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A STEADY STATE AND DYNAMIC ANALYSIS OF A MOORING SYSTEM.(U)

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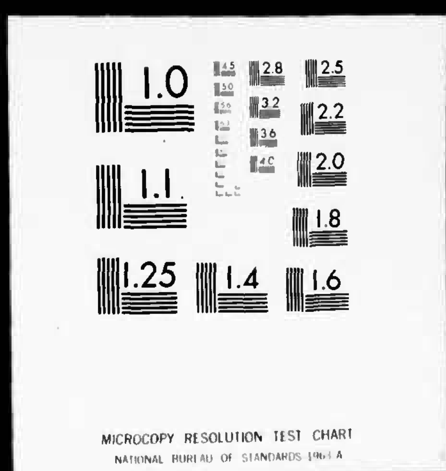
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A Steady State and Dynamic Analysis of a Mooring System

James P. Radochia
Special Projects Department

25 March 1977

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report investigates the forces acting upon a cable-buoy-ship system and develops a digital computer simulation of its dynamics in three dimensions. The system that is discussed is excited by ship motions caused by ocean waves.

Equilibrium equations are written for the subsurface buoys and cable for the steady state case, in which ship motions are assumed to be zero. A Runge-Kutta scheme is used to solve the cable equations, and an iterative process

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20. Abstract (Cont'd)

cont

is employed to effect the correct solution for the system.

For the dynamic case, in which ship motions do exist, a lumped mass model of the cable and subsurface buoys is used. The equations of motion for each lumped mass element are numerically integrated simultaneously in the time domain. A particular cable-buoy-ship system is investigated, and the results are analyzed.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONT'D)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONT'D)

Appendix C

LIST OF ILLUSTRATIONS (CONT'D)

LIST OF TABLES

LIST OF SYMBOLS AND NOTATIONS

Symbols

A — Transform matrix from cable coordinates to inertial coordinates

b — Integration step-size in time domain for dynamic model

B — Net buoyancy of subsurface buoy (buoy displacement minus air weight of buoy; also defined to be excess buoyancy)

c_B — Current magnitude at ocean bottom

c_{DN} — Normal drag coefficient for cable

c_{DS} — Coefficient of drag for spherical subsurface buoy

c_{DT} — Tangential drag coefficient for cable

c_x — Current magnitude at surface

c_y — Current magnitude at depth D

d — Outside diameter of the cable

d_S — Effective strength member diameter of cable

D — Depth of water above which current varies exponentially, and below which it varies linearly

D_F — Current drag on subsurface buoy

D_x", D_y", D_z" — Cable drag components in cable coordinates

E_A — Distance between calculated location and actual location of ship

E_c — Modulus of elasticity of cable

f_h — Highest natural frequency of system

G — Horizontal distance between anchor and ship

Symbols (Cont'd)

H	Water depth
$\hat{i}, \hat{j}, \hat{k}$	Direction indices
Ky^n	Spring constant
ΔL_n	Length of n'th segment
mh_{x^n}, mh_{y^n}, mh_{z^n}	Hydrodynamic mass components in cable coordinates
Re	Reynolds number
R_s	Radius of subsurface buoy
s	Stretched length of cable
s_o	Unstretched length of cable
S_{hx_i}, S_{hz_i}	Constants used to describe ship motions
t	Time
T	Tension vector
T_{AN}	Corrected tension at anchor
T_{BD}	Tension in cable from ship at subsurface buoy
T_{BB}	Tension in cable from anchor at subsurface buoy
Ty^n	Tension in n'th cable segment
u, v, w	Components of ocean currents in inertial coordinates
U_{RN}, V_{RN}, W_{RN}	Resultant velocity components of the water relative to the cable components in inertial coordinates
v_c	Current velocity
w_b	In water weight of subsurface buoy
w_c	In water weight per unit length of cable

Symbols (Cont'd)

x, y, z	Spatial coordinates
$\bar{X}, \bar{Y}, \bar{Z}$	Force components acting on cable
z_{SH}	The calculated "z" coordinate of the ship
δ_A	Positive number which is successively reduced in iteration scheme
ε	Maximum closure error
ε_i	Phase angle
θ	Cable angle in horizontal plane
θ_c	Current angle in horizontal plane
ϕ	Cable angle in vertical plane
ρ_w	Water mass density
μ_m	Cable mass per unit length
ν	Kinematic viscosity of seawater
ω_i	Wave frequency

Subscripts

A	Anchor
D	Point of attachment of cable from ship at subsurface buoy
E	Point of attachment of cable from anchor at subsurface buoy
n	Lumped mass element number
N	Iteration number for procedure used to find tension at anchor

I. INTRODUCTION

This study describes an analysis and simulation of the dynamics of simple moored oceanic buoy systems which are tethered to a surface ship. The effects of the wave induced motion of this vessel, the forces due to the waves and currents on the buoy system, and the weight of the cable and buoy are all included. Because of the nonlinearities of the differential equations used to model the system, numerical techniques are used to effect solutions.

The basic problem this simulation will address is the decoupling of the cable connecting the anchor to the subsurface buoys from the wave induced motion of the ship. This will help alleviate the problem that has caused much concern among researchers and navies throughout the world about possible failures in a moored cable due to the fatigue of the cable caused by the wave excited motions of the tethered ship.

Most analyses of the type undertaken in the present study have dealt with some type of moored buoy configuration. Almost all of these studies did not consider systems in which a ship was present; thus, the wave induced motions were limited to affecting only the surface buoy.

Barber [1] compared three methods for obtaining cable displacements, and then examined what effect these displacements would have in the steady state upon current meters.

His main concern was in obtaining accurate data for closely spaced current meters near the top of the mooring.

Martin [2] developed a computer program to determine the steady state geometry and cable tensions in single-point mooring systems. It was based on an iterative, numerical-integration routine for the cable equations, allowing for elastic cables, drag and weight forces, variation of current speed with depth, instruments supported in the mooring line, and the effects of specific buoy shapes.

Griffin and Radochia [3] derived a program to find the steady state configuration and tension of a very long underwater towed cable. A numerical-integration routine was also used to solve the cable equations, which considered the elasticity of the cable, a constant current profile, drag and weight forces, and a drogue at the end of the cable.

Griffin [4] non-dimensionalized the steady state cable equations for single point mooring systems and solved them for different values of the non-dimensional parameters. He plotted the spatial coordinates of the end point as a function of the dimensionless coefficients for drag, cable weight, excess buoyancy-to-tension ratio, current profile, and buoy geometry so that, for a given set of buoy and cable parameters and specific current profiles, the horizontal and vertical excursions of the buoy could be determined.

Shepard [5] described a dynamic model of a vertical moored taut cable which was subjected to a low velocity transverse flow and which underwent small harmonic oscillations in the vertical direction at its upper end. Calculations based on this model yielded estimates of the dynamic force-displacement relations at the upper end of the cable.

Griffin [6] investigated the forces acting upon a cable-towed body system and developed a digital computer simulation of its dynamics in a plane. The towed system was excited by ship motions caused by deep-ocean waves. Equations of motion for the towed body were written and reduced to a set of ordinary nonlinear differential equations having nonconstant coefficients. A lumped mass model of the towline was employed and the equations of motion for the cable were numerically integrated simultaneously with the towed body equations of motion in the time domain.

Paquette and Henderson [7] used an analog computer to simulate the dynamics of buoy mooring ropes under conditions typical of the open sea. They solved the set of second-order partial differential equations associated with single-point mooring systems under the action of wind and current forces that were unidirectional and coplanar. The cable was simulated by up to ten straight segments joined at node points where all forces and mass were assumed to be lumped.

Brainard [8] analyzed the dynamic motion of a single point, taut, compound mooring. His model consisted of a series of discrete masses connected with linear springs; motion was assumed to be one-dimensional along the longitudinal axis of the model. The analysis predicted the natural frequencies of the model without damping. These results were used as a basis for analyzing motion of the masses and tensions in the springs when the model was driven with an external force and where damping, from tangential drag, was assumed to be proportional to velocity squared. Solutions were obtained by computer programmed numerical techniques; both steady state and transient cases were studied. Response of the system with alterations of drag and spring stiffness were also studied.

Patton (9) investigated a digital computer simulation of buoy system dynamics for simple buoy systems, that is, a surface buoy moored on a single mooring line. The buoy system could be excited by winds, waves, and currents. Winds could act from any compass direction, and currents could vary in strength and direction as a function of depth in the water column. Wind waves were simulated by first computing their properties with the Sverdrup-Munk (12) - Bretschneider (13) method and then by using Bargman's (14) energy partitioning scheme on a two-parameter Bretschneider spectrum to compute component sine wave amplitudes, phases, and frequencies.

Equations of motion for the buoy, assumed to be an oblate spheroid, were developed for six degrees of freedom-three translational and three rotational. Hydrostatic and hydrodynamic forces and moments acting on an oblate spheroid moving on the free surface of an infinite body of water were investigated in detail. The set of integro-differential equations for buoy motions were reduced to a set of nonlinear, ordinary differential equations with nonconstant coefficients by using the Haskind [15] hypothesis to evaluate the hydrodynamic force and moment integrals and to represent them as frequency dependent coefficients. Buoy motions were coupled to the hydrostatic, hydrodynamic, and mooring line forces.

Cable dynamics were also investigated. A set of coupled, hyperbolic, partial differential equations for cable motions were developed and characteristic equations were derived to effect a method of characteristics solution. A unique numerical method of characteristics technique, based upon Hartree's [16] method, was developed for the solution of the cable equations in the time-space domain. Buoy motions, which were dependent upon the cable tensions, served as the upper boundary conditions. Lower boundary conditions were prescribed at the anchor, where there could be no motion.

For certain buoy systems, where many mass discontinuities existed along the cable, or for shallow water moorings, where slack cable conditions could exist, a lumped mass method of computing cable dynamics was developed as opposed to the finite difference method just described. In general, for cable dynamics the lumped mass numerical method was an order of magnitude faster in computation time than the finite difference method.

The equations of motion developed for the buoy were solved numerically in the time domain using a fourth-order, Runge-Kutta integration method. Cable equations could be solved by finite difference methods or by integrating with the Runge-Kutta algorithm for the lumped mass model.

In order to validate the numerical models developed, two buoy systems were instrumented and deployed in Block Island Sound. The motion data from these experiments, along with data published in the literature [10, 11], were compared with simulated buoy motion data. This comparison [9] indicated that steady state buoy system forces and configurations could be predicted within approximately five percent and that buoy system dynamics could be predicted within approximately fifty percent. There were some indications that the surge and sway hydrodynamic forces acting on the buoy were being underestimated by the computer model.

Webster [17] tested models of three buoys; in these tests, the effects of both waves and currents were simulated. As a result of the tests, a single-point mooring configuration for a new buoy was developed. Of particular interest during this study was the visibility of the buoys in various sea and current conditions. The test results were used to predict the fraction of time that the buoys remained within two, three, and four degrees of the vertical.

Mercier [18] presented the results of hydrodynamic tests of several models of typical buoy shapes. Measurements of lift, drag, and pitch moment were made for the heave, surge, and pitch modes of motion in calm water and for the model held fixed with surface waves passing by. These results were necessary for evaluating the motions of these bodies for arbitrary mass distributions, using the equations of motion. Coefficients expressing the inertial and damping characteristics of these models, based on the assumption of linearity of forces with motion and wave amplitude were presented in tables. Amplitudes and phases for the wave exciting forces were tabulated. Models that had been tested included a half-immersed sphere, a half-immersed torus, a one-fiftieth scale model of the "Monster Buoy", a shallow draft rectangular barge, and a cylinder with a square damping plate at the lower end and with a hemispherical bottom cap.

The problem considered by Reid [19] dealt with the motions of and tensions within a quasi-elastic mooring line which was anchored at the sea floor while attached to a ship er buoy at or near the sea surface and subject to the influence of time varying currents. This was a natural extension of previous studies, such as those of Wilson,[20, 21], dealing with the equilibrium configuration of an anchored cable in the presence of steady, coplanar currents.

The design concept and a summary of the motion analysis of the mathematical model of a tri-moored buoyant structure were presented by Savage [22] for project SEASPIDER. The need to adapt the structural design to the anticipated oceanographic environment in order to obtain a near-motionless system was discussed. Critical components of the total system were discussed, and experience with these components during sea trials was recorded. Sea trials of the system conducted on the Blake Plateau in 2600 feet of water were reviewed and the results using the system as a base for acoustic, temperature, and current measurements were presented. Evidence of the near-motionless characteristics of this tri-moored buoyant structure was presented and discussed. The purpose of project SEASPIDER had been to prove the feasibility of tri-moored buoyant structures with neutrally buoyant legs as instrument bases for all types of oceanographic measurements in the water column of the deepest parts of the ocean.

Correll [23] reported the results of an analytical design study and a prototype experimental program which investigated the characteristics and performance of a buoy system for the U.S. Naval Oceanographic Hysurch Program. The buoy system served as a reference station for a hyperbolic navigation system for coastal hydrographic survey. The work consisted of an analytical evaluation of several classes of buoy systems, a detailed design of a prototype buoy system, an experimental program with a full scale prototype buoy system in two oceanic environments, and an evaluation of the operational characteristics of the prototype system. The prototype evaluation showed that a highly compliant taut-wire moored surface buoy configuration could provide vertical stabilities of less than eight degrees variation and a watch circle of approximately ten percent of depth, in sea conditions of up to sea state four and with ocean currents up to three quarters of a knot.

Most analyses of the type undertaken in the studies described above have dealt simply with moored buoy-cable systems. The present study will include the dynamic effects of a ship which is tethered to the system as an extension of previous works. In addition to this excitation of the system due to the response of the ship to ocean waves, the other forces which will be considered include water drag (normal and tangential), cable tension, cable and buoy weight, and inertial forces. These will be assumed to be acting at discrete points along the cable in a lumped mass-spring model. In order to provide initial conditions for this dynamic case, a steady state model will first be developed.

II. STEADY STATE MODEL

2.1 Cable Equations of Motion

The equilibrium equations, originally given by Patton[9], were modified by Griffin and Radochia[3] and used to model extremely long towed arrays. The differential equations generated to describe the equilibrium condition for an element of cable subject to weight and steady hydrodynamic forces are given as:

$$\frac{d\theta}{ds_0} = \left(\frac{1}{T\cos\phi}\right)\left(\frac{1}{2}\rho_w d\, C_{DN}\, u''|u''|\right) \tag{1a}$$

$$\frac{dT}{ds_0} = w_c \sin\phi - \frac{1}{2}\rho_w \pi d\, C_{DT}\, v''|v''| \tag{1b}$$

$$\frac{d\phi}{ds_0} = \left(\frac{1}{T}\right)\left(w_c \cos\phi - \frac{1}{2}\rho_w d\, C_{DN}\, w''|w''|\right) \tag{1c}$$

$$\frac{ds}{ds_0} = 1 + \frac{4T}{\pi d_s^2 E_c} \tag{1d}$$

Equations (1a) through (1c) are the equilibrium equations for the cable in the x", y", and z" directions respectively.

(See figures 2 through 6.) Equation (1d) is derived by using Hooke's law [22] (strain=stress/modulus of elasticity), which is valid for linear elastic materials. (Strain, $\left(\frac{ds}{ds_1} - 1\right)$, is assumed to be very small, and temperature effects on the strain are neglected.) All of the above are for cables with circular cross section.

The parameters used in equation (1) are defined as follows:

$$C_{DN} = \frac{\text{normal drag along } x'' \text{ axis/unit length}}{(\frac{1}{2})(\rho_w)(d)(u'')^2}$$

$$C_{DN} = \frac{\text{normal drag along } z'' \text{ axis/unit length}}{(\frac{1}{2})(\rho_w)(d)(w'')^2}$$

C_{DN} = the normal drag coefficient of the element along the x" axis and z" axis

$$C_{DT} = \frac{\text{tangential drag/unit length}}{(\frac{1}{2})(\rho_w)(\pi)(d)(v'')^2}$$

C_{DT} = the tangential drag coefficient of the element along the y" axis

d = the outside diameter of the element (see figure 1)

d_e = the effective strength member diameter (see figure 1)

E_e = the modulus of elasticity of the effective strength member

s = the stretched length of the element

s_o = the unstretched length of the element

T = the tension at the element

w_c = the in water weight per unit length of the cable element (For the cable, weight is defined as a positive quantity; the equilibrium equations of the cable take into account the fact that the positive weight is acting in the negative z direction.)

u'', v'', w'', = the fluid velocity components in the double primed coordinate system along the x'', y'', and z'' axes respectively (See figures 2 through 4.)

ρ_w = the mass density of sea water

θ, ϕ = the angles of the cable in the double primed coordinate system, defined in figures 2 through 4.

Equation (1) uses two different values for the cable diameter. The first, d, is the outside diameter; the second, d_s, is the strength member diameter. A cable may sometimes have a buoyancy material, such as thermoplastic rubber, extruded over the load bearing member (see figure 1). This will have little effect upon the stress-strain relations of the cable, but will affect the drag forces on the cable. This fact is taken into consideration when deriving equation (1).

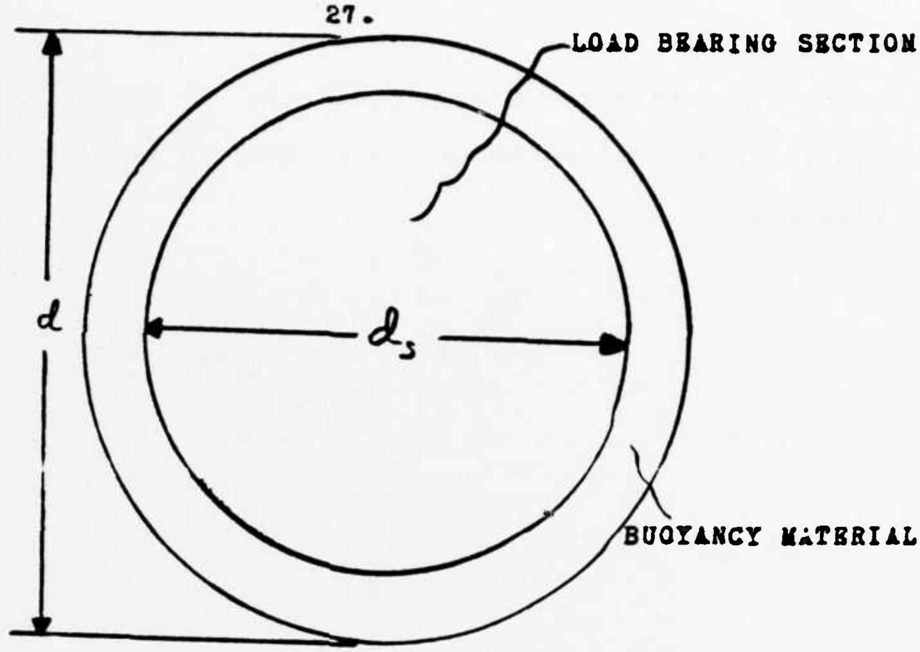

Figure 1. Cable Diameters

To transform from inertial (unprimed) to cable (double primed) coordinates, first rotate the x-z plane about the z axis as shown in figure 2:

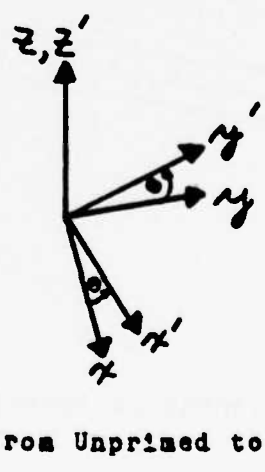

Figure 2. Rotation from Unprimed to Primed System

Next rotate the primed system to the double primed system by a rotation about the x' axis as shown below in figure 3:

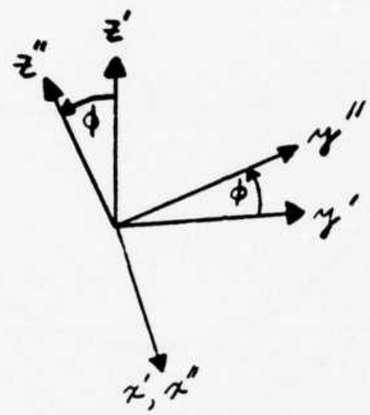

Figure 3. Rotation from Primed to Double Primed System

The cable element is aligned with the y'' axis in the double primed coordinate system as shown in figure 4:

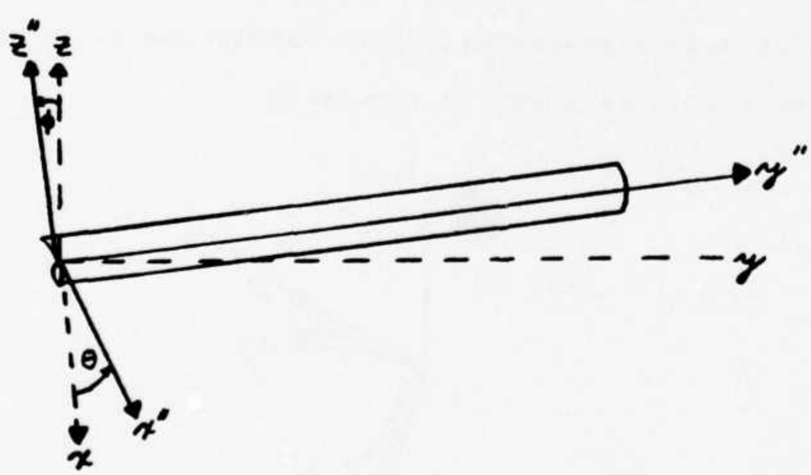

Figure 4. Cable Element in Inertial and Cable Coordinates

The changes in the horizontal angle θ and the vertical angle ϕ in the inertial system are shown below in figures 5 and 6:

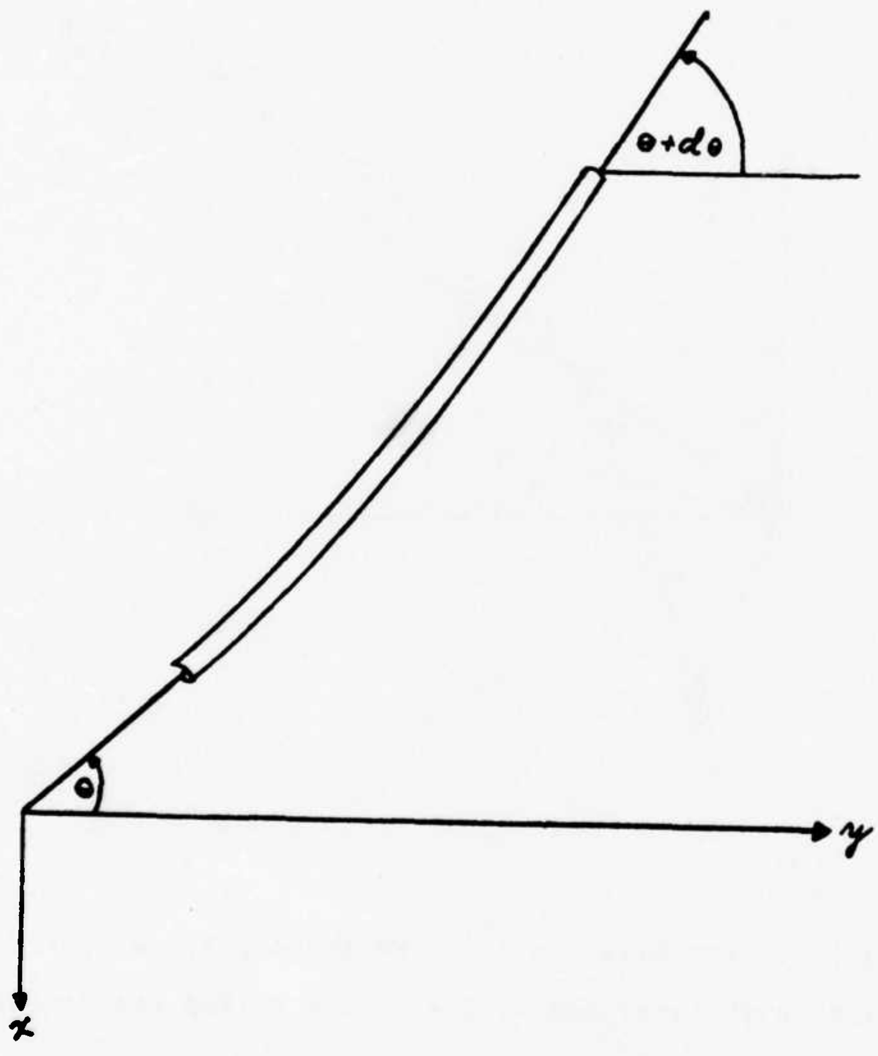

Figure 5. Horizontal Angle Change

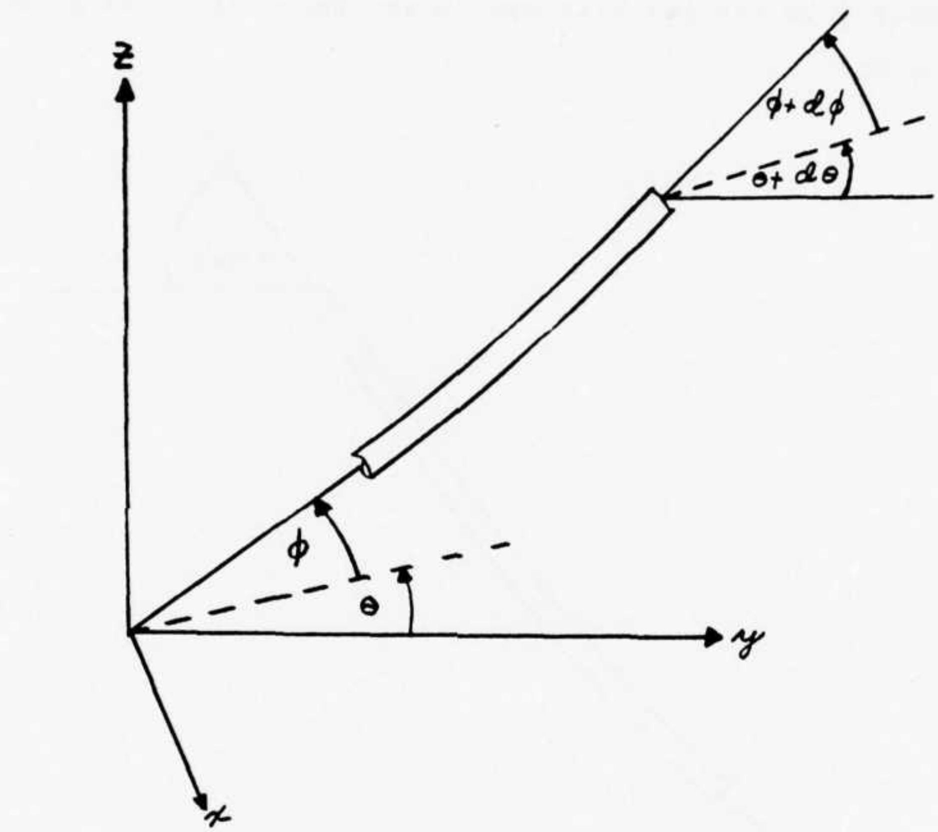

Figure 6. Vertical Angle Change

Griffin and Radechia [3] give the transform matrix to change from the unprimed to the double primed coordinate system as:

$$A = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta\cos\phi & \cos\theta\cos\phi & \sin\phi \\ \sin\theta\sin\phi & -\cos\theta\sin\phi & \cos\phi \end{bmatrix} \qquad (2)$$

Its inverse is given as:

$$A^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta\cos\phi & \sin\theta\sin\phi \\ \sin\theta & \cos\theta\cos\phi & -\cos\theta\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \quad (3)$$

Using the above relations u", v", and w" may be defined as the fluid velocity components in the x", y", and z" directions respectively:

$$u'' = u\cos\theta + v\sin\theta \quad (4a)$$

$$v'' = -u\sin\theta\cos\phi + v\cos\theta\cos\phi + w\sin\phi \quad (4b)$$

$$w'' = u\sin\theta\sin\phi - v\cos\theta\sin\phi + w\cos\phi \quad (4c)$$

where u, v, and w are the current components in the x, y, and z directions respectively (the inertial coordinate system). Note that u", v", and w" may be a function of depth, if desired.

