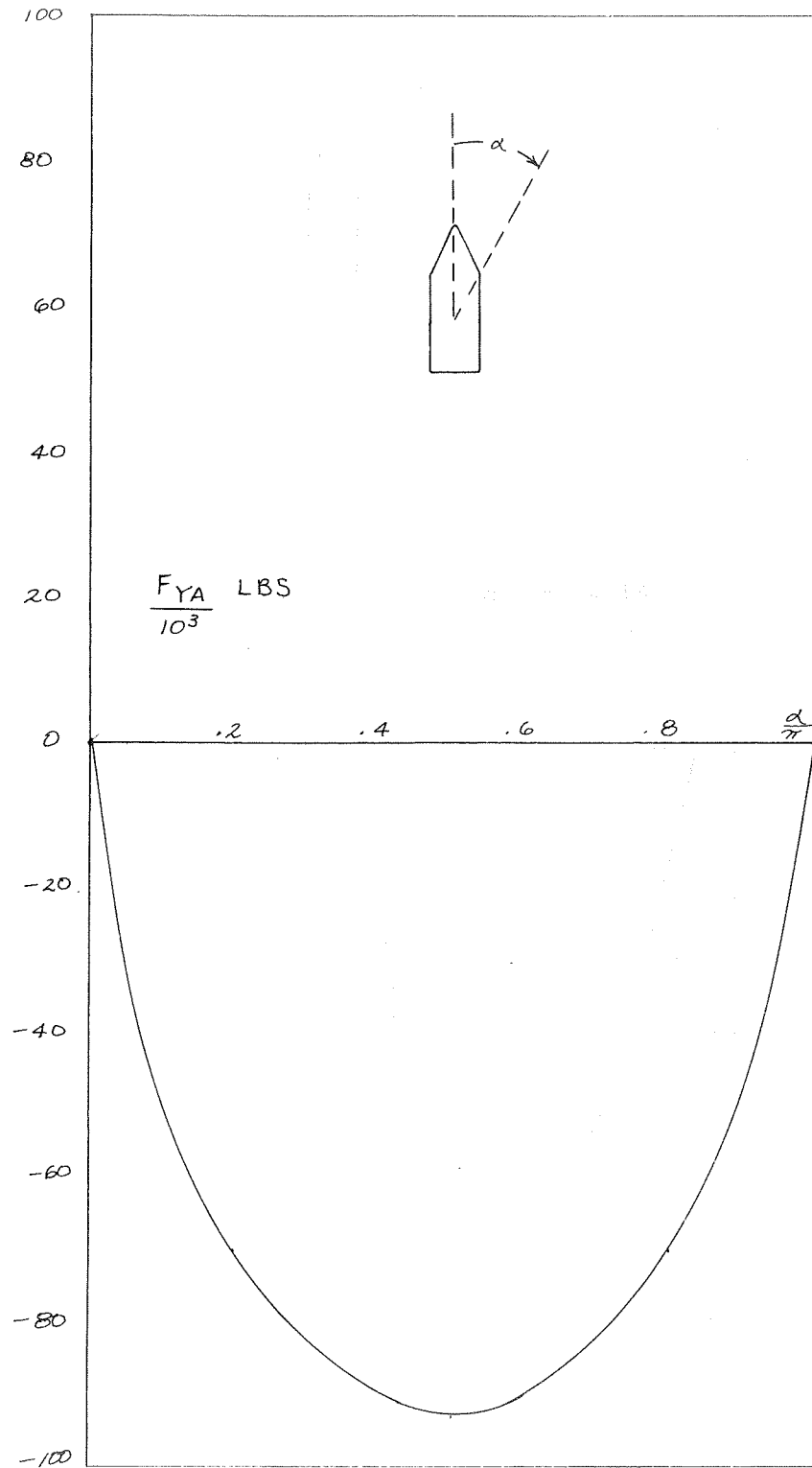
$\Psi$  -HYDRODYNAMIC DRAG FORCE

FIGURE B.3



X-AERODYNAMIC DRAG FORCE

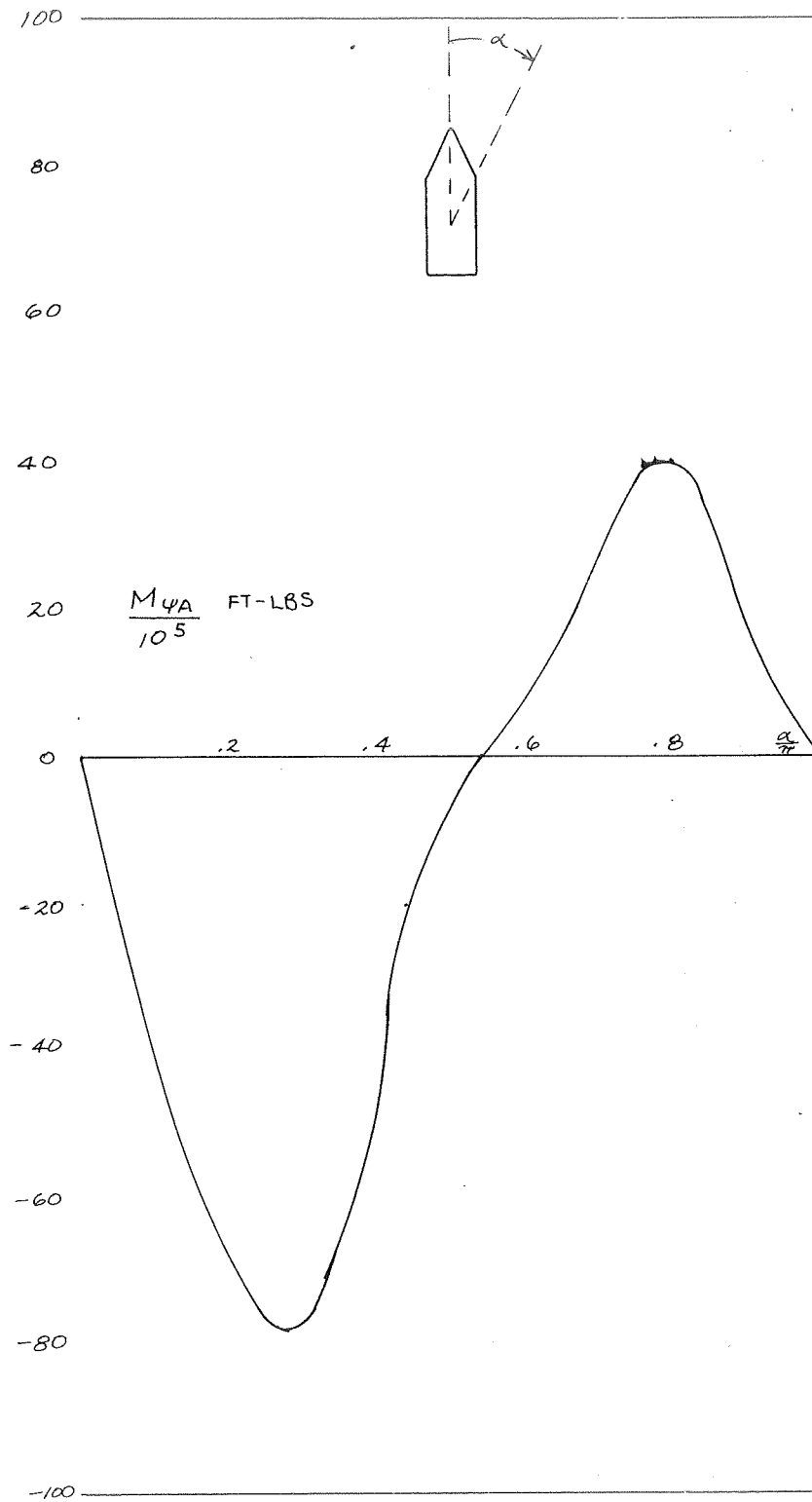
FIGURE B.4



Y-AERODYNAMIC DRAG FORCE

FIGURE B.5





$\psi$  - AERODYNAMIC DRAG FORCE

FIGURE B.6

APPENDIX C  
DIGITAL PROGRAM



```

DIMENSION XLOCA(250,10),ID(250),TEST(250,5)
REAL*8 RCBAD(4),CCWAD(2),RCBDA(4),CCWDA(2),RCBSN(4),CCWSN
REAL*8 RCBMD(4),CCWMD,RCBCN(4),CCWCN
INTEGER*2 LOCR(12),LOCW(15)
INTEGER*2 LOCS,ICONO,ICON1
INTEGER*2 MIC,MOP,MHLD
DATA ICONO,ICON1/0,1/,NB/2/
DATA MIC,MOP,MHLD/16,8,4/
DATA LOCR(1),NRD/09,10/,LOCW(1),NWR/11,12/
DATA T,XA,XB/2.,.07,.0714/,YA,YB/.09,.12207/,SA,SB/.175,.17993/
DATA AMAX,AMIN/8191.,-8191./,KSEC/38400/
DATA TWOPI/6.28318/,RAD/57.296/
DATA H41,H42,H43,H44/2.5,1.5,.75,1.25/
DATA P41,P42,P43,P44/10.1,4.9,2.3,3.6/
DATA H61,H62,H63,H64/5.,4.,2.,1./
DATA P61,P62,P63,P64/12.2,5.8,3.5,4.2/
DATA H81,H82,H83,H84/19.1,12.6,9.8,6.8/
DATA P81,P82,P83,P84/11.4,8.7,14.05,7.14/
DATA FYA1,FYA2,FYA3,FYA4,FYA5/-100.8,-7.229,2.821,2.438,1.763/
DATA FXA1,FXA2,FXA3,FXA4,FXA5/-46.07,9.587,-2.272,2.257,-1.829/
DATA FMA1,FMA2,FMA3,FMA4,FMA5/-506.5,-272.3,-72.55,12.86,12.45/
DATA FYH1,FYH2,FYH3,FYH4,FYH5/-.7105,.0710,.0416,.0376,.0252/
DATA FXH0,FXH1,FXH2,FXH3,FXH4/-.1387,-.6200,-.1809,.1457,-.0562/
DATA FXH5,FXH6,FXH7/.0503,-.0481,-.0372/
DATA FMH1,FMH2,FMH3,FMH4,FMH5/-.5180,.2034,.0725,-.0654,.0565/
DATA FMH6/.0394/

```

C \*\*\* SET UP VARIOUS REMOTE CONTROL BLOCKS AND CHANNEL CONTROL WORDS \*\*\*

```

CALL FRCBSU (RCBAD,29,CCWAD)
CALL READAD (CCWAD,NRD,0,LOCX)
CALL FRCBSU (RCBDA,30,CCWDA)
CALL WRITDA (CCWDA,0,NWR,LOCW)
CALL FRCBSU (RCBSN,28,CCWSN)
CALL SENSE (CCWSN,LOCS,NB)
CALL FRCBSU (RCBCN,28,CCWCN)
CALL CONTRL (CCWCN,LOCS,NB)
CALL FRCBSU (RCBMD,28,CCWMD)

```

C \*\*\* PLACE ANALOG COMPUTER IN INITIAL CONDITION MODE \*\*\*\*\*

```

CALL MODE (CCWMD,MIC)
CALL FRTIO (RCBMD)
CALL FCHECK (RCBMD,IRET,1)

```

C \*\*\* INITIALIZE VARIOUS CONTROL SYSTEM CONSTANTS \*\*\*\*\*