Equations (1) are numerically integrated using a fourth order Runga-Kutta method[25]. A brief description of this method is presented in Appendix A; further details may be found in Kelly [26] or Nielsen [27].

The following inertial coordinates of the element are computed once a solution for T, θ, and ϕ is obtained for each element of cable, ds. (It is assumed in this study that the unstretched length of ds is 20 feet.)

$$dx = -ds \sin\theta \cos\phi \tag{5a}$$

$$dy = ds \cos\theta \cos\phi \tag{5b}$$

$$dz = ds \sin\phi \tag{5c}$$

The Runge-Kutta method used in this simulation has been checked for accurate performance by White [25] for many representative differential equations. The intent was to provide a subroutine which performed the "dirty work" and required the programmer only to write expressions for the derivatives involved in his particular differential equations. For the present study, this formulation was found to provide sufficient accuracy with rapid convergence.

2.2 Subsurface Buoy Equations

2.2.1 Force Equilibrium Equations

As discussed in the previous section, a numerical integration procedure is used to solve the cable equations. At a buoy, however, this scheme must be interrupted, and the force and moment equilibrium equations for the buoy must be solved in order for the integration to proceed at the next cable element on the "other side" of the buoy.

A free body diagram of the subsurface buoy, which is assumed to be spherical in shape, is shown below:

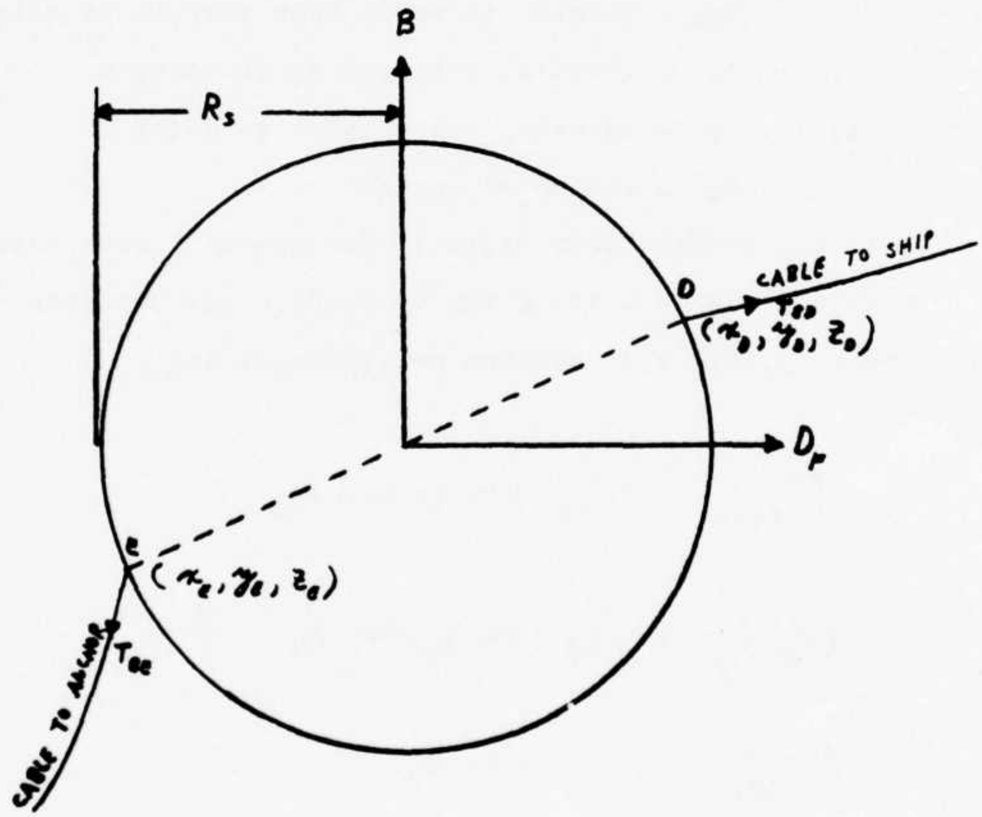

Figure 7. Free Body Diagram of Subsurface Buoy

where

B = net buoyancy of buoy (buoy displacement minus air weight of buoy)

D_B = drag (assumed to be in the horizontal plane, ie., no vertical currents exist)

T_{BE} = tension on cable from anchor at point E

T_{BD} = tension on cable from surface at point D

x_D, y_D, z_D = inertial coordinates of point D

x_E, y_E, z_E = inertial coordinates of point E

R_s = radius of sphere

The tension components in the inertial coordinate system at point E are given by Griffin and Radochia [3] in the x, y, and z directions respectively as:

$$(T_{BE})_x = -T_{BE} \sin\theta_{BE} \cos\phi_{BE} \tag{6a}$$

$$(T_{BE})_y = T_{BE} \cos\theta_{BE} \cos\phi_{BE} \tag{6b}$$

$$(T_{BE})_z = T_{BE} \sin\phi_{BE} \tag{6c}$$

where θ_{BE} and ϕ_{BE} are the horizontal and vertical angles respectively of the cable at point E described earlier in figures 2 through 6. These are considered to be measured positive counterclockwise from the y axis and positive upwards from the x-y plane respectively. (This will be true whenever the symbols θ and ϕ are used at any point.) The tension magnitude T_{BE} and the angles θ_{BE} and ϕ_{BE} are already known from the solution of the cable equations at point E.

The tension components at point D may be given by:

$$\left(T_{BD}\right)_x = -T_{BD} \sin\theta_{BD} \cos\phi_{BD} \tag{7a}$$

$$\left(T_{BD}\right)_y = T_{BD} \cos\theta_{BD} \cos\phi_{BD} \tag{7b}$$

$$\left(T_{BD}\right)_z = T_{BD} \sin\phi_{BD} \tag{7c}$$

where θ_{BD} and ϕ_{BD} are the horizontal and vertical angles respectively of the cable at point D. The tension magnitude T_{BD} and the angles θ_{BD} and ϕ_{BD} are three of the unknowns in this problem.

The buoyancy force, B, will always be acting vertically upwards; thus, its only component is in the z direction.

The drag, D_F, will be assumed to be acting in the horizontal plane. This is a consequence of the assumption that the current velocity vector at any depth is contained in a horizontal plane, that is, $w = \phi = 0$. Furthermore, the current velocity attenuation with depth is insignificant and can be assumed to be non-existent across the sphere. Thus, the current magnitude is given as v_c and its direction as θ_c, where θ_c is measured positive counterclockwise from the inertial y axis. Berteaux [28] gives the drag force as:

$$D_F = \frac{1}{2} \rho_w C_D A v_c^2 \tag{8}$$

where ρ_w = mass density of sea water

c_D = coefficient of drag for the buoy

A = projected area of the buoy in the vertical plane

For a sphere,

$$A = \pi R_s^2 \tag{9}$$

Thus, the components of drag for the subsurface buoy are given as:

$$(D_F)_x = \frac{1}{2} \rho_w C_{DS} (\pi R_s^2)(-v_c \sin\theta_c)(|-v_c \sin\theta_c|) \tag{10a}$$

$$(D_F)_y = \frac{1}{2} \rho_w C_{DS} (\pi R_s^2)(v_c \cos\theta_c)(|v_c \cos\theta_c|) \tag{10b}$$

where c_{DS} is the coefficient of drag for a sphere at Reynolds Number Re, where Re is a function of the current velocity, buoy diameter, and the kinematic viscosity of seawater(ν) as follows:

$$R_e = \frac{2 V_c R_s}{\nu} \tag{11}$$

Using the above expressions for the cable tension, drag, and gravitational force, three force equilibrium equations may be written to solve for the three unknown tension components. They are written, for the x, y, and z directions respectively, as:

$$-(T_{BE})_x + (D_F)_x - (T_{BD})(\sin\theta_{BD})(\cos\phi_{BD}) = 0 \tag{12a}$$

$$-(T_{BE})_y + (D_F)_y + (T_{BD})(\cos\theta_{BD})(\cos\phi_{BD}) = 0 \tag{12b}$$

$$-(T_{BE})_z + (B) + (T_{BD})(\sin\phi_{BD}) = 0 \tag{12c}$$

These equations are solved in Appendix B.1; their solution, from equations (B9), (B12), and (B13) in Appendix B, is as follows:

$$\theta_{BD} = \tan^{-1}\left[\frac{AEX}{AEY}\right] \tag{13a}$$

$$\phi_{BD} = \tan^{-1}\left[\left(\frac{AEZ}{AEY}\right)\left(\cos\theta_{BD}\right)\right] \tag{13b}$$

$$T_{BD} = \left[\frac{AEZ}{\sin\phi_{BD}}\right] \tag{13c}$$

where

$$AEX = \left[-(T_{BE})_x + (D_F)_x\right] \tag{14a}$$

$$AEY = \left[(T_{BE})_y - (D_F)_y\right] \tag{14b}$$

$$AEZ = \left[(T_{BE})_z - (B)\right] \tag{14c}$$

2.2.2 Moment Equilibrium Equations

The moment equilibrium equations may be developed as follows. Let

$$x_{DE} = x_D - x_E \,, \tag{15a}$$

$$y_{DE} = y_D - y_E \,, \quad \text{and} \tag{15b}$$

$$z_{DE} = z_D - z_E \,. \tag{15c}$$

Then, the moments about point E may be written as:

$$(B)\left(\frac{y_{DE}}{2}\right) + (T_{ED})_z\,(y_{DE}) - (D_F)_y\left(\frac{z_{DE}}{2}\right) - (T_{ED})_y\,(z_{DE}) = 0 \tag{16a}$$

$$(D_F)_x\left(\frac{z_{DE}}{2}\right) + (T_{ED})_x\,(z_{DE}) - (B)\left(\frac{x_{DE}}{2}\right) - (T_{ED})_z\,(x_{DE}) = 0 \tag{16b}$$

$$(D_F)_y\left(\frac{x_{DE}}{2}\right) + (T_{ED})_y\,(x_{DE}) - (D_F)_x\left(\frac{y_{DE}}{2}\right) - (T_{ED})_x\,(y_{DE}) = 0 \tag{16c}$$

Since all the forces considered in the problem cut line $\overline{ED}$, equations (16) reduce from three to only two independent equations. A third independent equation, which states that line $\overline{ED}$ passes through the center of the sphere, may be written from the physical geometry of the buoy:

$$(2R_S)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \qquad (17)$$

Their solution is given in Appendix B.2, where equations (16a), (16b), and (17) have been used as the three independent equations. From equations (B-21), the coordinates of point D are given as:

$$x_D = x_E + x_{DB} \qquad (18a)$$

$$y_D = y_E + y_{DB} \qquad (18b)$$

$$z_D = z_E + z_{DB} \qquad (18c)$$

where, from equations (B20), (B19a), and (B19b):

$$z_{DB} = \frac{D_S}{\sqrt{\left(\frac{c_2}{c_1}\right)^2 + \left(\frac{c_3}{c_1}\right)^2 + 1}} \qquad (19a)$$

$$y_{DB} = \left(\frac{c_2}{c_1}\right)\left(z_{DB}\right) \qquad (19b)$$

$$x_{DB} = \left(\frac{c_3}{c_1}\right)\left(z_{DB}\right) \qquad (19c)$$

The constants in the above expressions are defined from equations (B17) as follows:

$$C_1 = \left[\left(\frac{B}{2}\right) + (T_{BD})_z\right] \qquad (20a)$$

$$C_2 = \left[\frac{(D_F)_y}{2} + (T_{BD})_y\right] \qquad (20b)$$

$$C_3 = \left[\frac{(D_F)_x}{2} + (T_{BD})_x\right] \qquad (20c)$$

$$D_S = (2)(R_S)$$

2.3 Iterative Solution for Finding Tension at Anchor

In order to start the integration of the cable equations, the boundary conditions at the anchor must be known. Since the tension and angles at the anchor depend on the final equilibrium configuration, an iterative technique is developed modifying the methods first described by Dominguez and Filmer [29] (which are based on Skop and O'Hara's [30] method of imaginary reactions) and later used by Griffin and Swope [31].

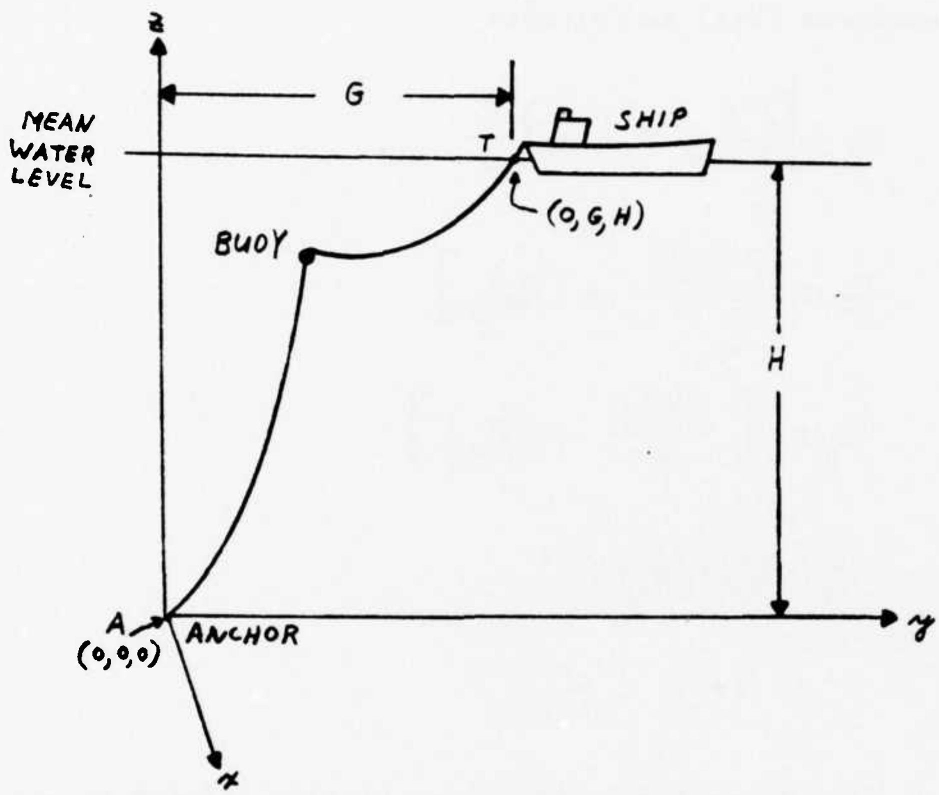

Figure 8. Inertial Coordinate System

It is seen from figure 8 that the anchor is located at $x = 0$, $y = 0$, and $z = 0$. The y axis is the horizontal projection of a straight line taken between the anchor and the first point of submergence into the water of the tether cable from the ship. The z axis is the vertical direction, and, of course, the x axis completes the right handed coordinate system. The first point of submergence into the water of the tether cable from the ship, T, is located at

$x = o$ (due to the alignment of the y axis), $y = G$ (this will be specified), and $z = H$ (the water depth).

The procedure begins by assuming the tension vector at the anchor, $\vec{T_A}$, which includes a magnitude T_A and the two angles θ_A and ϕ_A . (The weight of the anchor is considered to be sufficient to prevent any movement of the anchor; that is, the anchor is assumed to be fixed.) Integration then takes place over the cable up to the first subsurface buoy (if there is one). Equilibrium requirements are satisfied here (see equations 12), and the integration continues along the cable up to the second subsurface buoy (if there is one). After equilibrium requirements again are satisfied, the integration proceeds along the tether to the ship. At the ship, the calculated values for the position of the ship are compared to the specified location of the ship on the surface. (The water depth is known and the position of the ship is specified relative to the anchor due to operational considerations.) These errors are then used in "correcting" the tension at the anchor. The process is repeated until the error reaches a suitably small value. (For the present study, a closure error of ten feet was used at the ship.) This process is described in detail as follows:

$$\Delta x_A = \frac{\delta_A}{\sqrt{E_A}}(O - x_A) \tag{21a}$$

$$\Delta y_A = \frac{\delta_A}{\sqrt{E_A}}(G - y_A) \tag{21b}$$

$$\Delta z_A = \frac{\delta_A}{\sqrt{E_A}}(H - z_A) \tag{21c}$$

where x_A, y_A, and z_A are the calculated values for the position of the ship, and

$$E_A = (O - x_A)^2 + (G - y_A)^2 + (H - z_A)^2 \tag{22}$$

Let δ_A be some positive number which is reduced at certain iterations so that each iteration produces a smaller closure error, until the value of E_A is less than some prespecified value ε. Initially, the value of δ_A is taken to be equal to 3000 if there are no buoys in the system, the excess buoyancy of the buoy if there is one buoy, and the sum of the excess buoyancies of the buoys if there are two buoys. E_A is initially assumed to be ten times the initial value of δ_A. One can choose to reduce δ_A by a factor of two. (Convergence for this method has been indicated by

Dominguez and Filmer [29] and Griffin and Swope [31].)

The tension at the anchor is corrected as follows: Let the new tension be given by

$$T_{AN} = \sqrt{(T_{AN})_x^2 + (T_{AN})_y^2 + (T_{AN})_z^2} \tag{23}$$

where

$$(T_{AN})_x = (T_A)_x + \Delta x_A \tag{24a}$$

$$(T_{AN})_y = (T_A)_y + \Delta y_A \tag{24b}$$

$$(T_{AN})_z = (T_A)_z + \Delta z_A \tag{24c}$$

and, using equation (6),

$$(T_A)_x = -(T_A)(\sin\theta_A)(\cos\phi_A) \tag{25a}$$

$$(T_A)_y = (T_A)(\cos\theta_A)(\cos\phi_A) \tag{25b}$$

$$(T_A)_z = (T_A)(\sin\phi_A) \tag{25c}$$

$\vec{T}_{AN}$ may be broken up into a magnitude and two angles as follows:

$$T_{AN} = \sqrt{(T_{AN})_x^2 + (T_{AN})_y^2 + (T_{AN})_z^2} \tag{26a}$$

$$\phi_{AN} = \tan^{-1}\left[\frac{(T_{AN})_z}{\sqrt{(T_{AN})_x^2 + (T_{AN})_y^2}}\right] \tag{26b}$$

$$\theta_{AN} = \tan^{-1}\left[\frac{-(T_{AN})_x}{(T_{AN})_y}\right] \tag{26c}$$

where T_{AN}, ϕ_{AN}, and θ_{AN} are the "improved" tension and angles.

At the N'th iteration, E_{A_N} is compared with $E_{A_{N-1}}$. If $E_{A_{N-1}} < E_{A_N}$ the value of δ_A is reduced (by half here), and $\vec{T}_N$ is computed from $\vec{T}_{N-1}$ using the new value of δ_A.

The above process was the sole criterion for Dominguez and Filmer [29] and Griffin and Swope [31] for the reduction of δ_A. It was decided, however, that if a larger error could be predicted in advance, then convergence would be faster. The basic idea of this is to prevent an "over-correction" of the tension at the anchor; that is, if the N'th iteration produced an error significantly smaller than the (N-1)'th iteration, then δ_A should be reduced on the N'th iteration. Otherwise, too large a correction would be applied at the anchor, resulting in a larger error on the (N+1)'th iteration than on the N'th iteration. This is accomplished by using the following scheme: Let

$$ERRR = \frac{(E_A)_{N-1}}{(E_A)_N} \tag{27}$$

where $(E_A)_{N-1}$ and $(E_A)_N$ are the errors of the (N-1)'th and N'th iterations respectively. If ERRR is greater than two, then δ_A will be reduced in the following manner:

$$(\delta_A)_N = \left(\frac{1}{2}\right)(\delta_A)_{N-1} \tag{28}$$

and $\vec{T}_{AN}$ is recomputed using $\vec{T}_{A_{N-1}}$ and the new value of δ_{A_N}. One problem was encountered, however, using this second method: δ_A was sometimes reduced too quickly so that the error was unable to reach a suitably small value. (δ_A was reduced too much, resulting in the tension corrections (Δx, Δy, and Δz of equation (21)) becoming too small.) Thus, while the first method for reducing δ_A is implemented always, this second process is used only when the error is greater than 500 feet; that is, when the ship is calculated to be more than 500 feet from its specified location.

III. DYNAMIC MODEL

3.1 Cable Equations of Motion for a Lumped-Mass System

Many methods are available for analyzing the motions of a cable. The cable may be regarded as a continuum, a series of finite segments, or a series of lumped-mass (concentrated) elements. Both the finite element method and the methods that assume the cable to be continuous are numerical techniques that usually require a great amount of computer time. The lumped-mass method employed in this study to analyze the unsteady motions of a cable is Patton's[9], who states that "a lumped mass analysis can offer significant savings in computational time at the expense of simulation accuracy. In general, the lumped-mass analysis will truncate the high-frequency response of the system. However, for many engineering applications, the high-frequency, low-amplitude response is not of interest, and the cable can be represented as a small number of lumped masses." A similar approach was also taken by Griffin [6] in his model of a cable towed-body system.

The lumped mass models of Patton [9] and Griffin [6] assume that a uniform cable of length L can be broken up into n unstretched segments of length ΔL_n. Figures 9, 10, and 11 show these models for the no buoy, one buoy, and two buoy systems respectively used in this study.

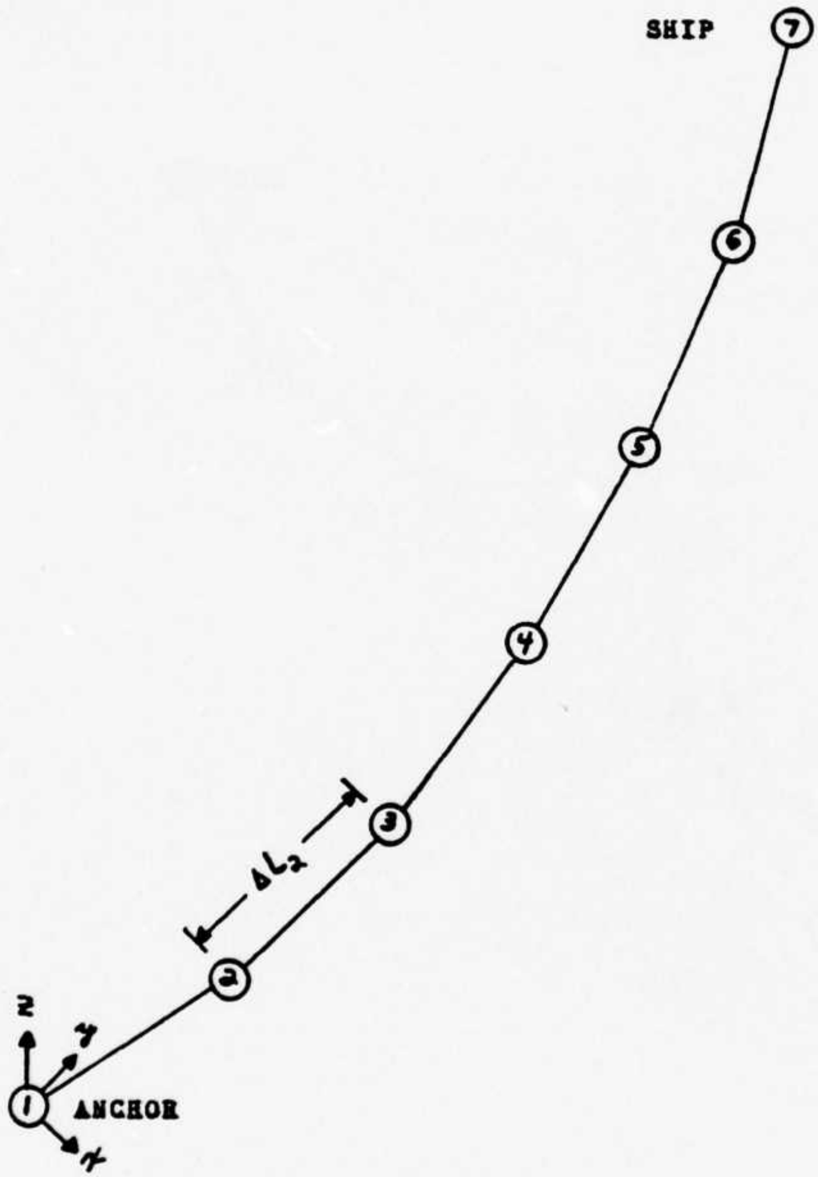

Figure 9. Lumped-Mass Cable Elements With No Buoys

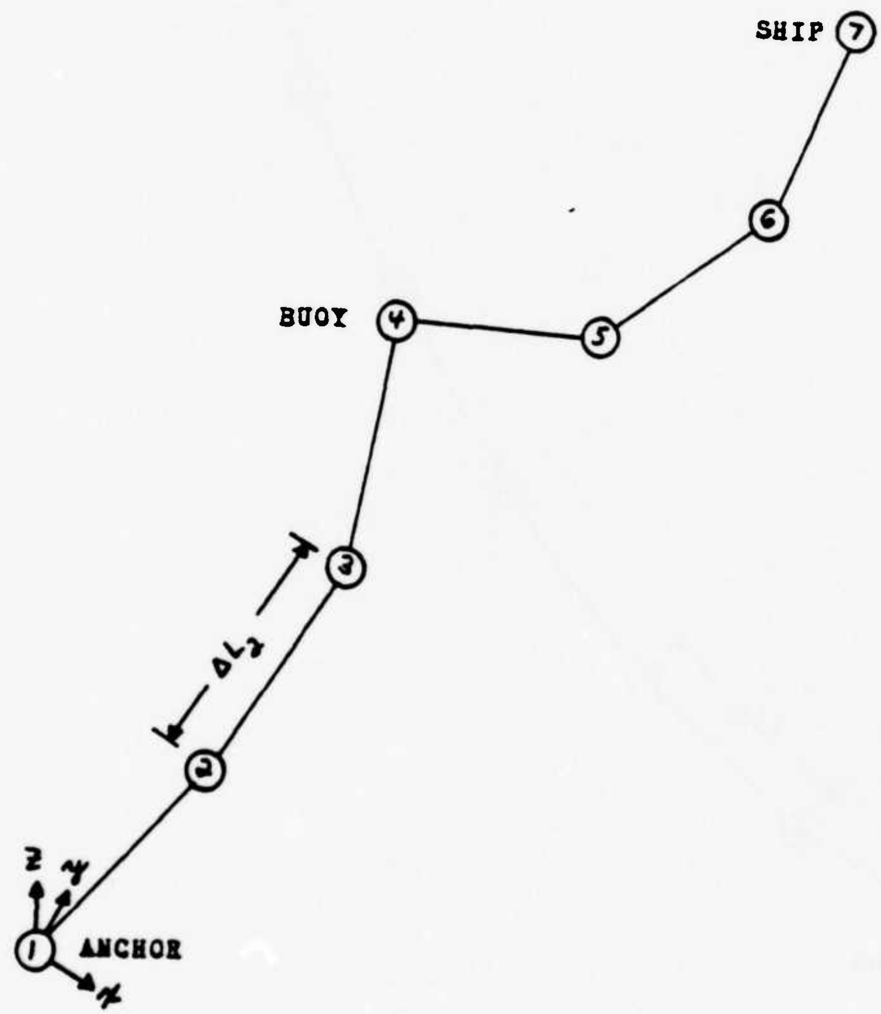

Figure 10. Lumped-Mass Cable Elements With One Buoy

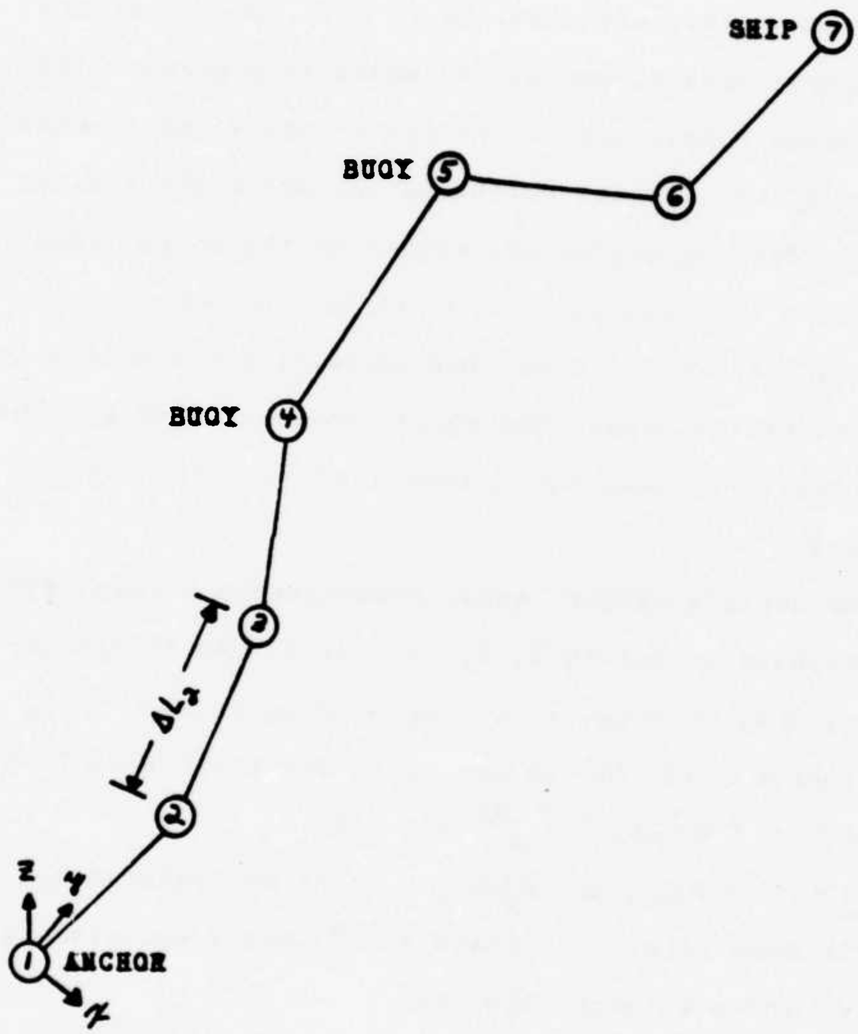

Figure 11. Lumped-Mass Cable Elements With Two Buoys

For the purposes of this study, the system is assumed to be divided up into six segments ($m = 6$), which results in seven lumped mass elements. As shown in figures 9, 10, and 11, element number one is the anchor and element number 7 is the ship. The forces acting on the cable are assumed to have no effect on either the anchor or the ship. That is, the anchor has neither accelerations nor velocities, and the ship has accelerations and velocities due solely to its wave induced motions. (The ship's motions, when attached to the system, are taken to be identical to those when it is unattached.)

If the cable's weight, mass, hydrodynamic forces, etc., are concentrated at points 2, 3, ..., 5, 6, (which are located ΔL_1, $\Delta L_1 + \Delta L_2$, ..., $\Delta L_1 + \Delta L_2 + \ldots + \Delta L_5$ from the anchor), all forces acting on the cable span from $(\Delta L_1 + \Delta L_2 + \ldots + \Delta L_{n-2} + \frac{\Delta L_{n-1}}{2})$ to $(\Delta L_1 + \Delta L_2 + \ldots + \Delta L_{n-1} + \frac{\Delta L_n}{2})$ will be concentrated at the n'th mass point. Cristecu's [32] cable equations are written for the n'th mass point as:

$$\left(\frac{\mu_n(s_0)\,\Delta L_n}{2} + \frac{\mu_{n-1}(s_0)\,\Delta L_{n-1}}{2}\right)\frac{d^2 x_n}{dt^2} =$$

$$\left(\frac{\overline{X}_n\,\Delta L_n}{2} + \frac{\overline{X}_{n-1}\,\Delta L_{n-1}}{2}\right) + \left(\vec{T}_n\cdot\hat{i} - \vec{T}_{n-1}\cdot\hat{i}\right) \qquad (29a)$$

$$\left(\frac{\mu_n(s_0)\,\Delta L_n}{2} + \frac{\mu_{n-1}(s_0)\,\Delta L_{n-1}}{2}\right)\frac{d^2 y_n}{dt^2} =$$

$$\left(\frac{\overline{Y}_n\,\Delta L_n}{2} + \frac{\overline{Y}_{n-1}\,\Delta L_{n-1}}{2}\right) + \left(\vec{T}_n\cdot\hat{j} - \vec{T}_{n-1}\cdot\hat{j}\right) \qquad (29b)$$

$$\left(\frac{\mu_n(s_0)\,\Delta L_n}{2} + \frac{\mu_{n-1}(s_0)\,\Delta L_{n-1}}{2}\right)\frac{d^2 z}{dt^2} =$$

$$\left(\frac{\overline{Z}_n\,\Delta L_n}{2} + \frac{\overline{Z}_{n-1}\,\Delta L_{n-1}}{2}\right) + \left(\vec{T}_n\cdot\hat{k} - \vec{T}_{n-1}\cdot\hat{k}\right) \qquad (29c)$$

where

$\mu_n(s_o)$ = the mass (structural) per unit length of the n'th cable segment

x_n, y_n, z_n = the inertial coordinates of the n'th mass point

t = time

$\bar{X}_n$, $\bar{Y}_n$, $\bar{Z}_n$ = the force components (weight, drag, and added mass forces) per unit length of the n'th cable segment

$\vec{T}_n$ = the cable tension vector of the n'th cable segment

$\hat{i}$, $\hat{j}$, $\hat{k}$ = unit vector components

To compute forces acting on each mass element, the cable angles θ and ϕ for each element must be defined. From the geometry between the successive mass elements, we see that:

$$\theta_n = \tan^{-1}\left(\frac{-(x_{n+1} - x_n)}{(y_{n+1} - y_n)}\right) \tag{30a}$$

$$\phi_n = \tan^{-1}\left(\frac{(z_{n+1} - z_n)}{\sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2}}\right) \tag{30b}$$

The stretched length between any two mass elements is computed as equal to:

$$\sqrt{(x_{n+1}-x_n)^2+(y_{n+1}-y_n)^2+(z_{n+1}-z_n)^2} \tag{30c}$$

Figure 12 shows the convention used for the subscripts:

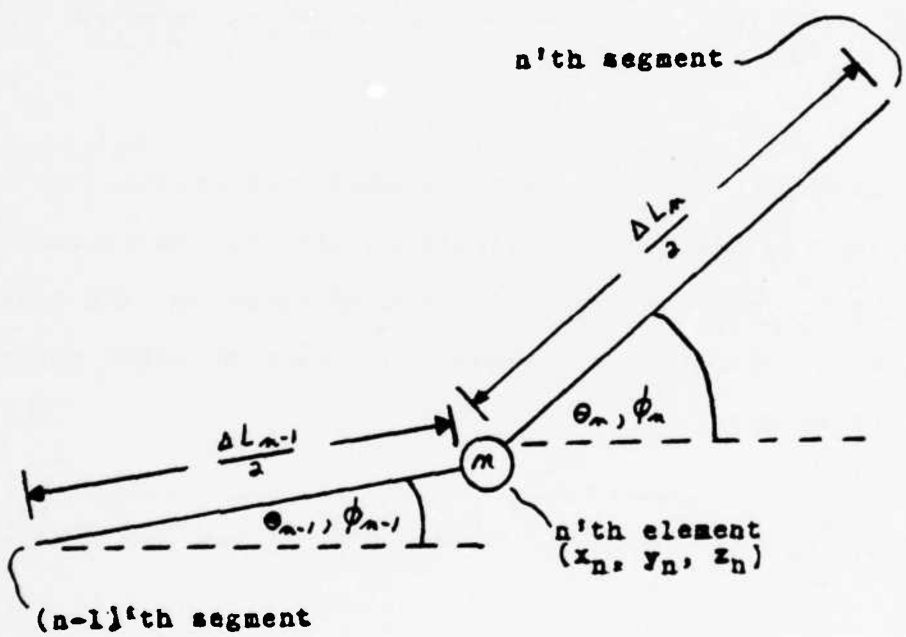

Figure 12. Subscript Convention for Lumped Mass Angles

To compute tensions between elements, the elastic properties of the cable and the cable deformation are used. That is, if the effective cable modulus is E_c and the cable element deformation is δ, then, using Hooke's Law [24], the spring constant along the cable is:

$$K_{y''_n} = \frac{F_n}{\delta_n} = \frac{\left(\frac{\pi d_{s_n}^2}{4}\right)(\sigma_n)}{\delta_n} = \left(\frac{\pi d_{s_n}^2}{4}\right)\left(\frac{E_{c_n}}{\Delta L_n}\right) \tag{31}$$

Assuming the cable cannot support compression, it must be specified that if the difference between the stretched and the unstretched length is zero or negative, the tension is zero. Otherwise, the tension in the n'th cable segment is defined by:

$$T_{y'_n} = K_{y'_n}\left(\sqrt{(x_{n+1}-x_n)^2+(y_{n+1}-y_n)^2+(z_{n+1}-z_n)^2} - \Delta L_n\right) \tag{32}$$

The tension in the inertial coordinate system is, from equation (6):

$$T_n = \begin{bmatrix} -T_{y''_n} \sin\theta_n \cos\phi_n \\ T_{y''_n} \cos\theta_n \cos\phi_n \\ T_{y''_n} \sin\phi_n \end{bmatrix} \tag{33}$$

The inertial tension components are used to compute the tension difference across the mass element given in equation (29).

Each of the forces $\bar{X}_n \Delta L_n$, $\bar{Y}_n \Delta L_n$, and $\bar{Z}_n \Delta L_n$ acting on each mass element consists of weight, viscous drag, and added mass forces. The weight force vector per unit length is, in the inertial coordinate system:

$$W_c = \begin{bmatrix} 0 \\ 0 \\ -w_c \end{bmatrix} \tag{34}$$

where w_c is, as before, the in-water weight per unit length of the cable.

The components of the ocean currents that exist are given as

$$\begin{bmatrix} u \\ v \\ 0 \end{bmatrix} \qquad (35)$$

and the velocity components of the n'th element are

$$\begin{bmatrix} \dot{x}_n \\ \dot{y}_n \\ \dot{z}_n \end{bmatrix} \qquad (36)$$

then the resultant velocity of the water relative to the cable components are:

$$\begin{bmatrix} U_{Rn} \\ V_{Rn} \\ W_{Rn} \end{bmatrix} = \begin{bmatrix} u - \dot{x}_n \\ v - \dot{y}_n \\ 0 - \dot{z}_n \end{bmatrix} \qquad (37)$$

For the purpose of calculating the cable drag and added mass forces, previous studies [6, 9] have used mean cable angles at the n'th element, defined to be:

$$\overline{\theta_n} = \frac{1}{2}\left(\theta_n + \theta_{n-1}\right) \tag{38a}$$

$$\overline{\phi_n} = \frac{1}{2}\left(\phi_n + \phi_{n-1}\right) \tag{38b}$$

Figure 13 shows such angles.

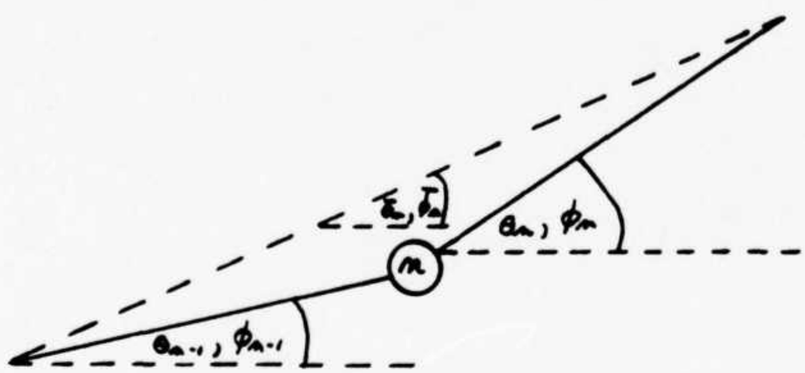

Figure 13. Mean Cable Angles

In using these mean cable angles, it was inherently assumed that the angles θ_{n-1}, θ_n, ϕ_{n-1}, and ϕ_n all lie in the same quadrant of a rectangular Cartesian coordinate system. After examining the preliminary results of the steady state model, however, it was seen that this was not often the case with the present study. Figure 14 shows one such configuration:

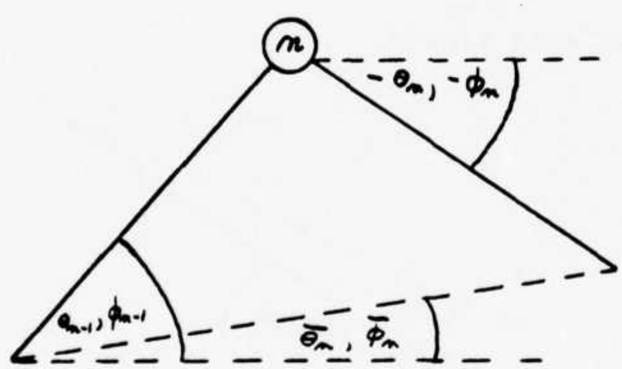

Figure 14. Possible Mean Cable Angles

It is obvious from figure 14 that the mean cable angles computed from equations (38) would yield erroneous results; thus they will not be employed. Rather, the forces considered to be acting at element n will be the summation of those acting on half of the (n-1)'th segment and half of the n'th segment.

The velocity components of the water relative to the cable, using equation (2), are transformed to cable coordinates to yield:

$$U_{R_n''} = (u - \dot{x}_n)(\cos\theta_n) + (v - \dot{y}_n)(\sin\theta_n) \tag{39a}$$

$$V_{R_n''} = -(u - \dot{x}_n)(\sin\theta_n \cos\phi_n) + (v - \dot{y}_n)(\cos\theta_n \cos\phi_n) + (-\dot{z}_n)(\sin\phi_n) \tag{39b}$$

$$W_{R_n''} = (u - \dot{x}_n)(\sin\theta_n \sin\phi_n) - (v - \dot{y}_n)(\cos\theta_n \sin\phi_n) + (-\dot{z}_n)(\cos\phi_n) \tag{39c}$$

The drag force components per unit length are, in cable coordinates:

$$D_{x''_n} = \frac{1}{2} \rho_w d_n c_{DN} \; U_{R''_n} \left| U_{R''_n} \right| \tag{40a}$$

$$D_{y''_n} = \frac{1}{2} \rho_w \pi d_n c_{DT} \; V_{R''_n} \left| V_{R''_n} \right| \tag{40b}$$

$$D_{z''_n} = \frac{1}{2} \rho_w d_n c_{DN} \; W_{R''_n} \left| W_{R''_n} \right| \tag{40c}$$

The drag forces per unit length are then transformed back to inertial coordinates so that they will be consistent with the coordinate system used in the expressions for the other forces.

Lumping the added mass terms with the structural mass terms and transforming from cable coordinates to inertial coordinates yields the added mass matrix:

$$\begin{bmatrix} m_{\ell_{\dot{x}_n}} \cos\theta_n - m_{\ell_{\dot{y}_n}} \sin\theta_n \cos\phi_n + m_{\ell_{\dot{z}_n}} \sin\theta_n \sin\phi_n \\ m_{\ell_{\dot{x}_n}} \sin\theta_n + m_{\ell_{\dot{y}_n}} \cos\theta_n \cos\phi_n - m_{\ell_{\dot{z}_n}} \cos\theta_n \sin\phi_n \\ m_{\ell_{\dot{y}_n}} \sin\phi_n + m_{\ell_{\dot{z}_n}} \cos\phi_n \end{bmatrix} \tag{41}$$

Patton [33] gives the added mass per unit length for very long cylinders as:

$$m_{\ell_{\ddot{x}_n}} = \pi \rho_w \left(\frac{d_n}{2}\right)^2 \tag{42a}$$

$$m_{\ell_{\ddot{y}_n}} = 0 \tag{42b}$$

$$m_{\ell_{\ddot{z}_n}} = \pi \rho_w \left(\frac{d_n}{2}\right)^2 \tag{42c}$$

Then the different terms of the cable equations for the n'th element are as follows.

The mass and added mass terms:

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell_{\ddot{x}_n}} \cos\theta_n - m_{\ell_{\ddot{y}_n}} \sin\theta_n \cos\phi_n$$

$$+ m_{\ell_{\ddot{z}_n}} \sin\theta_n \sin\phi_n \Big] \frac{\Delta L_n}{2} + \Big[\mu_{n-1}(s_0)$$

$$+ m_{\ell_{\ddot{x}_{n-1}}} \cos\theta_{n-1} - m_{\ell_{\ddot{y}_{n-1}}} \sin\theta_{n-1} \cos\phi_{n-1}$$

$$+ m_{\ell_{\ddot{z}_{n-1}}} \sin\theta_{n-1} \sin\phi_{n-1} \Big] \frac{\Delta L_{n-1}}{2} \Big\} \frac{d^2 x_n}{dt^2} \tag{43a}$$

$$\left\{\left[\mu_n(s_0) + m_{l x''_n} \sin\theta_n + m_{l y''_n} \cos\theta_n \cos\phi_n - m_{l z''_n} \cos\theta_n \sin\phi_n\right]\frac{\Delta L_n}{2} + \left[\mu_{n-1}(s_0) + m_{l x''_{n-1}} \sin\theta_{n-1} + m_{l y''_{n-1}} \cos\theta_{n-1} \cos\phi_{n-1} - m_{l z''_{n-1}} \cos\theta_{n-1} \sin\phi_{n-1}\right]\frac{\Delta L_{n-1}}{2}\right\}\frac{d^2 y_n}{dt^2} \qquad (43b)$$

$$\left\{\left[\mu_n(s_0) + m_{l y''_n} \sin\phi_n + m_{l z''_n} \cos\phi_n\right]\frac{\Delta L_n}{2} + \left[\mu_{n-1}(s_0) + m_{l y''_{n-1}} \sin\phi_{n-1} + m_{l z''_{n-1}} \cos\phi_{n-1}\right]\frac{\Delta L_{n-1}}{2}\right\}\frac{d^2 z_n}{dt^2} \qquad (43c)$$

the weight terms:

$$0 \qquad (44a)$$

$$0 \qquad (44b)$$

$$-\mu_c \qquad (44c)$$

the drag terms (after using equation (3) for the transformation from cable to inertial coordinates):

$$\Big[D''_{x_n} \cos\theta_n - D''_{y_n} \sin\theta_n \cos\phi_n + D''_{z_n} \sin\theta_n \sin\phi_n\Big]\frac{\Delta L_n}{2} + \Big[D''_{x_{n-1}} \cos\theta_{n-1} - D''_{y_{n-1}} \sin\theta_{n-1} \cos\phi_{n-1} + D''_{z_{n-1}} \sin\theta_{n-1} \sin\phi_{n-1}\Big]\frac{\Delta L_{n-1}}{2} \qquad (45a)$$

$$\Big[D''_{x_n} \sin\theta_n + D''_{y_n} \cos\theta_n \cos\phi_n - D''_{z_n} \cos\theta_n \sin\phi_n\Big]\frac{\Delta L_n}{2} + \Big[D''_{x_{n-1}} \sin\theta_{n-1} + D''_{y_{n-1}} \cos\theta_{n-1} \cos\phi_{n-1} - D''_{z_{n-1}} \cos\theta_{n-1} \sin\phi_{n-1}\Big]\frac{\Delta L_{n-1}}{2} \qquad (45b)$$

$$\Big[D''_{y_n} \sin\phi_n + D''_{z_n} \cos\phi_n\Big]\frac{\Delta L_n}{2} + \Big[D''_{y_{n-1}} \sin\phi_{n-1} + D''_{z_{n-1}} \cos\phi_{n-1}\Big]\frac{\Delta L_{n-1}}{2} \qquad (45c)$$

and the tension terms:

$$- T_{y''_n} \sin\theta_n \cos\phi_n \tag{46a}$$

$$T_{y''_n} \cos\theta_n \cos\phi_n \tag{46b}$$

$$T_{y''_n} \sin\phi_n \tag{46c}$$

The cable equations, after substituting into (29), are then:

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell_{x''_n}} \cos\theta_n - m_{\ell_{y''_n}} \sin\theta_n \cos\phi_n$$

$$+ m_{\ell_{z''_n}} \sin\theta_n \sin\phi_n \Big] \frac{\Delta L_n}{2} + \Big[\mu_{n-1}(s_0)$$

$$+ m_{\ell_{x''_{n-1}}} \cos\theta_{n-1} - m_{\ell_{y''_{n-1}}} \sin\theta_{n-1} \cos\phi_{n-1}$$

$$+ m_{\ell_{z''_{n-1}}} \sin\theta_{n-1} \sin\phi_{n-1} \Big] \frac{\Delta L_{n-1}}{2} \Big\} \frac{d^2 x_n}{dt^2} =$$

$$\Big[\Big(D_{x''_n} \cos\theta_n - D_{y''_n} \sin\theta_n \cos\phi_n$$

$$+ D_{z''_n} \sin\theta_n \sin\phi_n \Big) \frac{\Delta L_n}{2} + \Big(D_{x''_{n-1}} \cos\theta_{n-1}$$

$$- D_{y''_{n-1}} \sin\theta_{n-1} \cos\phi_{n-1} + D_{z''_{n-1}} \sin\theta_{n-1} \sin\phi_{n-1} \Big) \frac{\Delta L_{n-1}}{2} \Big]$$

$$+ \left(- T_{y''_n} \sin\theta_n \cos\phi_n + T_{y''_{n-1}} \sin\theta_{n-1} \cos\phi_{n-1} \right) \tag{47a}$$

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell x''_n} \sin\theta_n + m_{\ell y''_n} \cos\theta_n \cos\phi_n$$

$$- m_{\ell z''_n} \cos\theta_n \sin\phi_n\Big] \frac{\Delta L_n}{2} + \Big[\mu_{n-1}(s_0)$$

$$+ m_{\ell x''_{n-1}} \sin\theta_{n-1} + m_{\ell y''_{n-1}} \cos\theta_{n-1} \cos\phi_{n-1}$$

$$- m_{\ell z''_{n-1}} \cos\theta_{n-1} \sin\phi_{n-1}\Big] \frac{\Delta L_{n-1}}{2}\Big\} \frac{d^2 y_n}{dt^2} =$$

$$\Big[\Big(D_{x''_n} \sin\theta_n + D_{y''_n} \cos\theta_n \cos\phi_n$$

$$- D_{z''_n} \cos\theta_n \sin\phi_n \Big) \frac{\Delta L_n}{2} + \Big(D_{x''_{n-1}} \sin\theta_{n-1}$$

$$+ D_{y''_{n-1}} \cos\theta_{n-1} \cos\phi_{n-1} - D_{z''_{n-1}} \cos\theta_{n-1} \sin\phi_{n-1} \Big) \frac{\Delta L_{n-1}}{2} \Big]$$

$$+ \Big(T_{y''_n} \cos\theta_n \cos\phi_n - T_{y''_{n-1}} \cos\theta_{n-1} \cos\phi_{n-1} \Big) \qquad (47b)$$

$$\Big\{ \Big[\mu_n(s_0) + m_{\ell y''_n} \sin\phi_n + m_{\ell z''_n} \cos\phi_n \Big] \frac{\Delta L_n}{2}$$

$$+ \Big[\mu_{n-1}(s_0) + m_{\ell y''_{n-1}} \sin\phi_{n-1} + m_{\ell z''_{n-1}} \cos\phi_{n-1} \Big] \frac{\Delta L_{n-1}}{2} \Big\} \frac{d^2 z_n}{dt^2} =$$

$$\Big[-(w_c)\Big(\frac{\Delta L_n}{2}\Big) + -(w_c)\Big(\frac{\Delta L_{n-1}}{2}\Big) \Big] + \Big[\Big(D_{y''_n} \sin\phi_n + D_{z''_n} \cos\phi_n \Big) \frac{\Delta L_n}{2}$$

$$+ \Big(D_{y''_{n-1}} \sin\phi_{n-1} + D_{z''_{n-1}} \cos\phi_{n-1} \Big) \frac{\Delta L_{n-1}}{2} \Big]$$

$$+ \Big(T_{y''_n} \sin\phi_n - T_{y''_{n-1}} \sin\phi_{n-1} \Big) \qquad (47c)$$

The auxiliary relations are:

$$\theta_n = \tan^{-1}\left[\frac{-(x_{n+1} - x_n)}{(y_{n+1} - y_n)}\right] \tag{48a}$$

$$\phi_n = \tan^{-1}\left[\frac{(z_{n+1} - z_n)}{\sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2}}\right] \tag{48b}$$

$$T_{y_n''} = K_{y_n''}\left(\sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2 + (z_{n+1} - z_n)^2} - \Delta L_n\right) \tag{48c}$$

$$K_{y_n''} = \left(\frac{\pi d_{s_n}^2}{4}\right)\left(\frac{E_{c_n}}{\Delta L_n}\right) \tag{48d}$$

3.2 Subsurface Buoy Dynamics

The forces acting on the subsurface buoy are

a. an external gravitational force,

b. hydrostatic forces,

c. hydrodynamic forces (drag and added mass), and

d. cable tensions

Using Newton's Second Law,(34) the equations of motion for the subsurface buoy can be developed. In matrix form, the equations of motion are:

$$\mathcal{M}\ddot{Q} = \mathcal{M}G - \mathcal{B} - \mathcal{H} - \mathcal{T} \tag{49a}$$

or

$$\mathcal{M}\ddot{Q} = \mathcal{W} - \mathcal{H} - \mathcal{T} \tag{49b}$$

where

$\mathcal{M}$ = the structural mass matrix

$\ddot{Q}$ = the acceleration vector

G = the gravitational vector

$\mathbb{B}$ = the hydrostatic force vector

$\mathcal{H}$ = the hydrodynamic force vector

$\mathcal{T}$ = the cable tension vecter

$\mathcal{W}$ = the body weight in water veator

The structural mass matrix can be written as:

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & m \end{bmatrix} \tag{50}$$

where m is the mass of the buoy.