```

XW=XB*T
XTAU=-XA*T
XK1=2.*EXP(XTAU)*COS(XW)
XK2=-EXP(2.*XTAU)
XK3=EXP(XTAU)*SIN(XW)/XB
XIK1=(1.-XK1/2.-2.*XA*XK3)/(XA*XA+XB*XB)
XIK2=(-XK2-XK1/2.+2.*XA*XK3)/(XA*XA+XB*XB)
XIK3=1.+XK1

```

```

XIK4=XK2-XK1
XGAIN=XK3/(1.-XK1-XK2)
YW=YB*T
YTAU=-YA*T
YK1=2.*EXP(YTAU)*COS(YW)
YK2=-EXP(2.*YTAU)
YK3=EXP(YTAU)*SIN(YW)/YB
YIK1=(1.-YK1/2.-2.*YA*YK3)/(YA*YA+YB*YB)
YIK2=(-YK2-YK1/2.+2.*YA*YK3)/(YA*YA+YB*YB)
YIK3=1.+YK1
YIK4=YK2-YK1
YGAİN=YK3/(1.-YK1-YK2)
SW=SB*T
STAU=-SA*T
SK1=2.*EXP(STAU)*COS(SW)
SK2=-EXP(2.*STAU)
SK3=EXP(STAU)*SIN(SW)/SB
SIK1=(1.-SK1/2.-2.*SA*SK3)/(SA*SA+SB*SB)
SIK2=(-SK2-SK1/2.+2.*SA*SK3)/(SA*SA+SB*SB)
SIK3=1.+SK1
SIK4=SK2-SK1
SGAIN=SK3/(1.-SK1-SK2)
XPGAIN=.8
XDGAİN=140.
XIGAİN=.0008
YPGAİN=108.
YDGAİN=7000.
YIGAİN=.0108
SPGAİN=3.5
SDGAİN=132.
SIGAİN=.0005

```

C \*\*\* INITIALIZE ENVIRONMENTAL PARAMETERS \*\*\*\*\*

```

WINDV=0.
GUSTV=0.
ALPHA=0.
VELMAG=0.
THETA=0.
WH1=0.
WH2=0.
WH3=0.
WH4=0.
WP1=0.
WP2=0.
WP3=0.
WP4=0.