The acceleration vector is:

$$\ddot{Q} = \begin{bmatrix} \ddot{x}_c \\ \ddot{y}_c \\ \ddot{z}_c \end{bmatrix} \tag{51}$$

where x_c, y_c, and z_c are the x, y, and z coordinates of the center of the buoy.

The in water weight vector is:

$$W = \begin{bmatrix} 0 \\ 0 \\ -w_l \end{bmatrix} \tag{52}$$

(Note that $(-w_b)$ will be positive for a positively buoyant buoy.)

The tension vector is:

$$\mathbf{T} = \begin{bmatrix} -T_S \sin\theta_S \cos\phi_S + T_R \sin\theta_R \cos\phi_R \\ T_S \cos\theta_S \cos\phi_S - T_R \cos\theta_R \cos\phi_R \\ T_S \sin\phi_S - T_R \sin\phi_R \end{bmatrix} \tag{53}$$

where T_S and T_R are the tension magnitudes of the cable segments above and below the buoy respectively (see equation (32)), and θ_S, ϕ_S, θ_R, and ϕ_R are the horizontal and vertical angles of these segments as defined in equation (30).

The hydrodynamic forces acting upon the buoy are caused by the motion of the body in the fluid. These forces are considered to be inertial (added mass) and dissipative. Dissipative forces caused by viscosity will be discussed as separate force components, as will the inertial forces caused by buoy motion.

The added mass matrix is established as follows, where the off-diagonal terms have been taken to be zero due to the symmetry of the buoy:

$$M_\ell = \begin{bmatrix} m_{\ell_x} & 0 & 0 \\ 0 & m_{\ell_y} & 0 \\ 0 & 0 & m_{\ell_z} \end{bmatrix} \tag{54}$$

Patton (33) gives the hydrodynamic mass for a sphere of radius R_S as:

$$m_{\ell_x} = \frac{2}{3} \pi \rho_w (R_s)^2 \tag{55a}$$

$$m_{\ell_y} = \frac{2}{3} \pi \rho_w (R_s)^2 \tag{55b}$$

$$m_{\ell_z} = \frac{2}{3} \pi \rho_w (R_s)^2 \tag{55c}$$

The viscous force matrix may be given as:

$$D = \begin{bmatrix} D_{B_x} \\ D_{B_y} \\ D_{B_z} \end{bmatrix} \tag{56}$$

or

$$\mathbb{D} = \begin{bmatrix} \frac{1}{2} \rho_w C_{DS} (\pi R_s^2) (U_{RN}) (|U_{RN}|) \\ \frac{1}{2} \rho_w C_{DS} (\pi R_s^2) (V_{RN}) (|V_{RN}|) \\ \frac{1}{2} \rho_w C_{DS} (\pi R_s^2) (W_{RN}) (|W_{RN}|) \end{bmatrix} \quad (57)$$

Hydrodynamic forces are computed by considering water mass movements relative to the body. Assume that the buoy is deep enough so it is not influenced by surface waves and that the water mass movement is some steady flow resulting from steady ocean currents. Then the relative acceleration of the water mass surrounding the buoy is given in equation (51) as:

$$\ddot{Q} = \begin{bmatrix} \ddot{x}_c \\ \ddot{y}_c \\ \ddot{z}_c \end{bmatrix} \quad (58)$$

The velocity vecter of the body relative to the water mass is defined in equation (37) to be:

$$\dot{Q} = \begin{bmatrix} U_{RN} \\ V_{RN} \\ W_{RN} \end{bmatrix} \tag{59}$$

The equations of motion for the buoy can be summarized as:

$$M\ddot{Q} = W - H - T \tag{60}$$

Substituting for the hydrodynamic forces

$$H = M_{\ell}\ddot{Q} + D \tag{61}$$

yields

$$M\ddot{Q} = W - M_{\ell}\ddot{Q} - D - T \tag{62}$$

which simplifies to

$$(M + M_\ell)\,\ddot{Q} = W - D - T \tag{63}$$

with all the coefficients as previously discussed.

The inertial term becomes:

$$\begin{bmatrix} (m + m_{\ell x})\,\ddot{x}_c \\ (m + m_{\ell y})\,\ddot{y}_c \\ (m + m_{\ell z})\,\ddot{z}_c \end{bmatrix} \tag{64}$$

The viscous force term is:

$$\begin{bmatrix} D_{\ell x} \\ D_{\ell y} \\ D_{\ell z} \end{bmatrix} \tag{65}$$

The weight term becomes:

$$\begin{bmatrix} 0 \\ 0 \\ -w_\ell \end{bmatrix} \tag{66}$$

The tension term is:

$$\begin{bmatrix} -T_S \sin\theta_S \cos\phi_S + T_R \sin\theta_R \cos\phi_R \\ T_S \cos\theta_S \cos\phi_S - T_R \cos\theta_R \cos\phi_R \\ T_S \sin\phi_S - T_R \sin\phi_R \end{bmatrix} \quad (67)$$

As was shown in figures 10 and 11, a buoy is located at the exact position of one of the cable mass elements. Thus, the equilibrium equations for the buoy will not be solved explicitly, but rather the inertial, viscous, and weight terms of equations (64), (65), and (66) respectively will be added to the inertial, viscous, and weight terms of the cable element of equations (43), (45), and (44) respectively for the appropriate lumped mass. This will give one set of equations for the element, with the forces acting on the cable and buoy lumped together for the solution.

3.3 Ship Motions

In order to determine the ship motions resulting from waves, M.I.T.'s five degrees of freedom seakeeping program [35] (surge neglected) was used. This program is based upon the theory developed by Salvesen,[36] and employs the section transformations used by Loukakis.[37] Appendix D gives a detailed description of the ship used in the present study.

The ship positions are given in the inertial coordinate system centered at the anchor as follows:

$$x_7 = \sum_{i=0}^{100} S_{\ell x_i} \sin(w_i t + \varepsilon_{x_i}) \tag{68a}$$

$$y_7 = G \tag{68b}$$

$$z_7 = H + \sum_{i=0}^{100} S_{\ell z_i} \sin(w_i t + \varepsilon_{z_i}) \tag{68c}$$

where

$S_{h_{x_1}}$, $S_{h_{z_1}}$ = amplitude of lateral and vertical motion of ship's point of attachment to cable

ω_1 = the wave frequency

ε_{x_1}, ε_{z_1} = the phase angles

Velocities at the ship are found by differentiation of equations (68) with respect to time:

$$\dot{x}_7 = \sum_{i=0}^{100} S_{\ell x_i} w_i \cos(w_i t + \varepsilon_{x_i}) \tag{69a}$$

$$\dot{y}_7 = 0 \tag{69b}$$

$$\dot{z}_7 = \sum_{i=0}^{100} S_{\ell_{z_i}} w_i \cos(w_i t + \varepsilon_{z_i}) \tag{69c}$$

Accelerations at the ship may be obtained by differentiating the velocities of equations (69) with respect to time:

$$\ddot{x}_7 = -\sum_{i=0}^{100} S_{\ell_{x_i}} w_i^2 \sin(w_i t + \varepsilon_{x_i}) \tag{70a}$$

$$\ddot{y}_7 = 0 \tag{70b}$$

$$\ddot{z}_7 = -\sum_{i=0}^{100} S_{\ell_{z_i}} w_i^2 \sin(w_i t + \varepsilon_{z_i}) \tag{70c}$$

In order to calculate $S_{h_{x_1}}$, ε_{x_1}, $S_{h_{z_1}}$, and ε_{z_1}, the following method was used:

First, the spectra of the vertical motion and lateral motion of the point of interest for each sea state examined was calculated and punched out on cards. These calculations were performed at selected frequencies so as to have complete coverage of the spectrum of interest. The computations were performed by a modified version of M.I.T.'s seakeeping program.[35]

Second, each spectrum was transformed into a time series by selecting frequencies such that

$$\omega_i = a(i-1)^2 + \omega_{min} \qquad i = 1, 2, \ldots, n, n+1$$

where

$$a = \frac{(\omega_{max} - \omega_{min})}{n^2}$$

n = number of subdivisions

ω_{min} = minimum ω of spectrum definition

ω_{max} = maximum ω of spectrum definition

Each element of the time series was of the form:

$$A_i = \sin(\omega_i t + \varepsilon_{z_i})$$

where

$$A_i = \sqrt{(2 * \text{spectral ordinate}_{i+1} * (\omega_{i+1} - \omega_i))}$$

t = time

ε_{z_i} = phase angle generated randomly

The complete time series was of the form:

$$\sum_{i=1}^{n+1} A_i \sin(\omega_i t + \epsilon_{z_i})$$

Finally, the relation between ϵ_{x_1} and ϵ_{z_1} was determined using the regular wave results of the vertical and lateral motion.

Appendix F lists the values of ω_1, $S_{h_{x_1}}$, ϵ_{x_1}, $S_{h_{z_1}}$, and ϵ_{z_1} for each of the ship headings. (Chepter 4 describes the three ship headings and the particular sea state used for the calculations made in this study.)

3.4 Numerical Solution of Equations for Lumped-Mass System

The lumped-mass system has been assumed to consist of seven lumped-masses. (The anchor is element number one; the ship is element number seven.) At each element, three non-linear second order differential equations may be written. This yields twenty one second order equations to describe the system.

In order to solve these equations, the fourth-order Runge-Kutta method [25] used in section 2.1 is again applied.

The inertial coordinates of each element in the steady state model are used as the initial conditions (time = o) for the dynamic model. The anchor is always located at the origin of the coordinate system; velocities and accelerations at this point are thus always zero. The location, velocity, and acceleration of the ship are given by equations (68), (69), and (70) respectively. Locations, velocities, and accelerations of the other elements are calculated from equations (47), (48), (64), (65), and (66).

As noted by Patton,[9] the system's highest natural frequency is, in general, in the axial mode and along the strength member of the cable. An estimate of this value may be given by:

$$f_{\ell} = \frac{1}{2\pi}\sqrt{\left(\frac{2 E_{c_n} A_n}{\mu_n \Delta L_n}\right)} \qquad (71)$$

where

$E_{c_n}A_n$ = the product of the strength member's effective elastic modulus and effective cross-sectional area (see figure 1),

μ_n = the cable's mass per unit length,

L_n = the unstretched length of cable between two successive mass elements.

After the highest natural frequency has been computed, the integration step size in the time domain should be approximately 1/20 of the shortest period, i.e., to insure numerical stability:

$$b = 0.05 \left(\frac{1}{f_h}\right) \tag{72}$$

IV. RESULTS

Computations made through the implementation of the computer program described in this study may be used to design particular cable-buoy-ship systems. The system of interest here is subjected to certain operational constraints and design requirements, which are given below. This does not imply that the simulation is constrained, but rather, for this example, just certain physical paremeters are constrained.

Some parameters of the system components, such as cable properties, are fixed because they had been previously specified in the original design of the entire system. Others, such as the current profile, are considered to represent the "worst case condition" for the operating area of interest. These invariant system parameters are presented in Table 1,* where the terms used are defined in section C.5 of Appendix C.

The following constraints on the behavior of the system modeled have been imposed:

* Tables 1-5 and figures 15-34 are presented at the end of this chapter.

a. the steady state tension at the anchor must not exceed 1000 pounds,

b. the maximum steady state tension at any point along the cable must not exceed 5000 pounds,

c. the depth of the buoy or buoys must be minimized so that the buoys may be constructed out of inexpensive materials,

d. the number of buoys used in the system must be minimized for greater ease in handling and reduced costs,

e. the ship must be able to operate at horizontal ranges varying from 4000 feet to 12,000 feet from the anchor, and

f. sufficient decoupling of the wave-induced motions of the ship from the cable must take place up to and including sea state four.

(Note the magnitude of the tension at the anchor is not checked for the dynamic case because element number one is too long, about 5500 feet in this case.)

It should be noted these constraints are not necessary for other moored systems. Suppose, for example, that the following process is employed for the cable-buoy-anchor deployment. The system is layed out in a line on the ocean surface, anchor first, with appropriate buoyancy added to the anchor to keep it afloat. After the entire system has been layed out, the extra buoyancy at the anchor is jettisoned, and the system is allowed to free-fall to the bottom. If the cable is very long and is negatively buoyant, then problems may be encountered while it is being deployed on the surface if there is only one buoy. With one buoy, the system would assume a "W" shape. If more buoys were added, however, the deep catenaries would be minimized and the cable would assume more of a straight line configuration on or near the surface. Thus, for this type of system, requirement (d) would have to be modified.

Previous experience [38] has indicated that the bulk of the design of systems similar to the one being considered in the present study can be made primarily from detailed and numerous steady state calculations. After the system has been selected, however, its dynamic behavior must be checked. This plan has been followed here. Cases 1 to 11 are steady state simulations only; cases 12 to 14 are dynamic simulations. Table 2 summarizes which system parameters were varied for each case. (The terms used in table 2 are defined in section C.5 of Appendix C.) Figures 15 through 25 show three dimensional plots of the configurations of cases 1 to 11 respectively.

Cases 1 to 5 vary the horizontal distance between the anchor and the ship from 4000 feet to 12,000 feet. The significant results are presented in tables, 3, 4, and 5, where T, Θ, and ϕ are defined in section 2.1, and the coordinates x_B, y_B, and z_B and the subscripts BE and BD are defined in figure 7 of section 2.2.1. It can be seen that the highest tension at the anchor, the maximum tension (which is always T_{BS} of the first buoy), and the largest buoy depth all occur when the ship is 12,000 feet from the anchor (case 5). Thus, since this appears to be a "worst case" condition, subsequent cases assume this value to be fixed.

Cases 6 to 8 examine the effects of varying the excess buoyancy of the single buoy configuration; cases 9 to 11 divide the one buoy into two buoys such that the sum of the excess buoyancies of the two buoys of cases 9, 10, and 11 is identical to that of the one buoy of cases 6, 7, and 8 respectively. Maximum tensions are acceptable for all the cases. The tension at the anchor is above the 1000 pound limit for cases 8 and 11. Comparable cases indicate that the anchor tension is slightly lower for the two buoy cases compared to the one buoy cases. The buoy depth for the second buoy (buoy closest to the ship) in cases 9 and 10 is deeper than that of the single buoy of cases 6 and 7 respectively. (Even if the lower buoy of cases 9 or 10 were moved up the cable, the second buoy would always be deeper than the one of cases 6 or 7 until it reached the second buoy, at which point cases 9 and 10 would reduce to cases 6 and 7 respectively.)

Thus, the only advantage of the two buoy configuration is a slight reduction of tension at the anchor. It was decided by Brown and Griffin[38] that this benefit was not enough to justify adding complexity to the system, since there would be a second buoy. By increasing the cost of the buoys, there would not only be two of them, but also they would have to be constructed out of more expensive materials.

A choice then had to be made between the lower anchor tension of case 6 and the shallower buoy depth of case 7. Since the buoy of case 6 was over 500 feet deeper than that of case 7, and since the anchor tension of case 7 was in the acceptable range, case 7 was chosen as the optimal compromise system. This configuration satisfied the first five specifications mentioned earlier; the sixth and final requirement will now be checked.

The ship is assumed to be influenced by fully developed seas driven by 20 knot winds (significant wave height of 8 feet, sea state four), which is expected to be the worst conditions encountered during operations. (If conditions worsen, operations are ceased for this particular system.) Case 12 assumes beam seas, case 14 assumes head seas, and case 13 assumes a heading of 135° (bow quartering seas) in between cases 12 and 14.

Figures 26, 27, and 28 plot the lateral and vertical motions of the bow of the ship at the point of the cable attachment versus time for each case. Only a 50 second interval of the 2000 second simulation is shown here. Figures 29, 30, and 31 show the tension in segment number one (the anchor) and the tension in segment number six (the ship) as functions of time for each case. (See figure 10 for a sketch of this system.) Figures 32, 33, and 34 plot the tension in segment number three (just below the buoy) and the tension in segment number four (just above the buoy) versus time for each case.

Figures 26, 27, and 28 compare the ship's response in lateral and vertical motions for the identical sea state for three different ship headings. It is seen that the ship is stimulated most in case 13 (heading halfway between beam and head seas). Thus, one would expect that the tensions encountered in the system would be worst for this case. (This assumption will now be checked.)

In examining figures 29, 30, and 31 it can be seen that the above assumption holds: case 13 does show the largest tension variations at the ship. Tensions at the anchor, however, are similar for cases 13 and 14. Therefore, case 14 must also be carefully looked at.

The purpose of this study is to decouple the cable motions of the section below the buoy from the wave-induced motions of the upper section. Figures 32, 33, and 34 can be used to see how effective this decoupling mechanism is. It is clear from these plots that this system does indeed fulfill this requirement. While large variations are seen in segment number 4, much smaller variations in tension are seen in segment number 3. (The behavior of segment three is typical of those below the buoy; the behavior of segment four is typical of those above the buoy.)

TABLE

EAD	=	2.309×10^6
EEG	=	2.309×10^6
EGT	=	2.309×10^6
WAD	=	0.145
WEG	=	0.145
WGT	=	0.145
DAD	=	1.950
DEG	=	1.950
DGT	=	1.950
DSAD	=	0.622
DSEG	=	0.622
DSGT	=	0.622

CURRENT

H	=	17,700
CX	=	0.5
D	=	300
CY	=	0.3
CB	=	0
THEC	=	270

Table 1. Invariant System Parameters

CASE NO.	BUOY PARAMETERS					CABLE PARAMETERS			SHIP PARAMETERS	
	IBUOY	RA	PA	RB	PB	SAD	SEG	SGT	G	BETA
1	1	3100	26			16,700	6300		4000	
2	1	3100	26			16,700	6300		6000	
3	1	3100	26			16,700	6300		8000	
4	1	3100	26			16,700	6300		10,000	
5	1	3100	26			16,700	6300		12,000	
6	1	2700	26			16,700	6300		12,000	
7	1	3100	26			16,700	6300		12,000	
8	1	3500	26			16,700	6300		12,000	
9	2	1350	32	1350	26	8360	8340	6300	12,000	
10	2	1550	32	1550	26	8360	8340	6300	12,000	
11	2	1750	32	1750	26	8360	8340	6300	12,000	
12	1	3100	26			16,700	6300		12,000	90
13	1	3100	26			16,700	6300		12,000	135
14	1	3100	26			16,700	6300		12,000	180

Table 2. Variable System Parameters

CASE NO.	ANCHOR			FIRST BUOY					
	T	Θ	ϕ	T_{BB}	Θ_{BE}	ϕ_{BE}	T_{BD}	Θ_{BD}	ϕ_{BD}
1	361	-57.1	59.9	2739	-2.3	87.8	378	-0.9	-73.8
2	395	-42.9	55.9	2757	1.8	86.1	396	2.6	-62.0
3	469	-29.4	50.1	2796	3.3	84.1	429	3.8	-48.1
4	610	-18.5	44.4	2879	3.3	81.4	500	3.6	-30.5
5	914	-10.0	40.5	3091	2.4	77.0	700	2.6	- 7.2
6	585	-10.6	21.2	2687	3.6	78.3	549	3.8	- 7.2
7	914	-10.0	40.5	3091	2.4	77.0	700	2.6	- 7.2
8	1331	- 8.9	49.7	3540	1.7	75.9	863	1.9	- 4.4
9	381	-15.1	29.5	1436	-12.0	76.7	334	-11.9	8.2
10	697	-14.9	51.9	1810	-12.1	76.3	477	-12.1	25.8
11	1090	-13.6	60.4	2223	-11.2	76.0	674	-11.2	37.1

Table 3. Steady State Tensions and Angles at Anchor and First Buoy

CASE NO.	SECOND BUOY						SHIP		
	T_{BE}	Θ_{BE}	ϕ_{BE}	T_{BD}	Θ_{BD}	ϕ_{BD}	T	Θ	ϕ
1							555	60.5	72.4
2							590	49.3	68.1
3							658	39.3	62.4
4							787	29.7	56.0
5							1079	20.0	49.7
6							1004	24.4	56.7
7							1079	20.0	49.7
8							1208	16.5	44.5
9	1300	7.6	75.3	344	7.8	-15.7	882	36.4	66.5
10	1481	5.0	73.2	449	5.2	-17.2	890	30.0	60.4
11	1703	3.3	71.6	553	3.5	-14.0	946	24.8	55.0

Table 4. Steady State Tensions and Angles at Second Buoy and Ship

CASE NO.	FIRST BUOY				SECOND BUOY			
	x_B	y_B	z_B	DEPTH	x_B	y_B	z_B	DEPTH
1	1936	1409	16,457	1243				
2	1851	2319	16,340	1360				
3	1668	3514	16,102	1598				
4	1356	4938	15,704	1996				
5	938	6655	15,075	2625				
6	1074	7065	14,542	3158				
7	938	6655	15,075	2625				
8	791	6440	15,305	2395				
9	929	3568	7298	10,402	1423	7862	13,979	3725
10	778	3040	7703	9997	1296	7265	14,645	3055
11	646	2781	7852	9848	1123	6902	14,971	2729

Table 5. Positions of First Buoy and Second Buoy

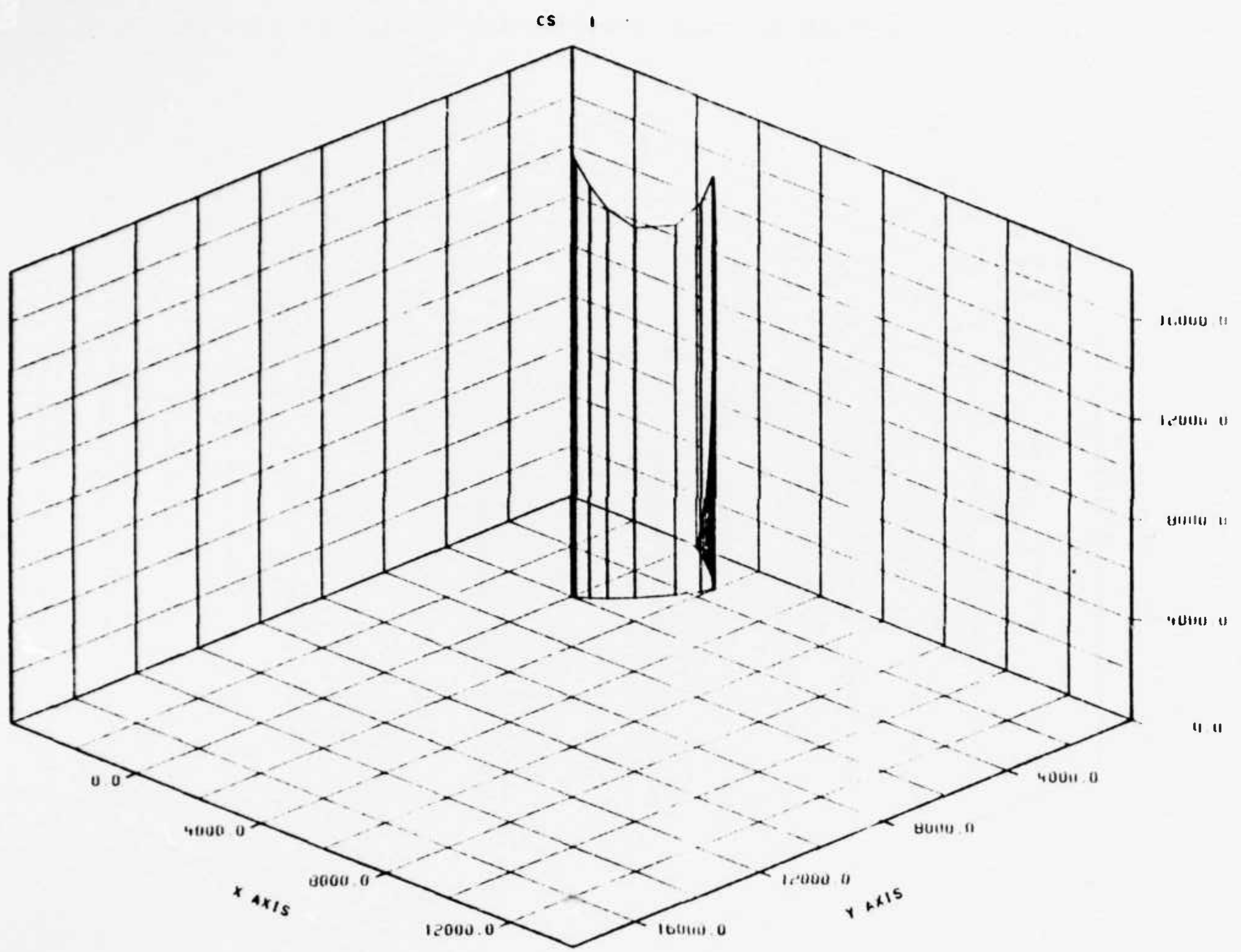

Figure 15. Three Dimensional Plot of Case 1

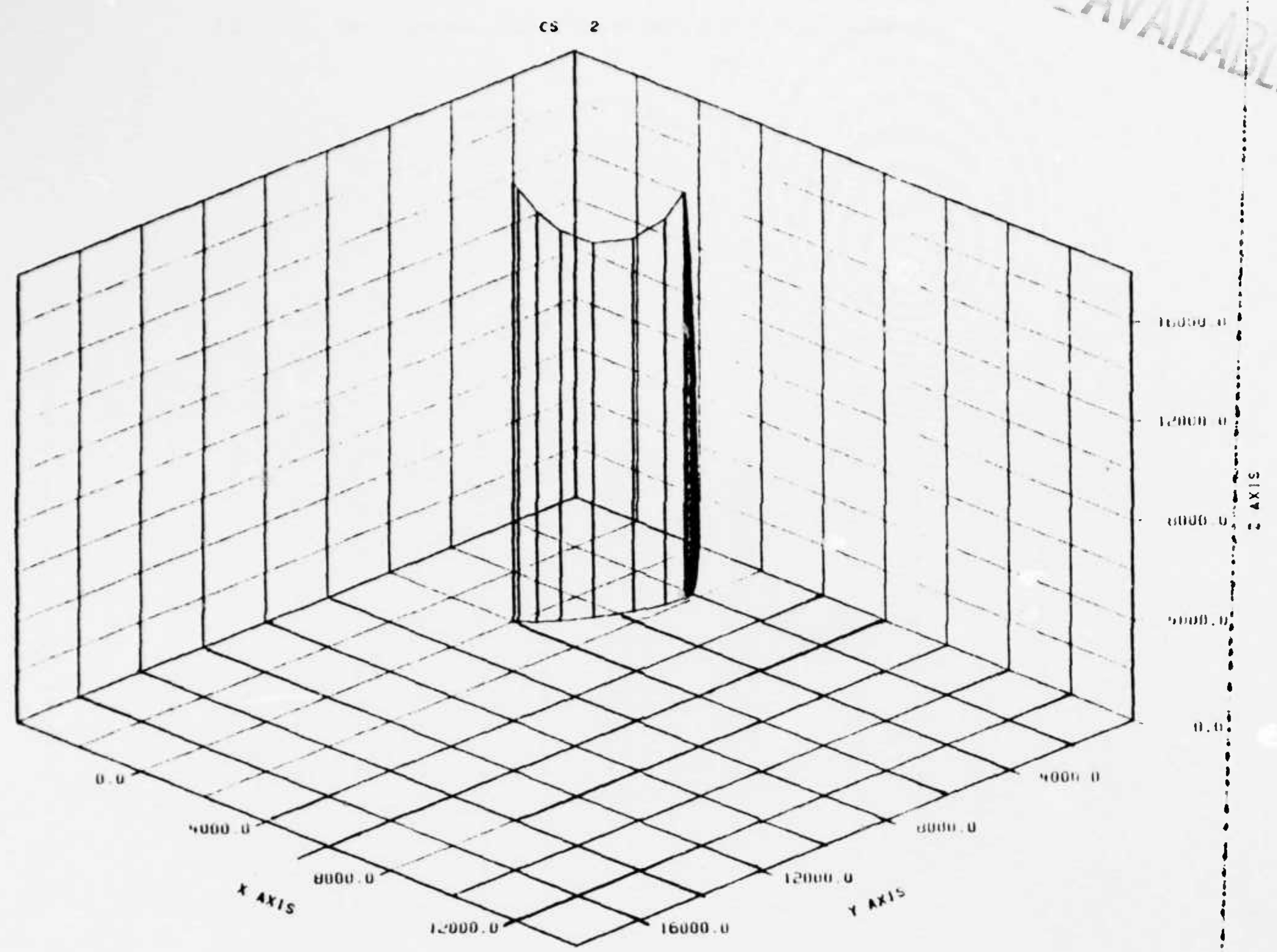

Figure 16. Three Dimensional Plot of Case 2

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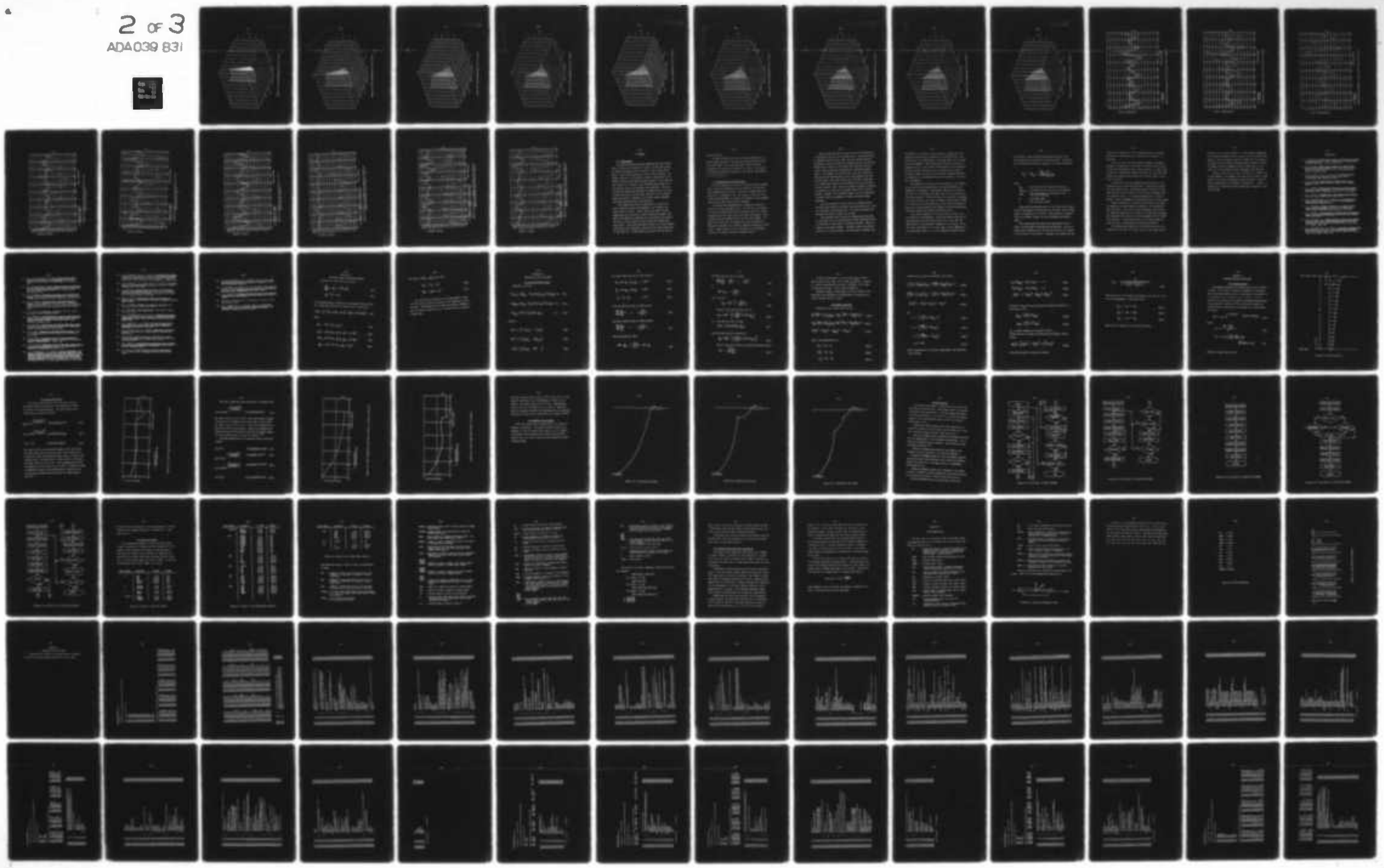

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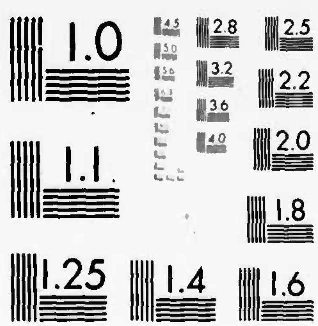