```

C \*\*\* LIST OPERATING INSTRUCTIONS FOR PROGRAM \*\*\*\*\*

```
WRITE(6,301)
```

```
301 FORMAT(1H1//10X'***** INFORMATION CONCERNING REAL TIME OPERATION 0
IF MAIN PROGRAM *****'///10X'THE FOLLOWING INFORMATION IS REQUESTED

```

```

2 BY THE TYPEWRITER TERMINAL'//
315X'N IS THE NUMBER OF PRINTED OUTPUT SAMPLES'//
420X'A SAMPLE IS TAKEN EVERY FIFTH TIME THROUGH THE TIMED CONTROL L
500P'//20X'IF N = 0 EXIT IS CALLED AND THE PROGRAM CONCLUDED'//
615X'ISCALE IS THE TIME SCALE FACTOR'//
715X'LOGIC IS AN INPUT THAT ENABLES PROGRAM OPTIONS'//
820X'LOGIC = 0 - EXISTING GAINS ARE USED AND OPERATION BEGINS'//
920X'LOGIC = 1 - NEW GAINS MAY BE INPUT FOR X-CHANNEL'//
A20X'LOGIC = 2 - NEW GAINS MAY BE INPUT FOR Y-CHANNEL'//
B20X'LOGIC = 3 - NEW GAINS MAY BE INPUT FOR PSI-CHANNEL'//
C20X'LOGIC = 4 - NEW GAINS INPUT FOR X,Y & PSI-CHANNELS'//
D20X'LOGIC = 5 - INPUT CURRENT - POLAR COORDINATES'//
E20X'LOGIC = 6 - INPUT SEA STATE (0,4,6,OR 8) AND DIRECTION'//
F20X'LOGIC = 7 - INPUT WIND - POLAR COORDINATES'//
G20X'LOGIC = 8 - INPUT GUST MAGNITUDE, PERIOD & VARIATION ANGLE'//
H20X'LOGIC = 9 - ANALOG CONTROL SYSTEM IS USED - NO GAINS INPUT'//
I15X'THE FOLLOWING RUN OPTIONS ARE AVAILABLE'//
J20X'USE SENSE LINE "1" TO MAKE A PARAMETER CHANGE DURING A RUN'//
K20X'USE SENSE LINE "0" TO MAKE A CONTINUOUS RUN'//

```

```

C *** START OF MAIN PROGRAM LOOP *****
998 CONTINUE

```

```

C *** I/O FOR PROGRAM OPTIONS AND ENVIRONMENTAL DATA *****

```

```

WRITE(15,304)
304 FORMAT(1X'INPUT N & ISCALE - 2I5')
READ(15,305) N,ISCALE
305 FORMAT(2I5)
IF(N.EQ.0) GO TO 999
WRITE(6,306) N,ISCALE
306 FORMAT(1H19X'NO. OF ITERATIONS...'15,5X'TIME SCALED BY...'15/)
997 WRITE(15,302)
302 FORMAT(1X'INPUT LOGIC - 1I')
READ(15,303) LOGIC
303 FORMAT(1I)
LOGIC=LOGIC+1
GO TO (30,31,32,33,34,35,36,37,38,39),LOGIC
31 WRITE(15,331)
331 FORMAT(1X'XP,XD & XI GAINS - 3F5.2')
READ(15,330) XPGAIN,XDGAIN,XIGAIN
330 FORMAT(3F5.2)
GO TO 997
32 WRITE(15,332)
332 FORMAT(1X'YP,YD & YI GAINS - 3F5.2')
READ(15,330) YPGAIN,YDGAIN,YIGAIN
GO TO 997
33 WRITE(15,333)
333 FORMAT(1X'SP,SD & SI GAINS - 3F5.2')
READ(15,330) SPGAIN,SDGAIN,SIGAIN
GO TO 997
34 WRITE(15,334)

```

```

334  FORMAT(1X'XP,XD,XI,YP,YD,YI,SP,SD & SI GAINS - 3(3F5.20)')
      READ(15,330) XPGAIN,XDGAIN,XIGAIN
      READ(15,330) YPGAIN,YDGAIN,YIGAIN
      READ(15,330) SPGAIN,SDGAIN,SIGAIN
      GO TO 997
35   WRITE(15,335)
335  FORMAT(1X'CURRENT - POLAR COORDINATES - 2F5.2')
      READ(15,330) VELMAG,ATHET
      THETA=ATHET/RAD
      GO TO 997
36   WRITE(15,336)
336  FORMAT(1X'SEA STATE & DIRECTION - 11,F5.2')
      READ(15,326) ISEA,ABET
326  FORMAT(11F5.2)
      BETA=ABET/RAD
      IF(ISEA.EQ.0) GO TO 324
      IF(ISEA-6) 327,328,329
C *** INITIALIZE A'S & W'S FOR SEA STATE 4 *****
327  WH1=H41
      WH2=H42
      WH3=H43
      WH4=H44
      WP1=P41
      WP2=P42
      WP3=P43
      WP4=P44
      GO TO 325
C *** INITIALIZE A'S & W'S FOR SEA STATE 6 *****
328  WH1=H61
      WH2=H62
      WH3=H63
      WH4=H64
      WP1=P61
      WP2=P62
      WP3=P63
      WP4=P64
      GO TO 325
C *** INITIALIZE A'S & W'S FOR SEA STATE 8 *****
329  WH1=H81
      WH2=H82
      WH3=H83
      WH4=H84
      WP1=P81
      WP2=P82
      WP3=P83
      WP4=P84
      GO TO 325
C *** SET A'S & W'S TO ZERO *****
324  WH1=0.

```

```

WH2=0.
WH3=0.
WH4=0.
WP1=0.
WP2=0.
WP3=0.
WP4=0.
325  W1=TWOPI/(WP1+1.E-10)
      W2=TWOPI/(WP2+1.E-10)
      W3=TWOPI/(WP3+1.E-10)
      W4=TWOPI/(WP4+1.E-10)
      WA1=WH1*W1
      WA2=WH2*W2
      WA3=WH3*W3
      WA4=WH4*W4
      GO TO 997
37   WRITE(15,337)
337  FORMAT(1X'INPUT WIND DATA - 2F5.2')
      READ(15,330) WIN,AALPH
      ALP=AALPH/RAD
      GO TO 997
38   WRITE(15,338)
338  FORMAT(1X'INPUT WIND GUST DATA - 3F5.2')
      READ(15,330) GUSTV,GUSTP,ADALPH
      DALPHA=ADALPH/RAD
      WGP=TWOPI/GUSTP
      GO TO 997
39   CALL CONTRL (CCWCN,ICONO,NB)
      CALL FRTIO (RCBCN)
      CALL FCHECK (RCBCN,IRET,1)
      WRITE(6,339)
339  FORMAT(10X'THIS RUN USES THE ANALOG CONTROL SYSTEM WITH DIGITAL US
      IED FOR SAMPLING PURPOSES ONLY'/)
      GO TO 40
30   CALL CONTRL (CCWCN,ICON1,NB)
      CALL FRTIO (RCBCN)
      CALL FCHECK (RCBCN,IRET,1)
      WRITE(6,340) XPGAIN,XDGAIN,XIGAIN,YPGAIN,YDGAIN,YIGAIN,SPGAIN,
1SDGAIN,SIGAIN
340  FORMAT(10X'XPGAIN'5X'XDGAIN'5X'XIGAIN'5X'YPGAIN'5X'YDGAIN'5X'YIGAI
IN'5X'SPGAIN'5X'SDGAIN'5X'SIGAIN'/6X9(1X,F10.4))
      WRITE(6,341) VELMAG,ATHET
341  FORMAT(/10X'CURRENT DATA - VELOCITY MAGNITUDE = 'F10.4,5X'DIRECTIO
IN = 'F10.4)
      WRITE(6,342) WH1,WP1,WH2,WP2,WH3,WP3,WH4,WP4,ABET
342  FORMAT(/10X'THE WAVE COMPONENTS ARE AS FOLLOWS'/10X'1 - AMPLITUDE
1& PERIOD'5X'2 - AMPLITUDE & PERIOD'5X'3 - AMPLITUDE & PERIOD'5X'4
2- AMPLITUDE & PERIOD'5X'DIRECTION'/16XF5.2,6XF5.2,11XF5.2,6XF5.2,1
31XF5.2,6XF5.2,11XF5.2,6XF5.2,7XF6.2/)