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

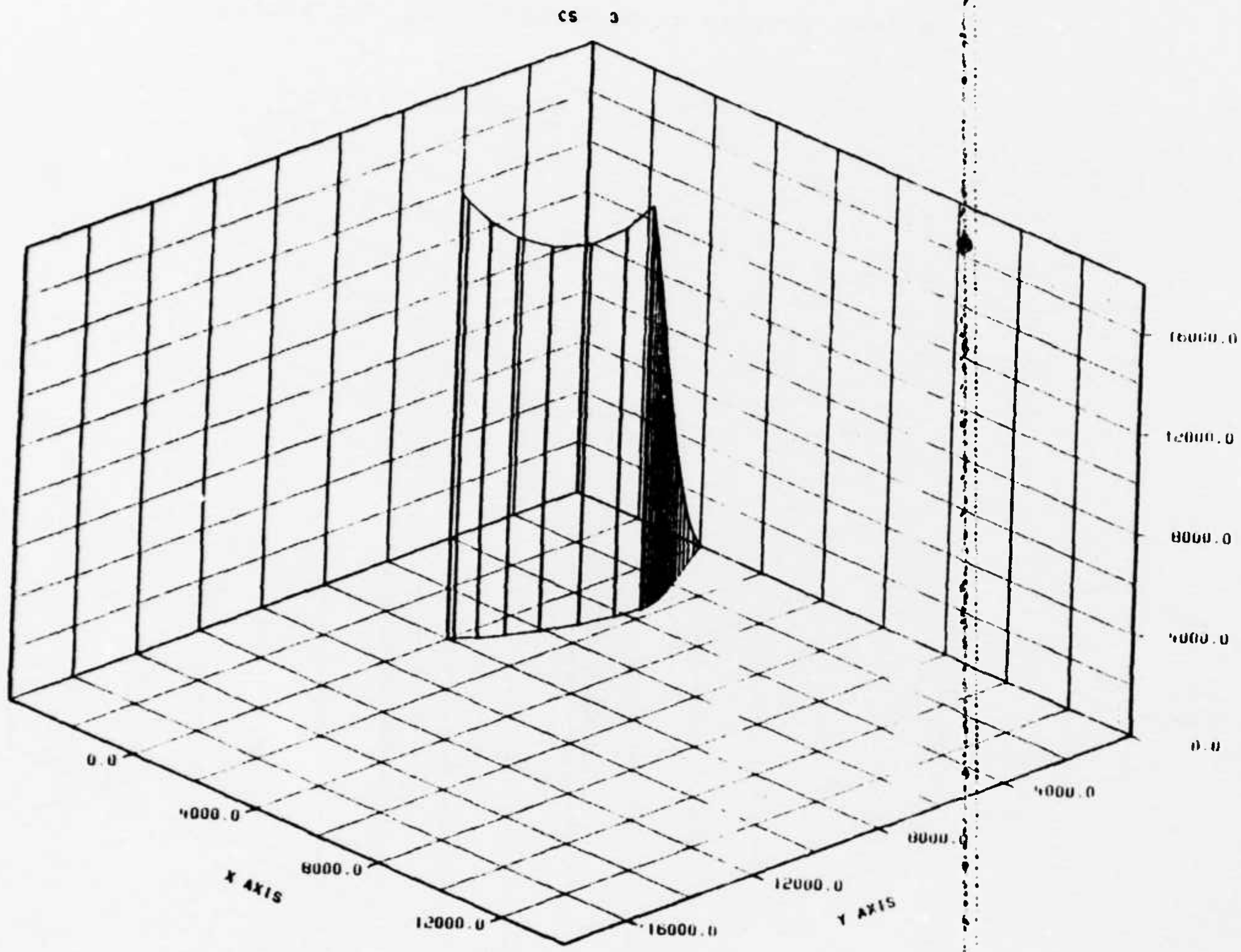


Figure 17. Three Dimensional Plot of Case 3

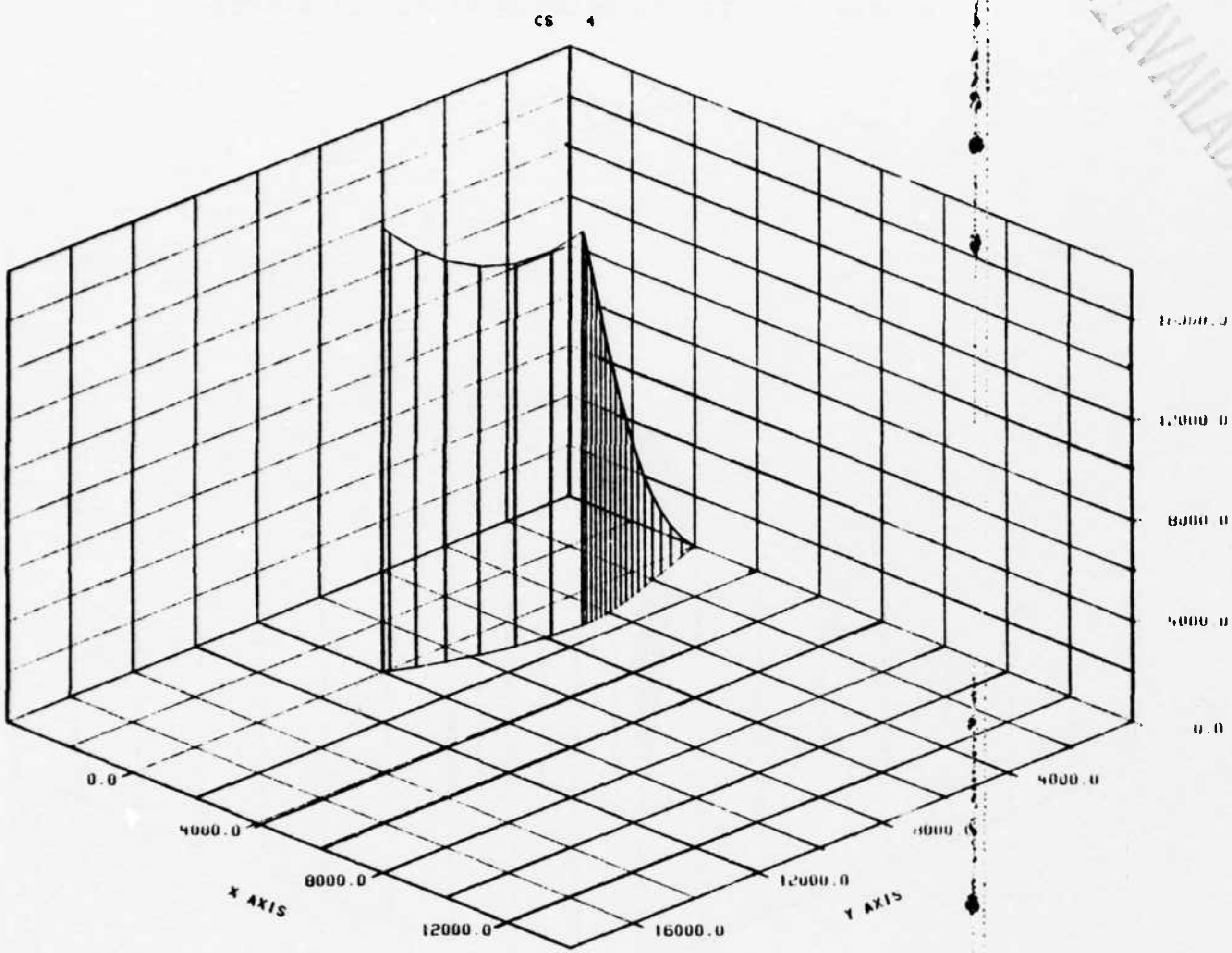


Figure 18. Three Dimensional Plot of Case 4

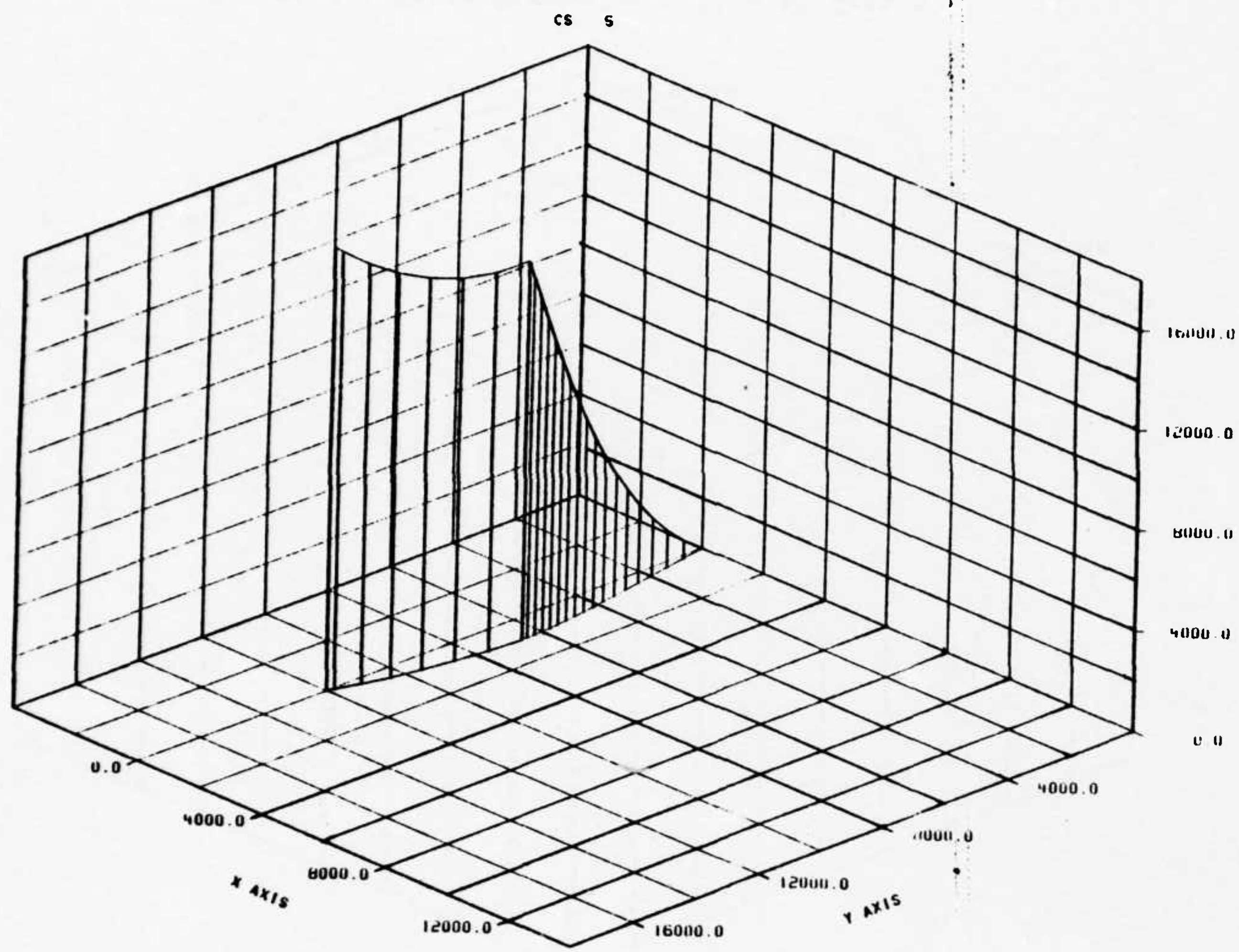


Figure 19. Three Dimensional Plot of Case 5

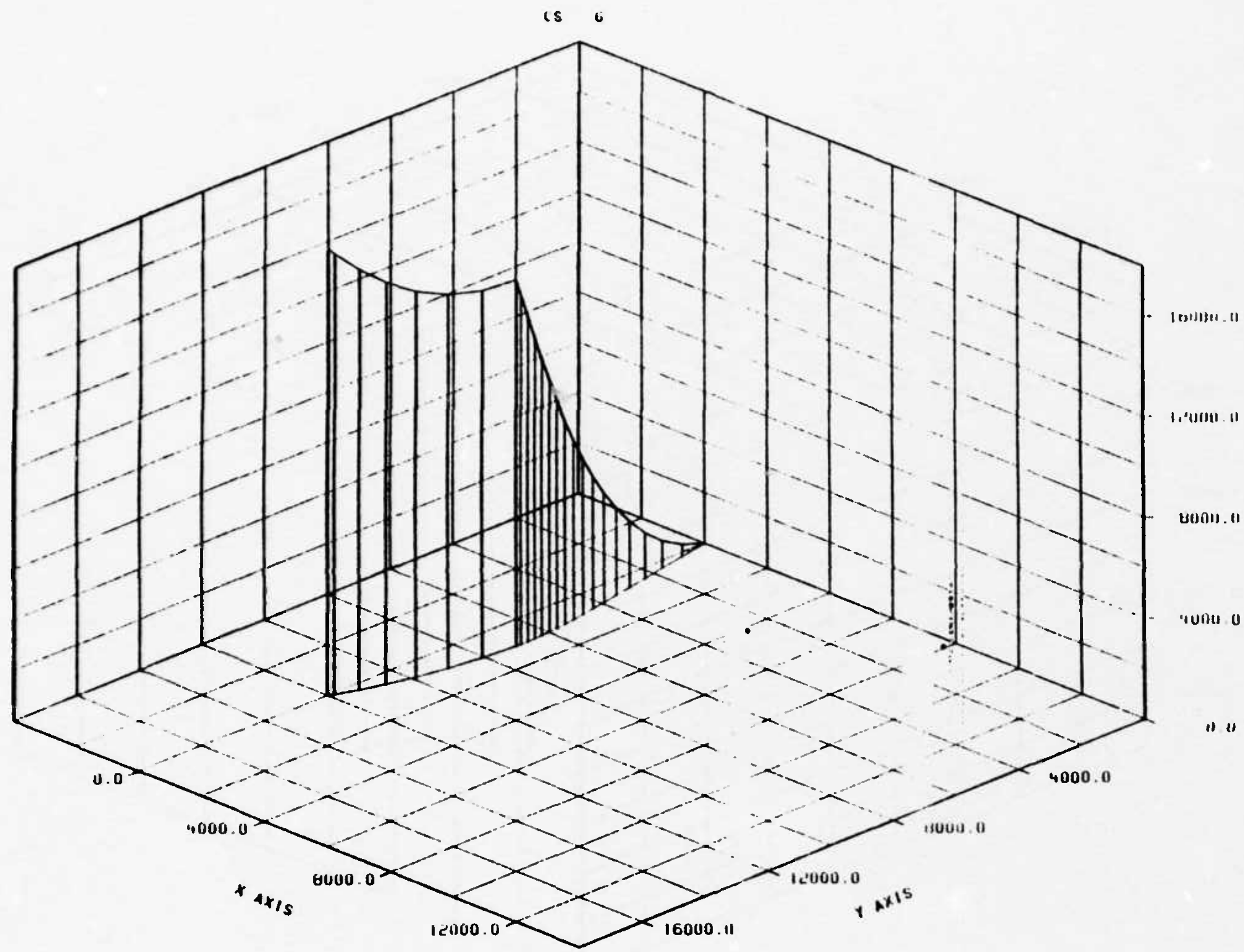


Figure 20. Three Dimensional Plot of Case 6

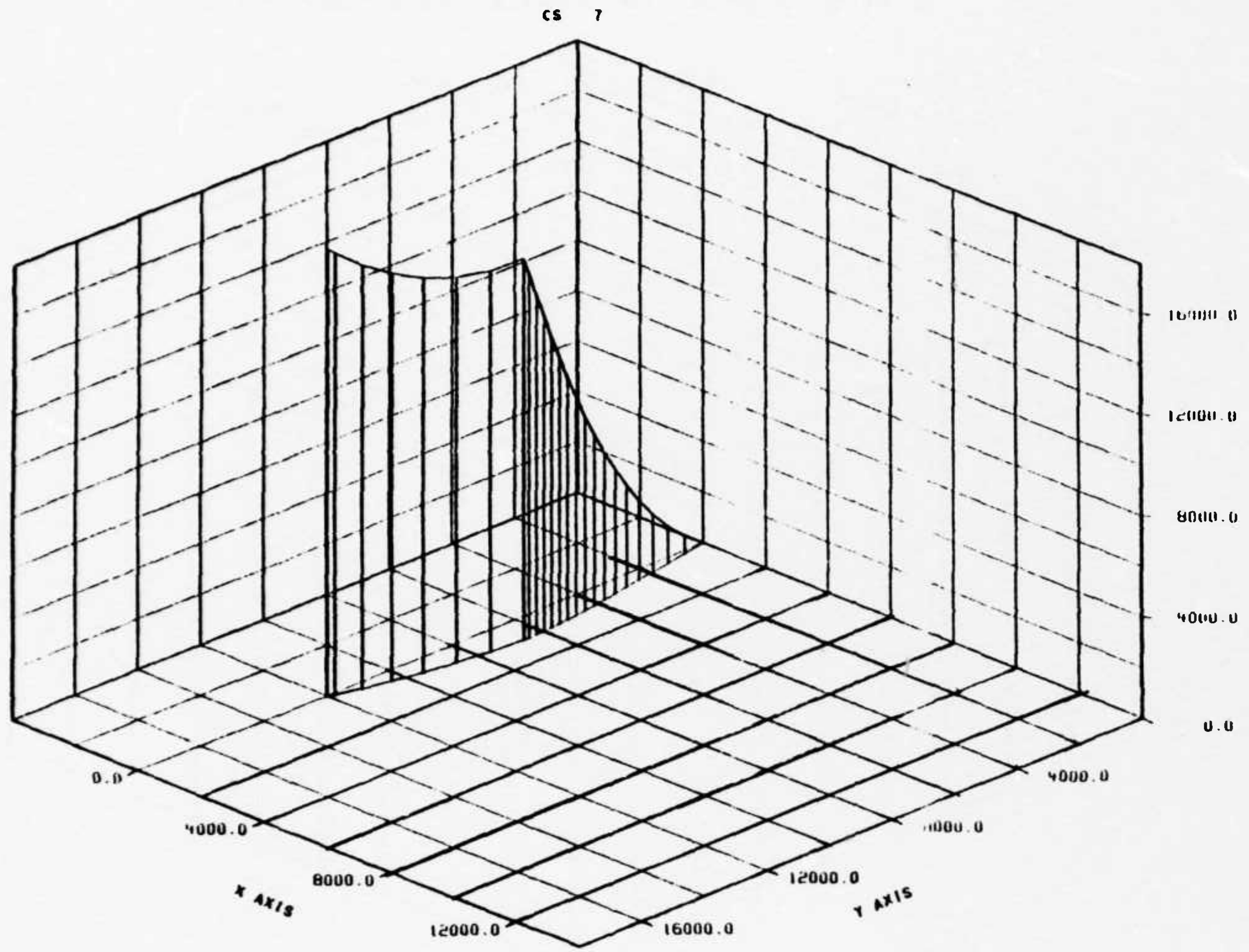


Figure 21. Three Dimensional Plot of Case 7

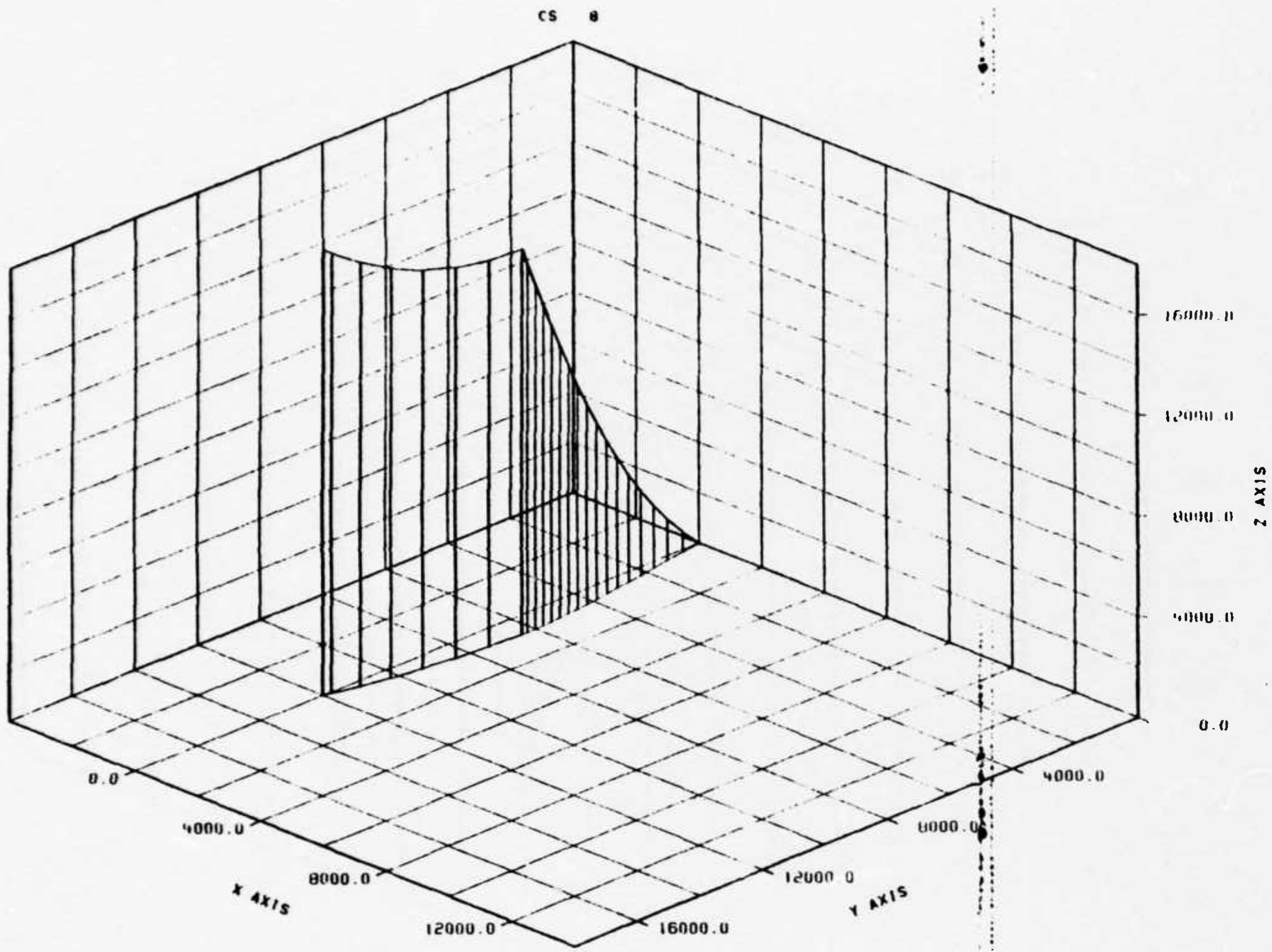


Figure 22. Three Dimensional Plot of Case 8

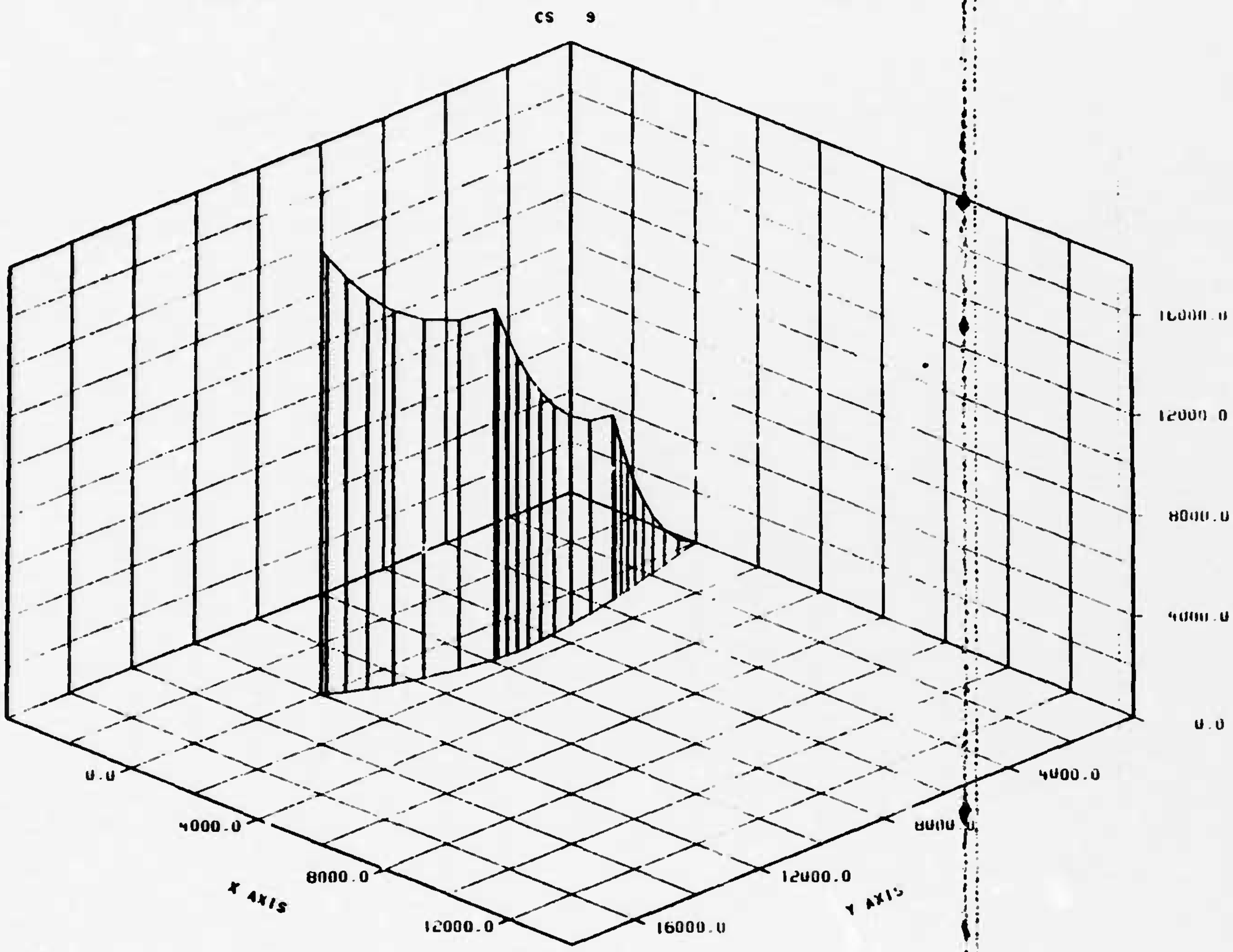


Figure 23. Three Dimensional Plot of Case 9

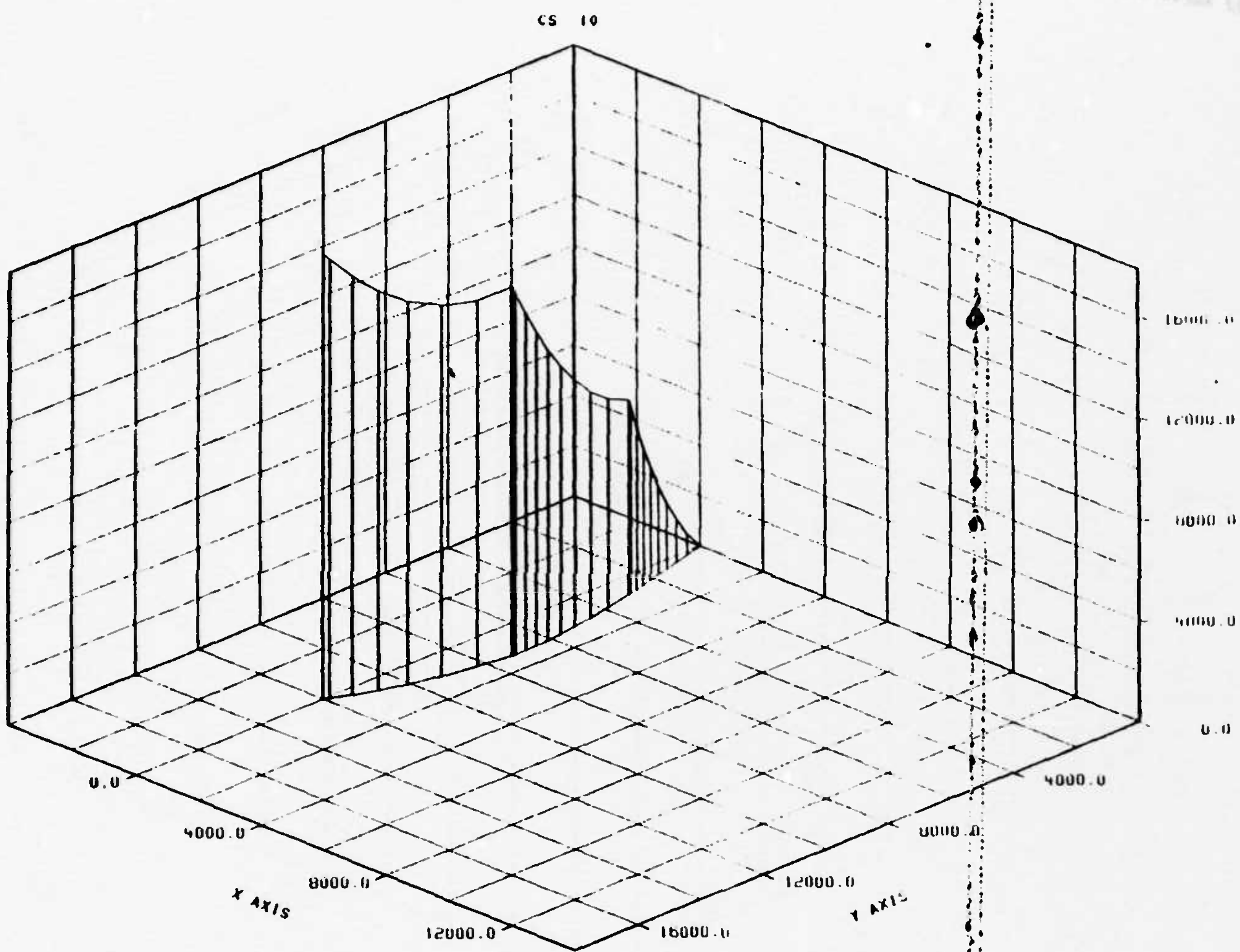


Figure 24. Three Dimensional Plot of Case 10

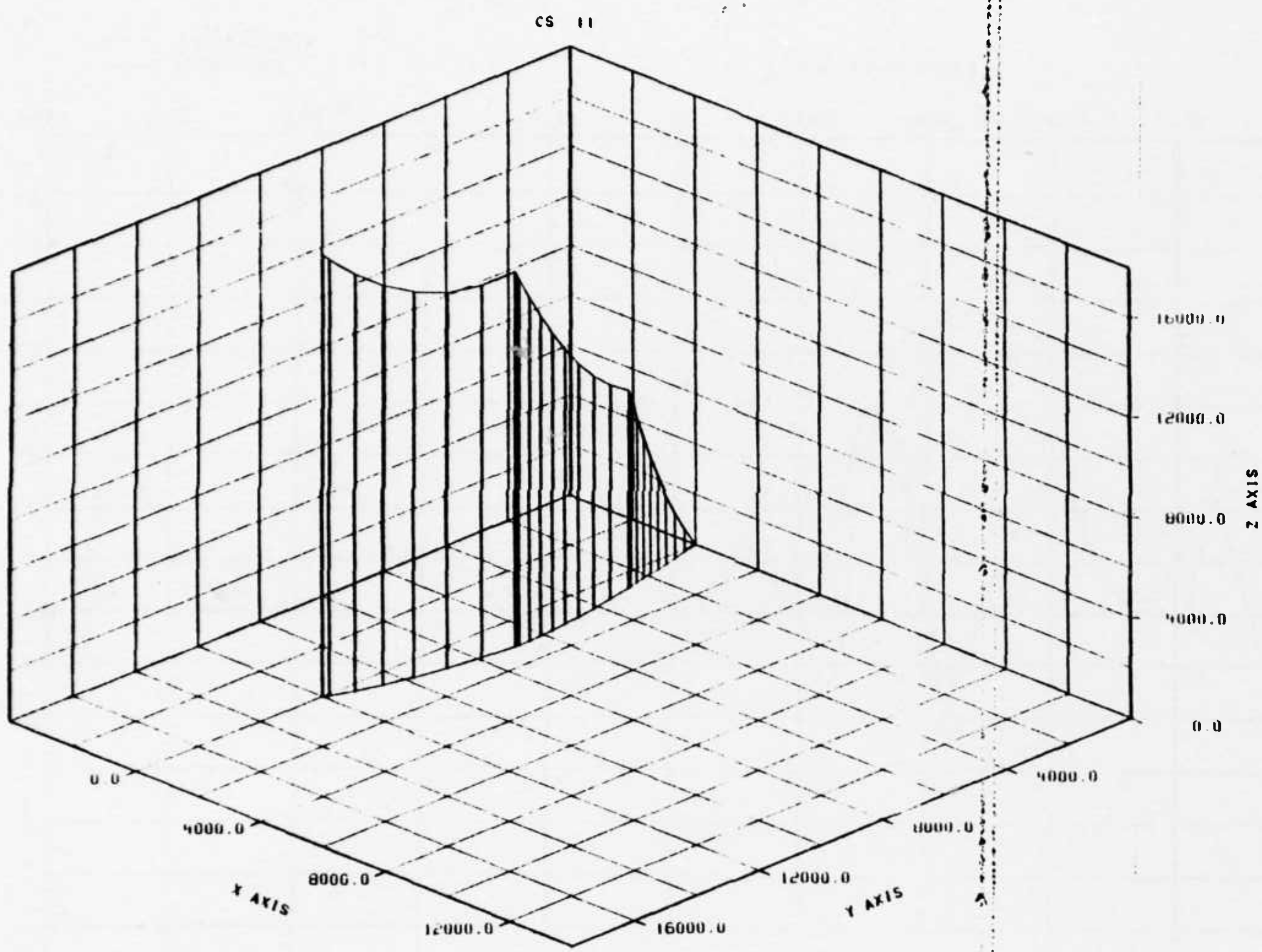


Figure 25. Three Dimensional Plot of Case 11

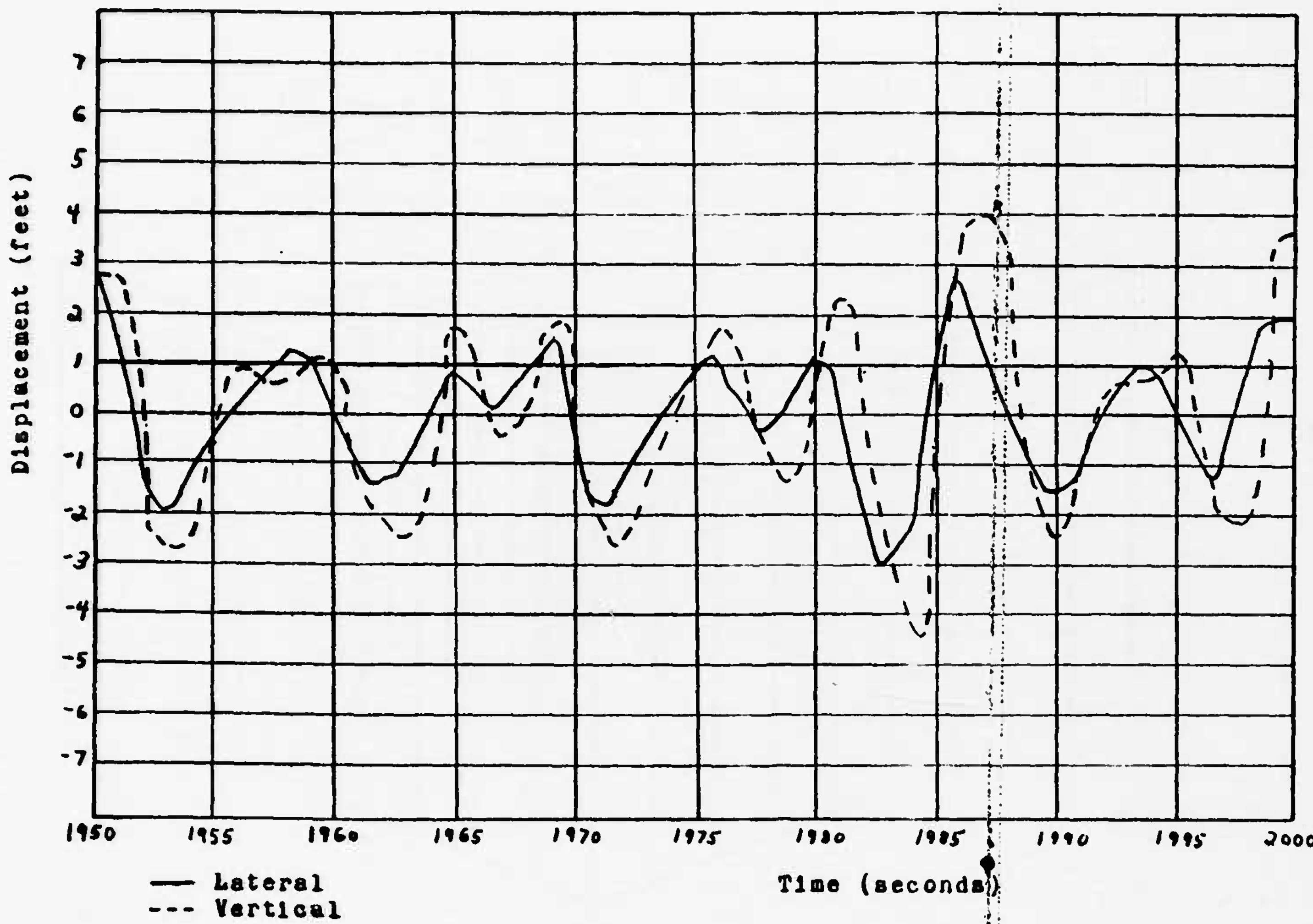


Figure 26. Displacement of Ship versus Time for Case 12

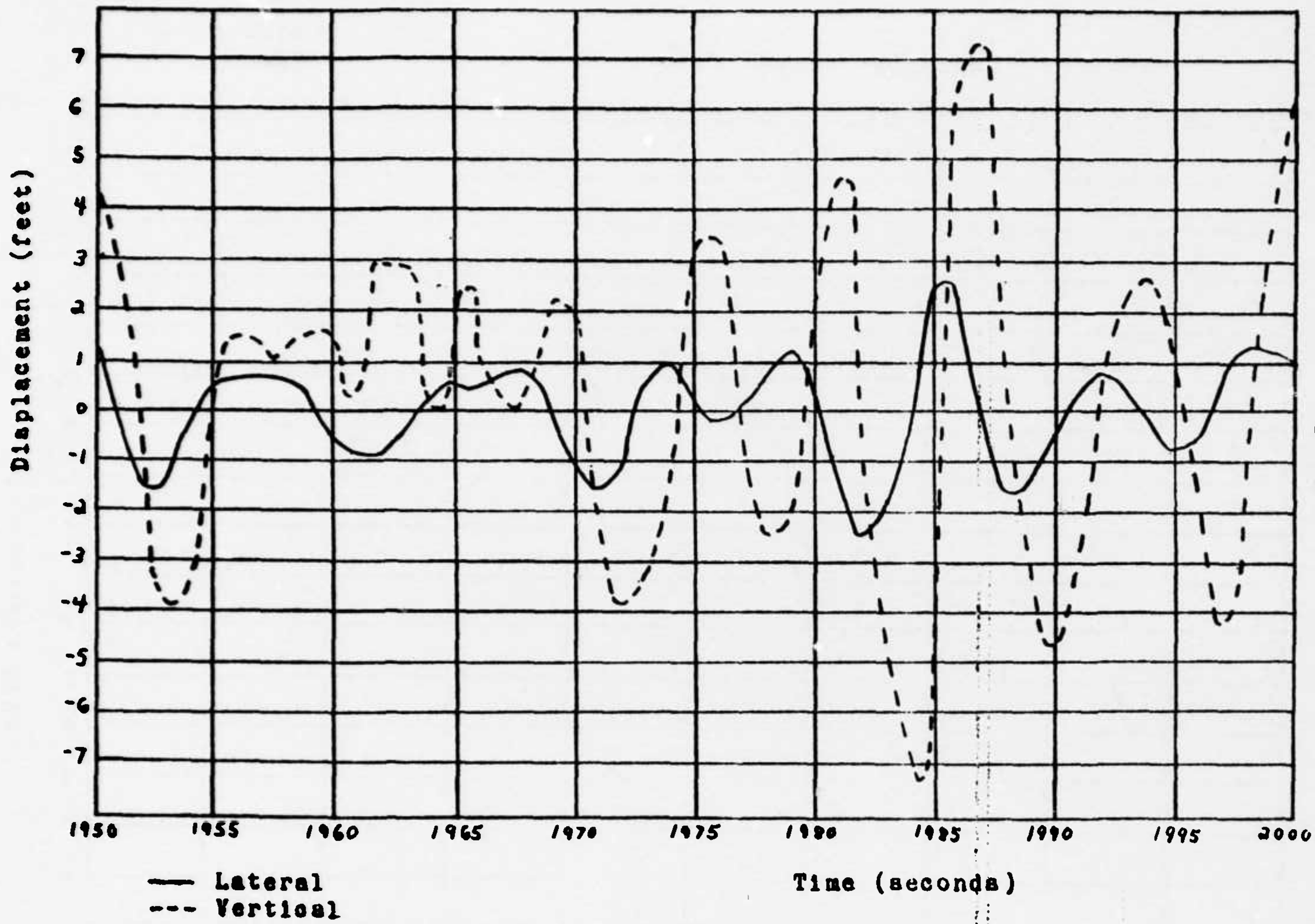


Figure 27. Displacement of Ship versus Time for Case 13

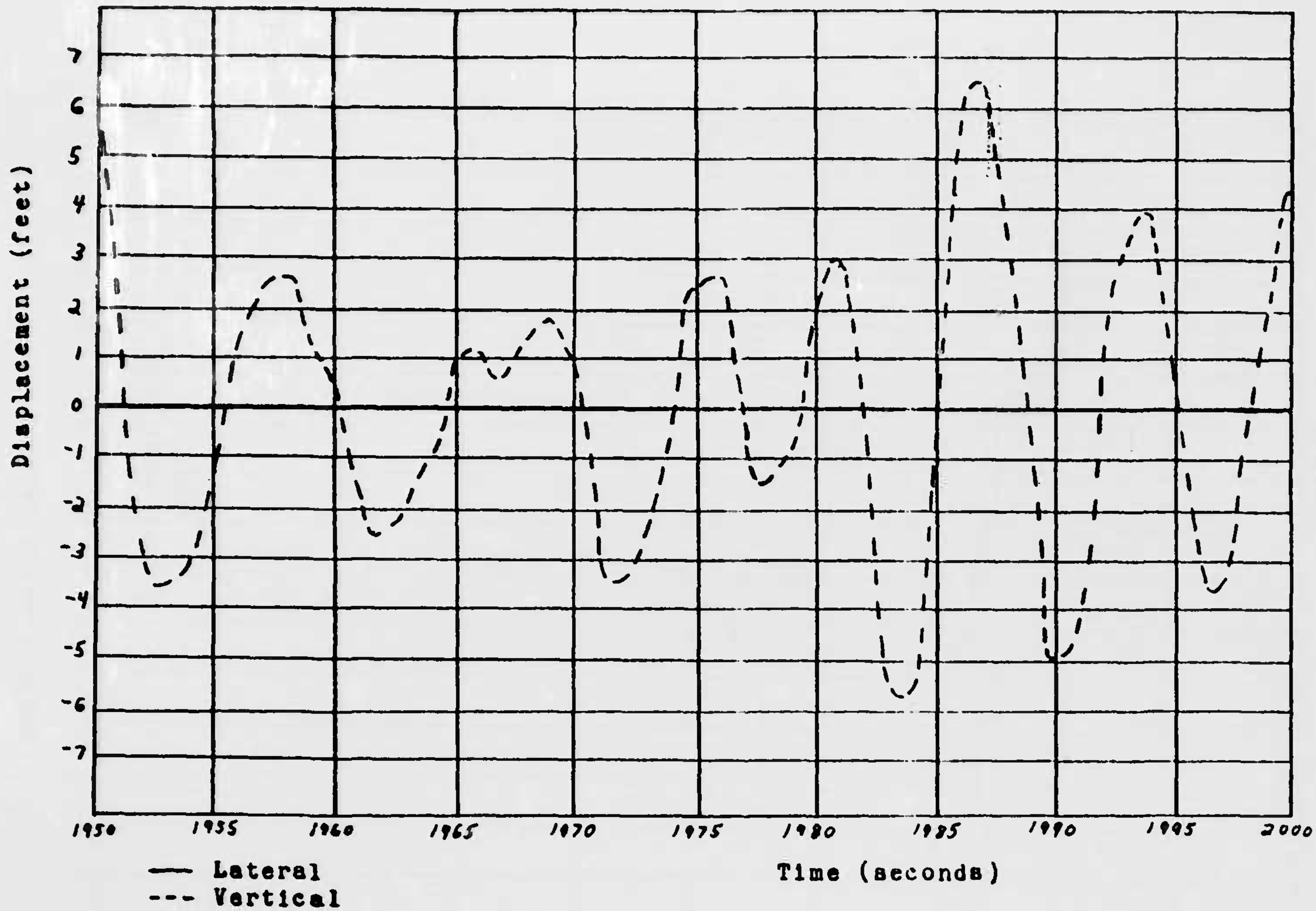


Figure 28. Displacement of Ship versus Time for Case 14

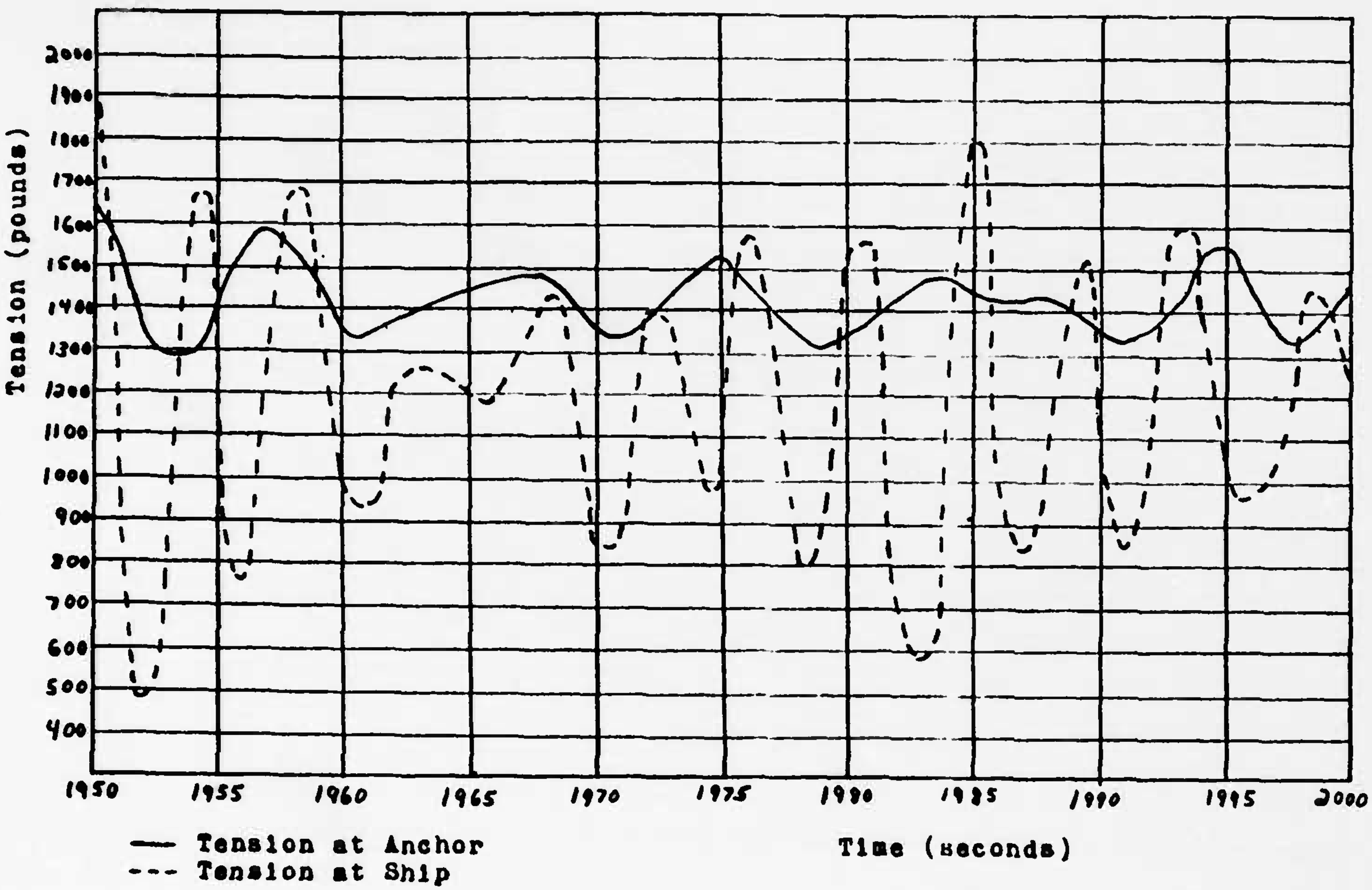


Figure 29. Tension at Anchor and Tension at Ship versus Time for Case 12

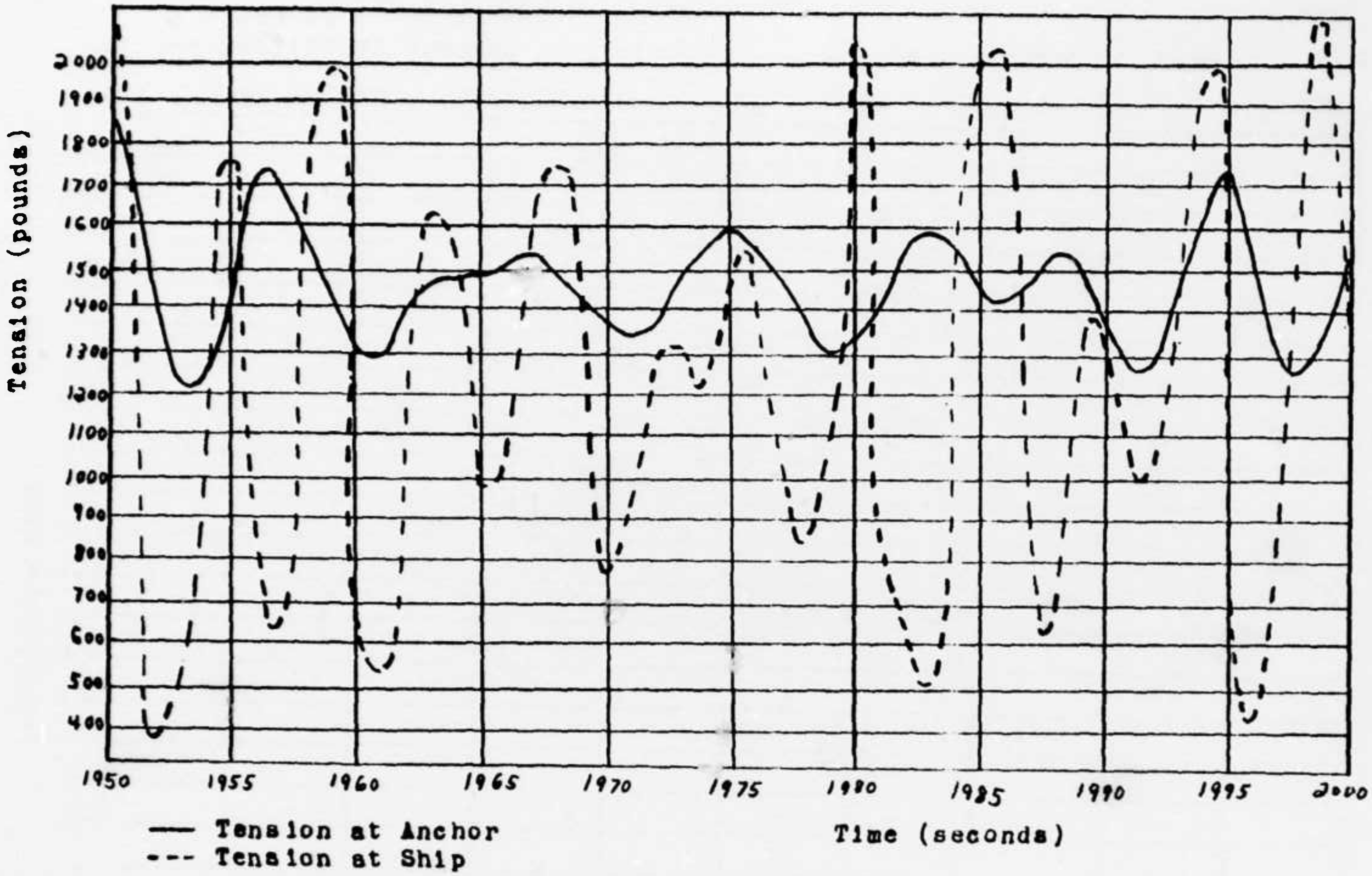


Figure 30. Tension at Anchor and Tension at Ship versus Time for Case 13

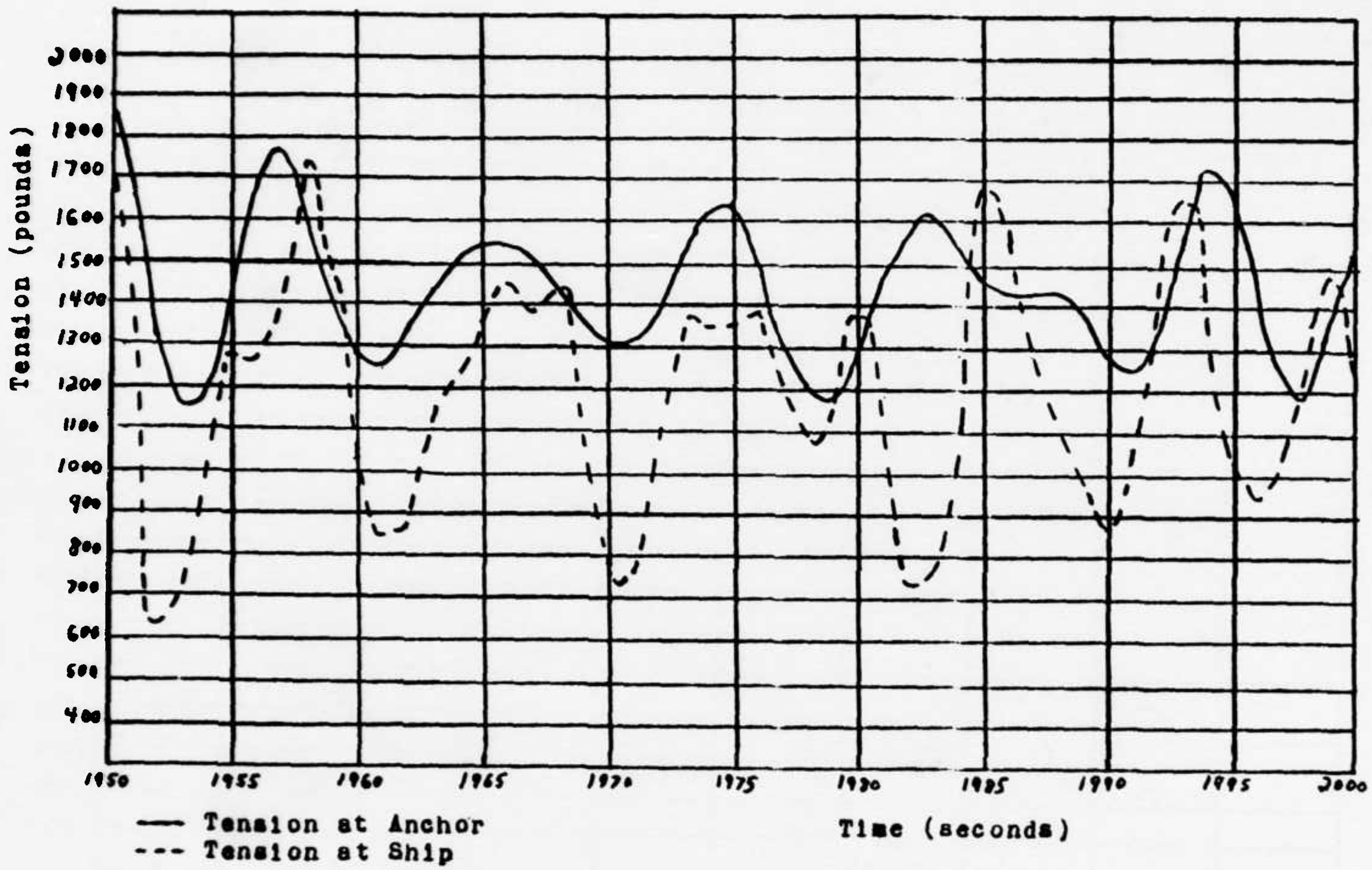
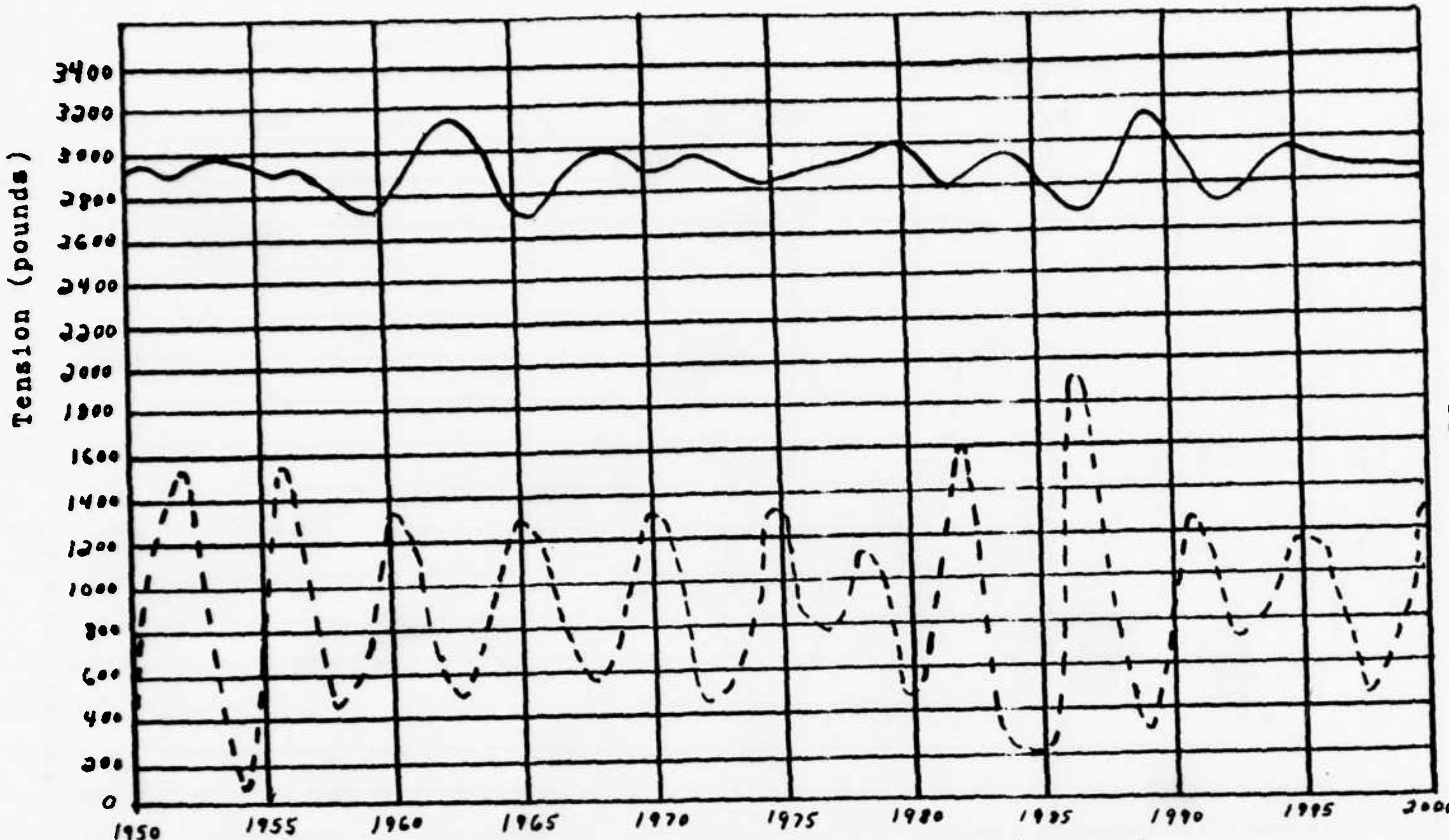


Figure 31. Tension at Anchor and Tension at Ship versus Time for Case 14



— Tension in segment 3 (below buoy)
--- Tension in segment 4 (above buoy)

Figure 32. Tension in Segment below Buoy and Tension in Segment above Buoy versus Time for Case 12

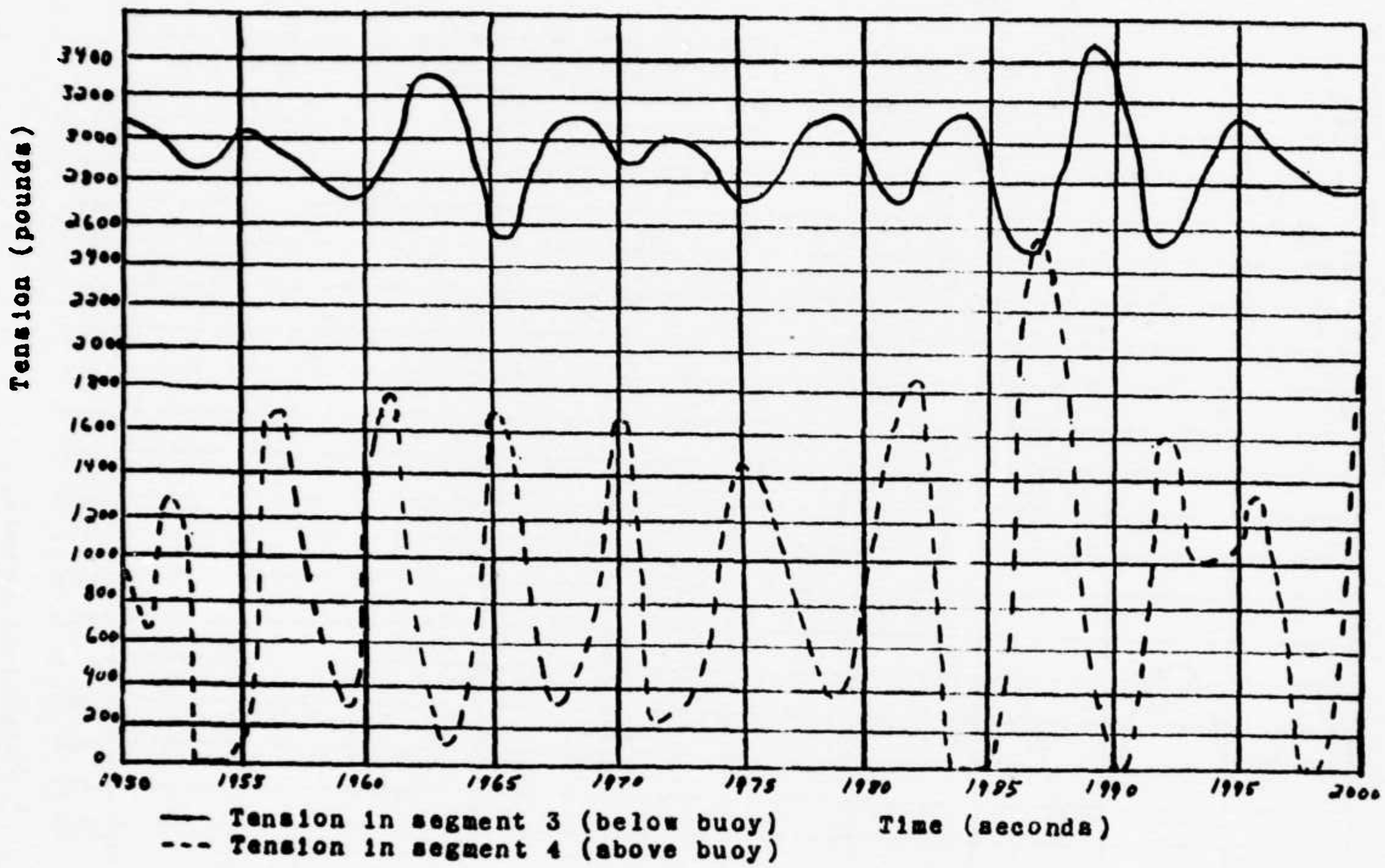


Figure 33. Tension in Segment below Buoy and Tension in Segment above Buoy versus Time for Case 113

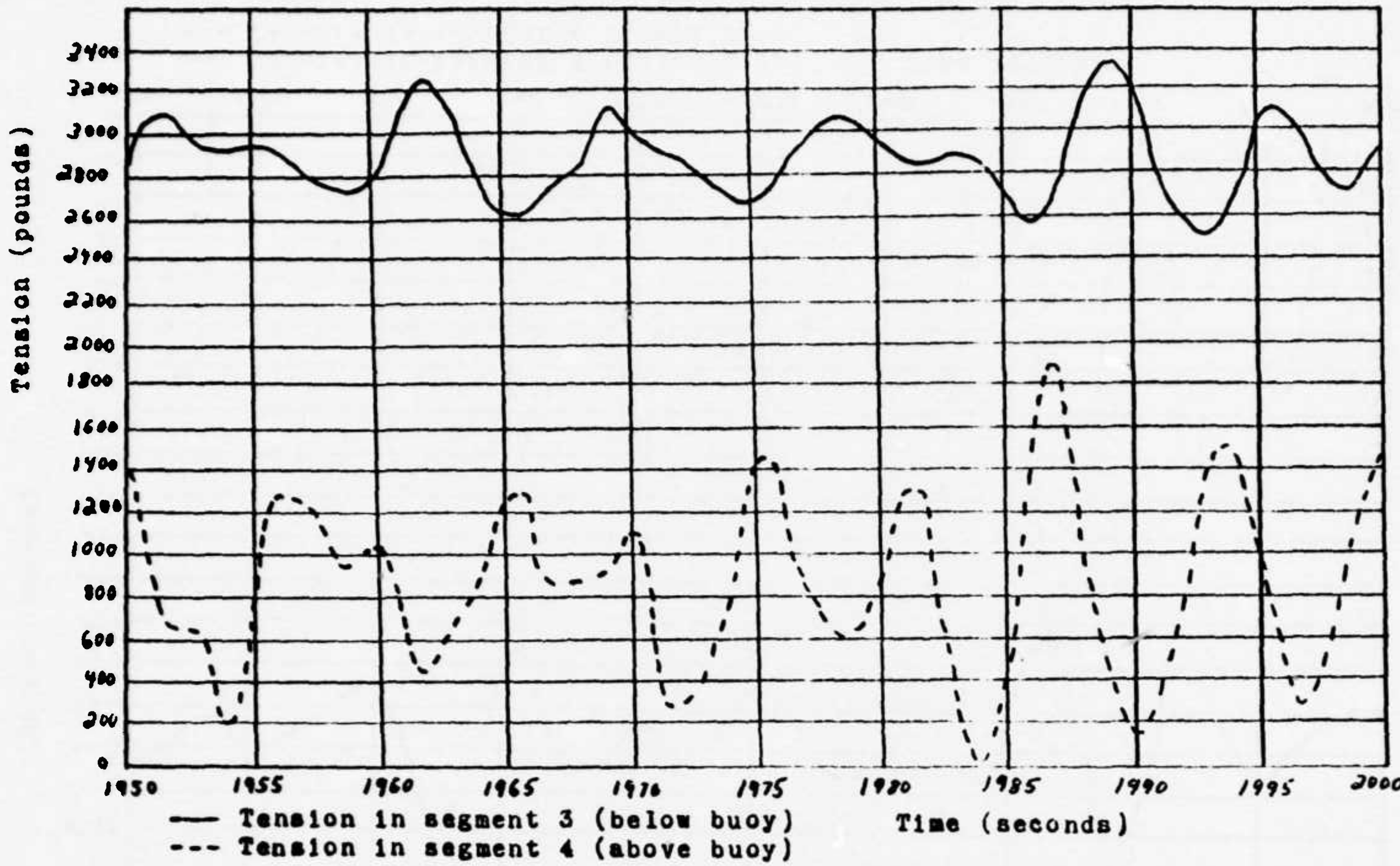


Figure 34. Tension in Segment below Buoy and Tension in Segment above Buoy versus Time for Case 14

V. SUMMARY

5.1 Conclusions

The cable-buoy-ship systems examined here were studied under a variety of conditions. First, the ship was placed at various distances from the anchor in the steady state model. Then, after selecting a "worst case" distance, the excess buoyancy of the buoy was varied. Subsequently, the effects of having two smaller buoys instead of one large one were looked at. Finally, after choosing what seemed to be the optimal system, its dynamics were examined. The ship driving the system was subjected to waves typical of a particular sea state, and its angle relative to the incident waves was varied. Tensions in the cable under simulated operating conditions were thus obtained.

The system could also be subjected to a variety of other conditions which were assumed to be constant, but which could be varied. These include the water current (magnitudes and direction), cable properties (length, diameter, and modulus of elasticity), the location of buoys on the cable, the sea state and the particular surface ship being used. This study considered these to be fixed because they were either previously specified (the cable properties or the ship) or a "worst case" condition (the sea state or water currents).

The models employed in this study have shown that the wave-induced motions of the ship can be sufficiently decoupled from those of the cable such that cable tensions throughout the system are acceptable. Thus, in this study, a system was designed in which all the initial requirements have been satisfied.

5.2 Suggestions for Further Study

Further research in the area of cable-buoy-ship systems should include investigation of the effects of additional buoys spaced along the cable. While the present model can account for a maximum of only two buoys, it would be relatively straightforward to modify the program so that systems consisting of many buoys could be modeled.

This would be accomplished by integrating along the cable up to each successive buoy. At each buoy, as before, the force and moment equilibrium equations would be solved. Integration up the cable would then take place again. This process would be repeated until the ship was reached. (It should be noted that the program has been successfully modified to account for a specific system consisting of four buoys. These results will be described in a forthcoming report of the Naval Underwater Systems Center.)

Another possible useful option would be the capability of specifying one buoy as a surface buoy. This was seriously considered during this study, but the results were not conclusive. When the iterative process used for finding the steady state tension at the anchor (see section 2.3) was tried, difficulties were encountered in obtaining convergence. The reason for this was that, when the tension at the anchor was "corrected" by only a few pounds, the draft of the surface buoy would change by a few feet, resulting in a significant change in the buoyancy force at the buoy. It was realized, then, that the iteration process of section 2.3 could not be used in its present form for the entire system. Instead, the following scheme, which is described in detail below is proposed to obtain the steady state tensions:

Let the problem be divided into two distinct parts; the first part looks at the cable from the anchor up to, but not including, the surface buoy. The second examines the surface buoy and the tether to the ship.

The procedure for finding the tensions and positions of the cable for the first section of cable mentioned above is identical to that used in previous sections. There is, however, one slight change: the model treats the surface buoy as if it were the ship. The horizontal distance from the anchor to the ship, G (see figure 8), becomes the horizontal distance from the anchor to the surface buoy. The water depth, H, is decreased by an amount which is 0.6 times the buoy diameter. (This means that the buoy is initially assumed to have a draft which is 60 percent of its diameter.) When the desired location of the surface buoy is finally attained through the use of the iteration process described in section 2.3, the surface buoy and its tether to the ship may be examined.

The tension in the cable from the anchor at the surface buoy, which was calculated using the above procedure, is assumed to be constant. The general idea now is to adjust the draft of the surface buoy such that the ship will be on the ocean surface. (Since the cable to the anchor is assumed to be very long, on the order of several miles long, a change of a few feet at the surface buoy in the vertical direction should not be significant with respect to cable tensions and positions between the anchor and surface buoy.)

The initial "guess" for the buoy draft is that it is 0.6 times the buoy diameter. Using this value, equilibrium equations may be written and solved at the buoy, and the cable tether is subsequently integrated to the ship. The z (vertical) coordinate of the ship, z_{SH}, is then compared to the known water depth, H. If the difference between these two values is less than some prescribed value ϵ, then this iteration has produced the final results. Otherwise, the following correction is applied to the next iteration:

$$H_{D_k} = H_{D_{(k-1)}} + \frac{z_{SH_k} - H}{(4)(k+19)^2}$$

where

H_{D_k}	=	the buoy draft of the k'th iteration
$H_{D(k-1)}$	=	the buoy draft of the (k-1)'th iteration
z_{SH_k}	=	the z coordinate of the ship of the (k-1)'th iteration
H	=	the water depth
k	=	the iteration number

Using this "corrected" value for the buoy draft, equilibrium requirements are satisfied at the buoy, and the cable again is integrated to the ship. This process is repeated until, as already stated, the error becomes sufficiently small.

The scheme described above was incorporated into a model, and successful convergence was obtained. (The iterations were repeated until the ship was found to be located on the surface of the water.) Although this method has been shown to be convergent, further examination of the assumptions must be made before the results can be taken to be accurate.

As is the case with most computer models of physical systems, a comparison of the results obtained from the simulation with experimental data should be made. It would thus be useful to compare the results predicted by this study with those of an actual system operating at sea in order to validate the model.

In addition, certain parameters and constants of the program could be given more accuracy. These could include the drag coefficients, hydrodynamic mass coefficients, etc. Modifications could be made such that cable strumming would be allowed to occur if it were appropriate for a certain system. (Cable strumming is neglected entirely in this study)

Useful information could most definitely be obtained by comparing the amplitudes and phases of the tension versus time plots. This would include examining the tensions at identical segments of the cable for various ship headings and comparing the tensions in various segments for the same ship heading. A detailed analysis of this type would require the use of sophisticated statistical methods.