```



```

WRITE(6,343) WIN,AALPH,GUSTV,GUSTP,ADALPH
343  FORMAT(10X'WIND DATA IS AS FOLLOWS'/10X'WIND MAGNITUDE'5X'DIRECTIO
IN'5X'GUST MAGNITUDE'5X'GUST PERIOD'5X'GUST ANGLE'/12XF10.4,6XF10.4
1,7XF10.4,8XF10.4,5XF10.4/)
40  CONTINUE
    X1=0.
    XC=0.
    X1P=0.
    XCP=0.
    X1D=0.
    XCD=0.
    X2I=0.
    X1I=0.
    XCI=0.
    Y1F=0.
    YCF=0.
    Y1=0.
    YC=0.
    Y1P=0.
    YCP=0.
    Y1D=0.
    YCD=0.
    Y2I=0.
    Y1I=0.
    YCI=0.
    S1=0.
    SC=0.
    S1P=0.
    SCP=0.
    S1D=0.
    SCD=0.
    S2I=0.
    S1I=0.
    SCI=0.
    TW=0.
    IDELT=KSEC/ISCALE-9
    KK=1
    K=1
    CALL MODE(CCWMD,MOP)
    CALL FRTIO(RCBMD)
    CALL FCHECK(RCBMD,IRET,1)
C#### ENTER TIMED CONTROL LOOP #####
9    KSTORE=ITIME(3)+IDELT
    IF(KK.EQ.1.AND.K.EQ.1) KDIF=ITIME(3)
    IF(K.GT.1) ID(K)=KSTORE-KTIME
    KTIME=KSTORE
C#### READ VELOCITY, POSITION, & POSITION ERROR FROM ANALOG #####
    CALL FRTIO(RCBAD)
    CALL FCHECK(RCBAD,IRET,1)

```

```

DO 12 I=1,NRD
12 XLOCA(K,I)=LOCR(I+1)/81.92
C#### X CONTROL LOOP #####
X2=X1
X1=XC
XC=LOCR(2)/XGAIN
X2P=X1P
X1P=XCP
XCP=XK3*X1+XK1*X1P+XK2*X2P
X2D=X1D
X1D=XCD
XCD=X1-X2+XK1*X1D+XK2*X2D
X3I=X2I
X2I=X1I
X1I=XCI
XCI=XIK1*X1+XIK2*X2+XIK3*X1I+XIK4*X2I-XK2*X3I
C#### X-THRUSTER FORCE #####
XCONF=XPGAIN*XCP+XDGAIN*XCD+XIGAIN*XCI
IF(XCONF.GT.AMAX) XCONF=AMAX
IF(XCONF.LT.AMIN) XCONF=AMIN
LOCW(2)=XCONF
TEST(K,1)=XCONF
C#### PSI CONTROL LOOP #####
S2=S1
S1=SC
SC=LOCR(8)/SGAIN
S2P=S1P
S1P=SCP
SCP=SK3*S1+SK1*S1P+SK2*S2P
S2D=S1D
S1D=SCD
SCD=S1-S2+SK1*S1D+SK2*S2D
S3I=S2I
S2I=S1I
S1I=SCI
SCI=SIK1*S1+SIK2*S2+SIK3*S1I+SIK4*S2I-SK2*S3I
C#### PSI MOMENT FORCE #####
SCONF=SPGAIN*SCP+SDGAIN*SCD+SIGAIN*SCI
IF(SCONF.GT.AMAX) SCONF=AMAX
IF(SCONF.LT.AMIN) SCONF=AMIN
LOCW(6)=SCONF
TEST(K,3)=SCONF
C#### Y CONTROL LOOP #####
Y2F=Y1F
Y1F=YCF
YCF=LOCR(5)/XGAIN
Y2=Y1
Y1=YC
YC=XK3*Y1F+XK1*Y1+XK2*Y2

```

```

YC=YC/YGAIN
Y2P=Y1P
Y1P=YCP
YCP=YK3*Y1+YK1*Y1P+YK2*Y2P
Y2D=Y1D
Y1D=YCD
YCD=Y1-Y2+YK1*Y1D+YK2*Y2D
Y3I=Y2I
Y2I=Y1I
Y1I=YCI
YCI=YIK1*Y1+YIK2*Y2+YIK3*Y1I+YIK4*Y2I-YK2*Y3I
C#### Y-THRUSTER FORCE #####
YCONF=YPGAIN*YCP+YDGAİN*YCD+YİGAİN*YCI
YMAX=AMAX-ABS(SCONF)
YMIN=-YMAX
IF(YCONF.GT.YMAX) YCONF=YMAX
IF(YCONF.LT.YMIN) YCONF=YMIN
LOCW(4)=YCONF
TEST(K,2)=YCONF
C#### CALCULATE WAVE AND WIND VELOCITY #####
WAVEL=WAI*COS(W1*TW)+WA2*COS(W2*TW)+WA3*COS(W3*TW)+WA4*COS(W4*TW)
LOCW(8)=WAVEL*81.92*5.
DELTA=SIN(WGP*TW)
ALPHA=ALP+DALPHA*DELTA
WINDV=WIN+GUSTV*DELTA
C#### INCREMENT REAL TIME BY 2 SECONDS #####
TW=TW+2.
C#### UNSCALE VESSEL VELOCITIES AND CORRECT SIGN #####
XVEL=-LOCW(4)/(81.92*5.)
YVEL=-LOCW(7)/(81.92*50.)
SVEL=-LOCW(10)/(81.92*1000.)
SI=LOCW(9)*.031428/81.92
C#### CHANGE ANGLE OF WAVES, CURRENT & WIND TO VESSEL COORDINATES #####
BET=BETA-SI
THET=THETA-SI
ALPH=ALPHA-SI
C#### CURRENT AND WAVE COMPONENT VELOCITIES #####
XCURV=-VELMAG*COS(THET)
YCURV=-VELMAG*SIN(THET)
XWAVE=-WAVEL*COS(BET)
YWAVE=-WAVEL*SIN(BET)
C#### VESSEL RELATIVE VELOCITIES #####
XRELV=XVEL-XCURV-XWAVE
YRELV=YVEL-YCURV-YWAVE
MXRV=XVEL-XCURV
MYRV=YVEL-YCURV
C#### VESSEL RESULTANT VELOCITY #####
RVNET=YRELV**2+XRELV**2
GAM=ATAN2(YRELV,XRELV)

```

```

MNETV=MXRV**2+MYRV**2
TEST(K,4)=RVNET
TEST(K,5)=GAM*RAD
C#### HYDRODYNAMIC AND AERODYNAMIC DRAG COEFFICIENTS #####
SIN1=SIN(GAM)
SIN2=SIN(2.*GAM)
SIN3=SIN(3.*GAM)
SIN5=SIN(5.*GAM)
FYHYD=FYH1*SIN1+FYH2*SIN2+FYH3*SIN3+FYH4*SIN5+FYH5*SIN(7.*GAM)
FXHYD=FXH0+FXH1*COS(GAM)+FXH2*COS(3.*GAM)+FXH3*COS(4.*GAM)+
1    FXH4*COS(5.*GAM)+FXH5*COS(7.*GAM)
FMHYD=FMH1*SIN2+FMH2*SIN1+FMH3*SIN3+FMH4*SIN5+FMH5*SIN(6.*GAM)
FXAER=FXA1*COS(ALPH)+FXA2*COS(3.*ALPH)+FXA3*COS(7.*ALPH)+
1    FXA4*COS(5.*ALPH)+FXA5*COS(9.*ALPH)
FYAER=FYA1*SIN(ALPH)+FYA2*SIN(3.*ALPH)+FYA3*SIN(7.*ALPH)
FMAER=FMA1*SIN(2.*ALPH)+FMA2*SIN(ALPH)+FMA3*SIN(4.*ALPH)
C#### WIND AND WATER DRAG FORCE CALCULATIONS #####
FADX=WINDV**2*FXAER*.4
FADY=WINDV**2*FYAER*.4
FADM=WINDV**2*FMAER*.4
FHDY= RVNET*FYHYD*1.7E4
FHDX= RVNET*FXHYD*149.
FADM=-SVEL*ABS(SVEL)*1.E9
FHDY=RVNET*FYHYD*2.65E6
C#### SUM ENVIRONMENTAL FORCES #####
FTDX=FHDY+FADY
FTDY=FHDX+FADM
FTDM=FADM+FHWM+FHDY
C#### SCALE ENVIRONMENTAL FORCES FOR ANALOG #####
FTDY=FTDY*81.92*.002
FTDX=FTDX*81.92*.002
FTDM=FTDM*81.92*1.E-5
IF(FTDX.LT.AMIN) FTDX=AMIN
IF(FTDY.LT.AMIN) FTDY=AMIN
IF(FTDM.LT.AMIN) FTDM=AMIN
IF(FTDX.GT.AMAX) FTDX=AMAX
IF(FTDY.GT.AMAX) FTDY=AMAX
IF(FTDM.GT.AMAX) FTDM=AMAX
C#### RESULTANT THRUSTER FORCE MAGNITUDE #####
RTHF=-(ABS(XCONF)+ABS(YCONF)+ABS(SCONF/200.))/2.
LOCW(3)=-FTDX
LOCW(5)=-FTDY
LOCW(7)=-FTDM
LOCW(10)=RTHF
C#### SEND CONTROL & ENVIRONMENTAL FORCES TO ANALOG #####
CALL FRTIO(RCBDA)
CALL FCHECK(RCBDA,IRET,1)
C#### INTERROGATE SENSE LINES #####
CALL FRTIO(RCBSN)

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      CALL FCHECK(RCBSN,IRET,1)
      IF(LOCS.EQ.1) K=1
      IF(LOCS.EQ.3) GO TO 13
C#### UPDATE VARIOUS COUNTERS #####
      IF(K.EQ.N) GO TO 11
      IF(KK.EQ.1) K=K+1
      IF(KK.EQ.05) KK=0
      KK=KK+1
      IF(KK.EQ.2.AND.K.EQ.2) KDIF=ITIME(3)-KDIF
10      IF(ITIME(3)-KTIME) 10,9,9
C#### END OF TIMED CONTROL LOOP #####
13      CALL MODE (CCWMD,MHLD)
      CALL FRTIO (RCBMD)
      CALL FCHECK (RCBMD,IRET,1)
      GO TO 997
11      CONTINUE
      CALL MODE(CCWMD,MIC)
      CALL FRTIO(RCBMD)
      CALL FCHECK(RCBMD,IRET,1)
C *** WRITE VALUES OF PARAMETERS FROM REAL TIME RUN *****
      WRITE(6,382) KDIF
382      FORMAT(10X'KDIF...'I10/)
      WRITE(6,381)
381      FORMAT(3X'TIMUN'2X'K'4X'MX0'3X'MX1'3X'MX2'3X'MX3'3X'MX4'3X'MX5'3X
1'MX6'3X'MX7'3X'MX8'3X'MX9'5X'TEST1'6X'TEST2'6X'TEST3'6X'TEST4'6X
2'TEST5'/)
      DO 16 K=1,N
16      WRITE(6,380) ID(K),K,(XLOCA(K,I),I=1,NRD),(TEST(K,I),I=1,5)
380      FORMAT(3XI5,1XI3,1X10F6.1,5(1X,E10.4))
      GO TO 998
999      CALL EXIT
      END

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Unclassified

Security Classification

## DOCUMENT CONTROL DATA - R &amp; D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)		2a. REPORT SECURITY CLASSIFICATION	
University of Houston		Unclassified	
		2b. GROUP	
		Unclassified	
3. REPORT TITLE			
A HYBRID COMPUTER STUDY OF A DYNAMIC SHIP POSITIONING SYSTEM			
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)			
Technical Report			
5. AUTHOR(S) (First name, middle initial, last name)			
Richard H. St. John, Jr. William P. Schneider			
6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS	
August, 1970	108	9	
8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)		
NGL-44-005-084	RE 8-70		
b. PROJECT NO.			
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)		
d.			
10. DISTRIBUTION STATEMENT			
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11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY	
13. ABSTRACT			
<p>Dynamic positioning is a method of anchoring a vessel in deep areas of the ocean. The essential components of a dynamic positioning system are a vessel with positioning forces; a position measuring system; a comparator; and a controller. These components position a vessel by interacting with each other and with the environment.</p> <p>Mathematical models define each component of the positioning system. The hybrid computer simulates the positioning system, and the aerodynamic and hydrodynamic forces present on the ocean's surface.</p> <p>This report investigates the excitation/response characteristics of the model for a variety of environment conditions. Optimum headings with respect to positioning thrust result for each environmental case. A vessel search algorithm is developed to locate an optimum heading.</p>			

Unclassified

Security Classification

A-31493

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
hybrid computer ship positioning control system deep sea exploration						

DD FORM 1 NOV 65 1473 (BACK)

S/N 0101-807-6821

Unclassified

Security Classification

A-31409