An interesting extension of this study would be to not assume that the anchor is fixed; that is, the anchor would be taken to be a certain weight. If the tension components at the anchor exceeded certain limits, then two things could happen. First, the anchor would be lifted off the bottom if the limit for the vertical component were exceeded. Second, the andhor would be dragged along the ocean floor if the limit for the horizontal tension component were exceeded.

Finally, ways could be found to reduce the running time of the program. For example, the step size in time, b, (see section 3.4) could be examined to see how large it can get before inaccurancies and numerical instability occur. A reduction in time would realize significant savings in cost for the user.

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Appendix A

THE FOURTH ORDER RUNGE-KUTTA METHOD

Consider the initial-value problem:

$$\frac{dy}{dx} = y' = F(x, y) \tag{A1}$$

$$y(x_0) = y_0 \tag{A2}$$

The increment Δy for advancing the dependent variable when the independent variable is advanced by h is given by

$$\Delta y = \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) + O(h^5) \tag{A3}$$

where

$$k_1 = h\,F(x_n, y_n) \tag{A4a}$$

$$k_2 = h\,F(x_n + \tfrac{1}{2}h,\ y_n + \tfrac{1}{2}k_1) \tag{A4b}$$

$$k_3 = h\,F(x_n + \tfrac{1}{2}h,\ y_n + \tfrac{1}{2}k_2) \tag{A4c}$$

$$k_4 = h\,F(x_n + h,\ y_n + k_3) \tag{A4d}$$

The values at (x_{n+1}, y_{n+1}) are then:

$$x_{n+1} = x_n + h \quad \text{(A5a)}$$

$$y_{n+1} = y_n + \Delta y \quad \text{(A5b)}$$

All intervals are computed in the same manner, using for the initial values the values at the beginning of each interval. The method does not need any special formulas to get the solution started, and it is well suited to computational form.

Appendix B

SOLUTION OF BUOY EQUATIONS

B.1 Equilibrium Equations

Equations (12) are:

$$-(T_{BE})_x + (D_F)_x - (T_{BD})(\sin\theta_{BD})(\cos\phi_{BD}) = 0 \quad \text{(B1a)}$$

$$-(T_{BE})_y + (D_F)_y + (T_{BD})(\cos\theta_{BD})(\cos\phi_{BD}) = 0 \quad \text{(B1b)}$$

$$-(T_{BE})_z + (B) + (T_{BD})(\sin\phi_{BD}) = 0 \quad \text{(B1c)}$$

Letting

$$AEX = \left[-(T_{BE})_x + (D_F)_x\right] \quad \text{(B2a)}$$

$$AEY = \left[(T_{BE})_y - (D_F)_y\right] \quad \text{(B2b)}$$

$$AEZ = \left[(T_{BE})_z - (B)\right] \quad \text{(B2c)}$$

the above equations may be rewritten as:

$$T_{BD} \sin\theta_{BD} \cos\phi_{BD} = AEX \tag{B3a}$$

$$T_{BD} \cos\theta_{BD} \cos\phi_{BD} = AEY \tag{B3b}$$

$$T_{BD} \sin\phi_{BD} = AEZ \tag{B3c}$$

Dividing equation (B3c) by (B3a) gives:

$$\frac{\tan\phi_{BD}}{\sin\theta_{BD}} = \frac{AEZ}{AEX} \tag{B4}$$

Dividing equation (B3c) by (B3b) yields:

$$\frac{\tan\phi_{BD}}{\cos\theta_{BD}} = \frac{AEZ}{AEY} \tag{B5}$$

Rewriting equation (B4):

$$\tan\phi_{BD} = \frac{AEZ}{AEX} \sin\theta_{BD} \tag{B6}$$

Putting equation (B6) into (B5):

$$\frac{\sin\Theta_{BD}}{\cos\Theta_{BD}} \cdot \frac{AEZ}{AEX} = \frac{AEZ}{AEY} \tag{B7}$$

or

$$\tan\Theta_{BD} = \frac{AEX}{AEY} \tag{B8}$$

which implies

$$\Theta_{BD} = \tan^{-1}\left(\frac{AEX}{AEY}\right) \tag{B9}$$

Equation (B6) may now be solved for

$$\phi_{BD} = \tan^{-1}\left[\left(\frac{AEZ}{AEX}\right)\sin\Theta_{BD}\right] \tag{B10}$$

or, from equation (B9), letting

$$AEX = (AEY)(\tan\Theta_{BD}) \tag{B11}$$

equation (B10) may be rewritten as:

$$\phi_{BD} = \tan^{-1}\left[\left(\frac{AEZ}{AEY}\right)(\cos\Theta_{BD})\right] \tag{B12}$$

Finally, T_{BD} may be found by rewriting equation (B3c):

$$T_{BD} = \frac{AEZ}{\sin\phi_{BD}} \tag{B13}$$

If ABY is calculated to be zero, then $\Theta_{BD} = 90^{\circ}$ if ABX is positive and $\Theta_{BD} = -90^{\circ}$ if ABX is negative. Similarly if ABY is calculated to be zero, then $\phi_{BD} = 90^{\circ}$ if ABZ is positive and $\phi_{BD} = -90^{\circ}$ if ABZ is negative.

Finally, if ϕ_{BD} is calculated to be zero (which is not expected), the program will automatically be stopped as it cannot evaluate equation (B13).

B.2 Moment Equations

Equations (16a), (16b), and (17) are:

$$(B)\left(\frac{y_{DB}}{2}\right) + (T_{BD})_z (y_{DB}) - (D_F)_y \left(\frac{z_{DB}}{2}\right) - (T_{BD})_y (z_{DB}) = 0 \qquad \text{(B14a)}$$

$$(D_F)_x \left(\frac{z_{DB}}{2}\right) + (T_{BD})_x (z_{DB}) - (B)\left(\frac{x_{DB}}{2}\right) - (T_{BD})_z (x_{DB}) = 0 \qquad \text{(B14b)}$$

$$(2R_s)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \qquad \text{(B14c)}$$

where, from equations (15):

$$x_{DB} = x_D - x_E \qquad \text{(B15a)}$$

$$y_{DB} = y_D - y_E \qquad \text{(B15b)}$$

$$z_{DB} = z_D - z_E \qquad \text{(B15c)}$$

Combining like terms of equations (B14) gives:

$$\left[\left(\frac{B}{2}\right) + (T_{BD})_z\right](y_{DB}) - \left[\left(\frac{(D_F)_y}{2}\right) + (T_{BD})_y\right](z_{DB}) = 0 \tag{B16a}$$

$$\left[\left(\frac{(D_F)_x}{2}\right) + (T_{BD})_x\right](z_{DB}) - \left[\left(\frac{B}{2}\right) + (T_{BD})_z\right](x_{DB}) = 0 \tag{B16b}$$

$$(2R_S)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \tag{B16c}$$

Let

$$C_1 = \left[\left(\frac{B}{2}\right) + (T_{BD})_z\right] \tag{B17a}$$

$$C_2 = \left[\left(\frac{(D_F)_y}{2}\right) + (T_{BD})_y\right] \tag{B17b}$$

$$C_3 = \left[\left(\frac{(D_F)_x}{2}\right) + (T_{BD})_x\right] \tag{B17c}$$

$$D_S = 2R_S \tag{B17d}$$

Then, substitution of the above expressions into equations (B16) yields:

$$(c_1)(y_{DB}) - (c_2)(z_{DB}) = 0 \tag{B18a}$$

$$(c_3)(z_{DB}) - (c_1)(x_{DB}) = 0 \tag{B18b}$$

$$(D_s)^2 = (x_{DB})^2 + (y_{DB})^2 + (z_{DB})^2 \tag{B18c}$$

Solving for y_{DB} and x_{DB} in equations (B18a) and (B18b) respectively gives:

$$y_{DB} = \left(\frac{c_2}{c_1}\right)(z_{DB}) \tag{B19a}$$

$$x_{DB} = \left(\frac{c_3}{c_1}\right)(z_{DB}) \tag{B19b}$$

(c_1 is never expected to be equal to zero.)

Substitution of the above expressions into equation (B18c) gives:

$$(D_s)^2 = \left[\left(\frac{c_2}{c_1}\right)^2 + \left(\frac{c_3}{c_1}\right)^2 + 1\right](z_{DB})^2 \tag{B19c}$$

This equation may be solved as follows:

$$z_{DB} = \frac{D_s}{\sqrt{\left(\frac{C_2}{C_1}\right)^2 + \left(\frac{C_2}{C_1}\right)^2 + 1}} \tag{B20}$$

The solution for the unknown coordinates, then, may be taken from a rearrangement of equations (B15):

$$x_D = x_E + x_{DB} \tag{B21a}$$

$$y_D = y_E + y_{DB} \tag{B21b}$$

$$z_D = z_E + z_{DB} \tag{B21c}$$

where all the terms are as previously defined.

Appendix C

COMPUTER PROGRAM DESCRIPTION

C.1 Current Profile

The program computes the current velocity as a function of depth. The current direction is assumed to be constant and the current velocity vector at any depth is contained in a horizontal plane. Assume that the current, V_c, has a velocity of c_x knots at the surface, decreases exponentially to c_y knots at a depth of D feet, and varies linearly at greater depths to c_B knots at the bottom, at a water depth of H feet:

$$v_c = c_x \, e^{-(H-z)(c_z)} \qquad \left(H \geq z \geq (H-D)\right) \qquad \text{(C1a)}$$

where

$$c_z = \frac{\ln\left(\frac{c_x}{c_y}\right)}{D} \qquad \text{(C1b)}$$

$$v_c = c_B + \left(\frac{z}{H-D}\right)\left(c_y - c_B\right)$$

$$\left((H-D) \geq z \geq 0\right) \qquad \text{(C2)}$$

Figure C-1 shows this profile:

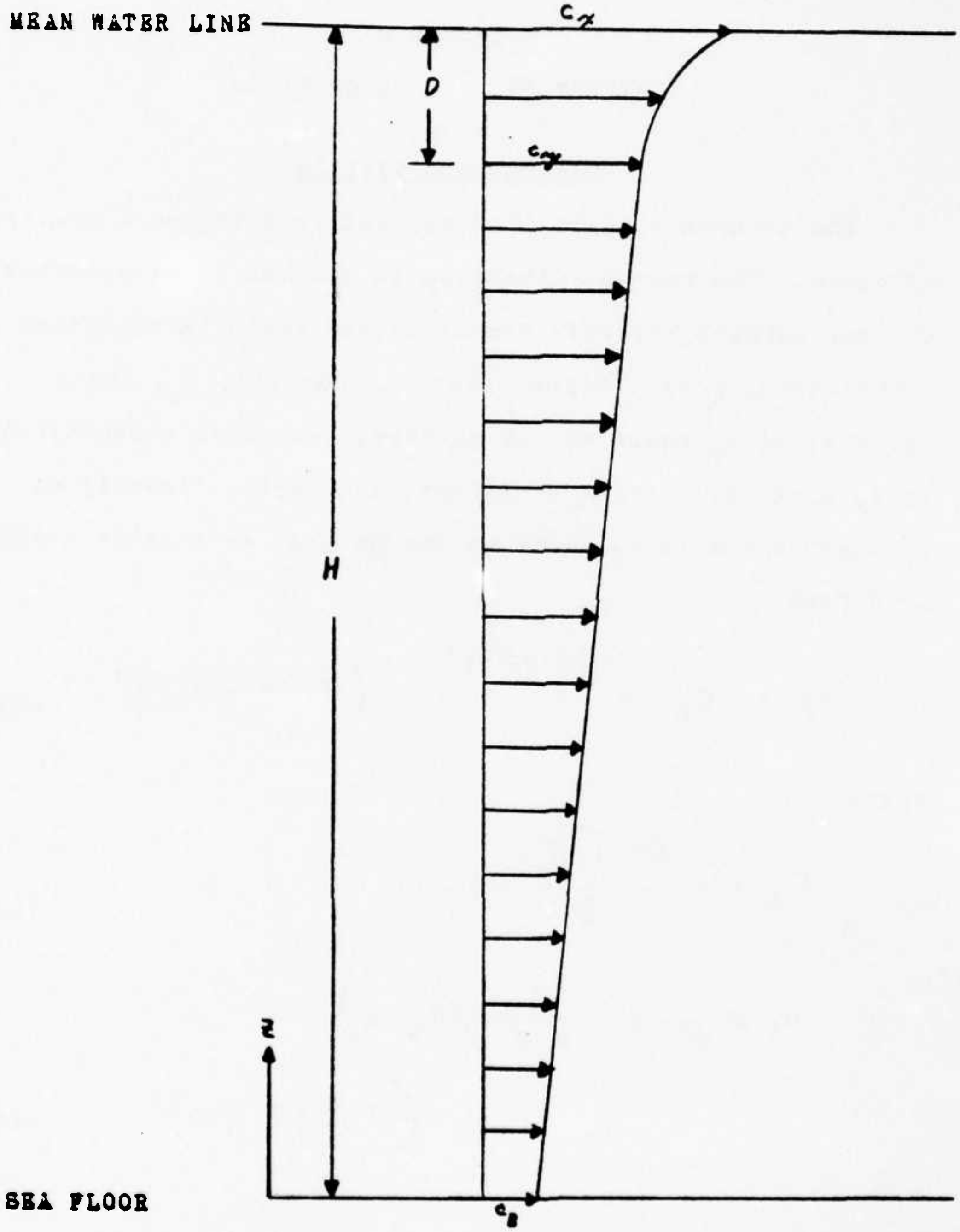

Figure C-1. Current Profile

C.2 Drag Coefficients

The drag coefficients for both the cable and the spherical buoys are specified in the program for different ranges of Reynolds numbers. The cable normal drag coefficient is given as follows:

$$C_{DN} = 1.2\,e^{-\left[\frac{Re - (2 \times 10^{2})}{(2.0 \times 10^{2})}\right]} \qquad (2.0 \times 10^{2}) \leq Re < (2.5 \times 10^{3}) \tag{C3a}$$

$$C_{DN} = 0.9\,e^{\left[\frac{Re - (2.5 \times 10^{3})}{(4.3 \times 10^{4})}\right]} \qquad (2.5 \times 10^{3}) \leq Re < (1.5 \times 10^{4}) \tag{C3b}$$

$$C_{DN} = 1.2 \qquad (1.5 \times 10^{4}) \leq Re < (2.0 \times 10^{5}) \tag{C3c}$$

The lower bound for the Reynolds number for the cable normal drag coefficient is given as (2.0×10^2), which, for a 20,000 foot long 2 inch diameter cable (which is used in the present study), corresponds to a normal drag of 1.5 pounds. The upper bound is (2.0×10^5). (The maximum Reynolds number expected in this study is (3.5×10^4).) Figure C-2 shows a comparison between the approximations of equations (C3) and the actual normal drag coefficient for smooth cylinders.[39]

— Actual values
··· Approximate values

Figure C-2. Actual Normal Drag Coefficients for Circular Cylinders

The cable tangential drag coefficient is specified as:

$$C_{DT} = 0.006\, e^{-\left[\frac{Re-(2\times10^{3})}{(2.2\times10^{5})}\right]} \qquad (2.0\times10^{3}) \le Re \le (2.0\times10^{5}) \qquad \text{(C4)}$$

The lower bound for Re is (2.0×10^3) which gives a tangential drag of 2.3 pounds for the cable used in this study; the upper bound is (2.0×10^5). (Re is not expected to exceed (3.5×10^4) in this study.) Figure C-3 compares the values calculated from equation (C4) and the actual tangential drag coefficients for smooth cylinders.[28]

The drag coefficient for a spherical buoy is given as follows:

$$C_{DS} = 0.5 \qquad (3.0\times10^{4}) \le Re \le (2.0\times10^{5}) \qquad \text{(C5a)}$$

$$C_{DS} = 0.5\, e^{-\left[\frac{Re-(2\times10^{5})}{(4.9\times10^{4})}\right]} \qquad (2.0\times10^{5}) \le Re < (2.5\times10^{5}) \qquad \text{(C5b)}$$

$$C_{DS} = 0.18\, e^{\left[\frac{Re-(2.5\times10^{5})}{(1.4\times10^{6})}\right]} \qquad (2.5\times10^{5}) \le Re < (4.0\times10^{5}) \qquad \text{(C5c)}$$

$$C_{DS} = 0.2 \qquad (4.0\times10^{5}) \le Re \le (1.0\times10^{7}) \qquad \text{(C5d)}$$

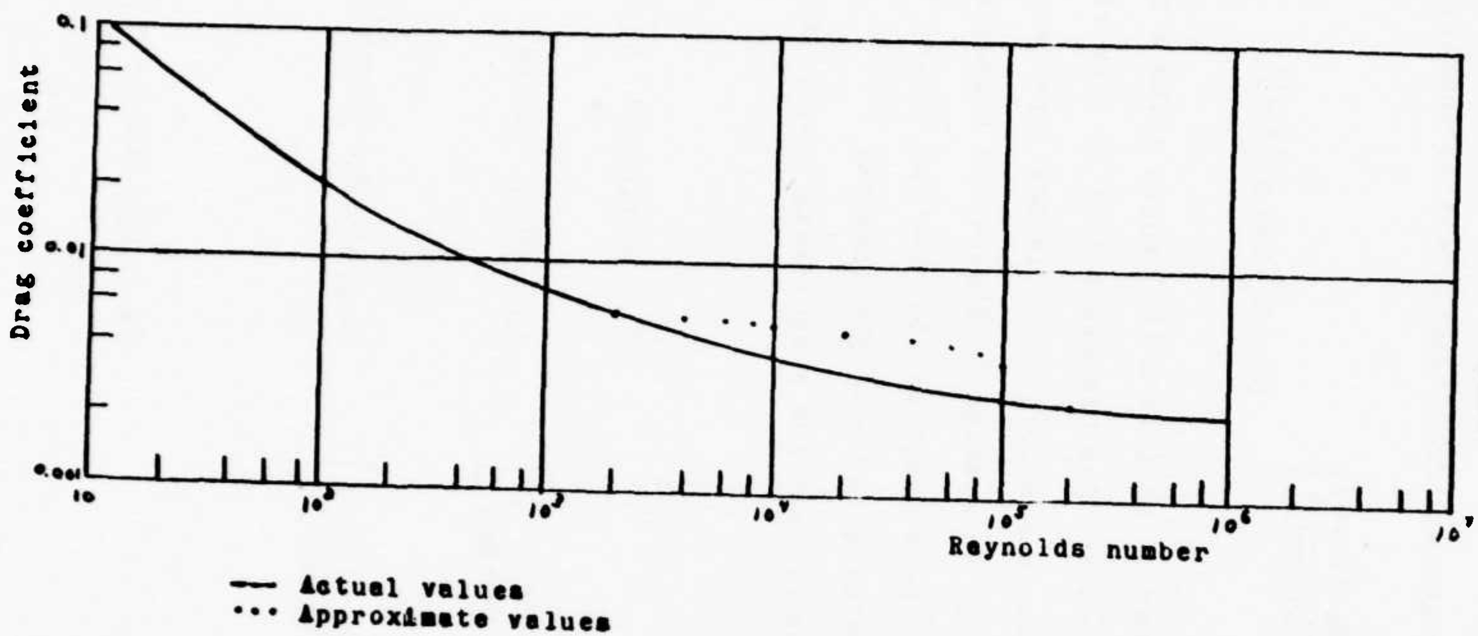

Figure C-3. Actual Tangential Drag Coefficients for Circular Cylinders

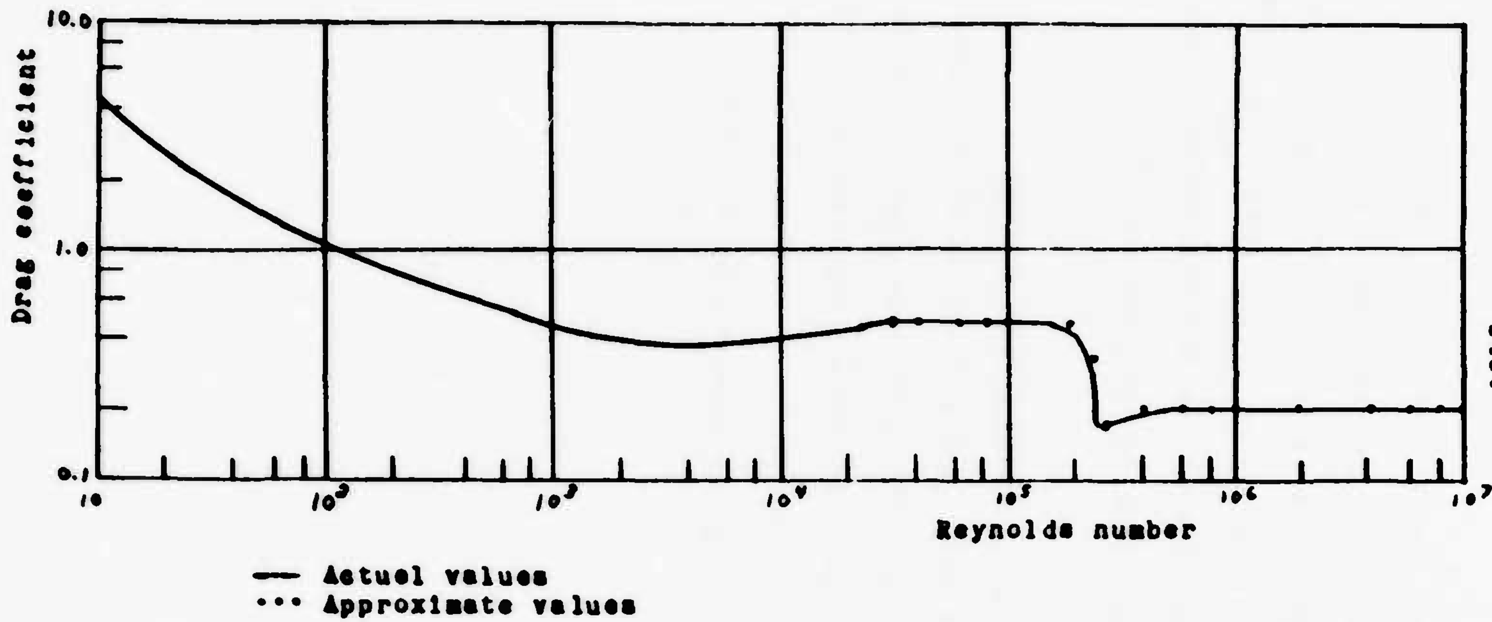

Figure C-4. Actual Drag Coefficients for Spheres

The lower bound for Re is (3.0×10^4), which, for a 6 foot diameter spherical buoy, corresponds to a drag of 0.09 pounds. The upper bound is (1.0×10^7). (The maximum value for Re in this study is (1.3×10^6).) Figure C-4 gives a comparison between the approximations of equations (C5) and the actual drag coefficient for a sphere.[28,39]

C.3 Possible Buoy Systems

There are several buoy systems which the program is capable of handling. The present program allows for a maximum of only two subsurface buoys but, with minimal alterations to the program, more buoys could be added. Figures C-5, C-6, and C-7 show the three possible system configurations.

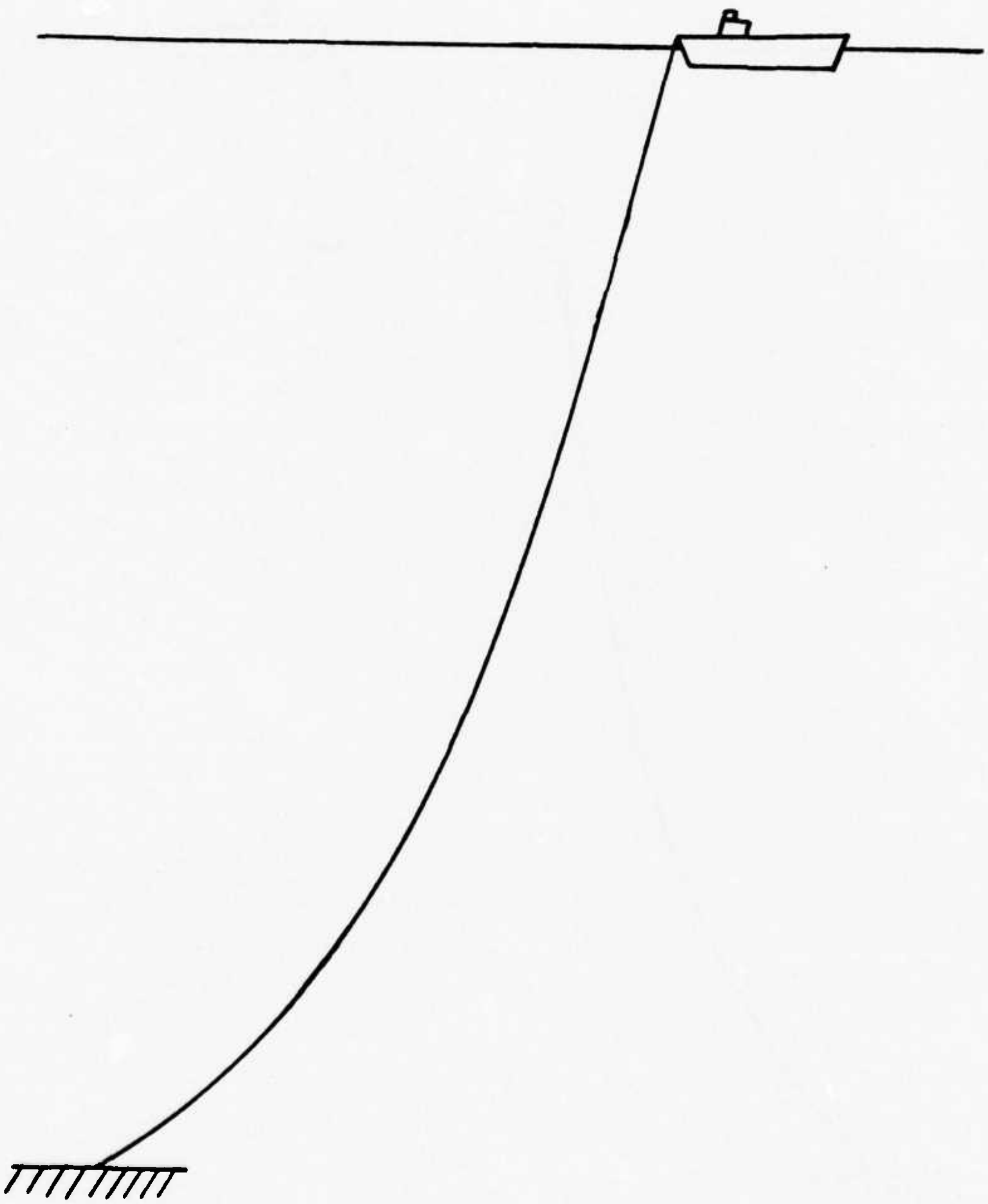

Figure C-5. System With No Buoys

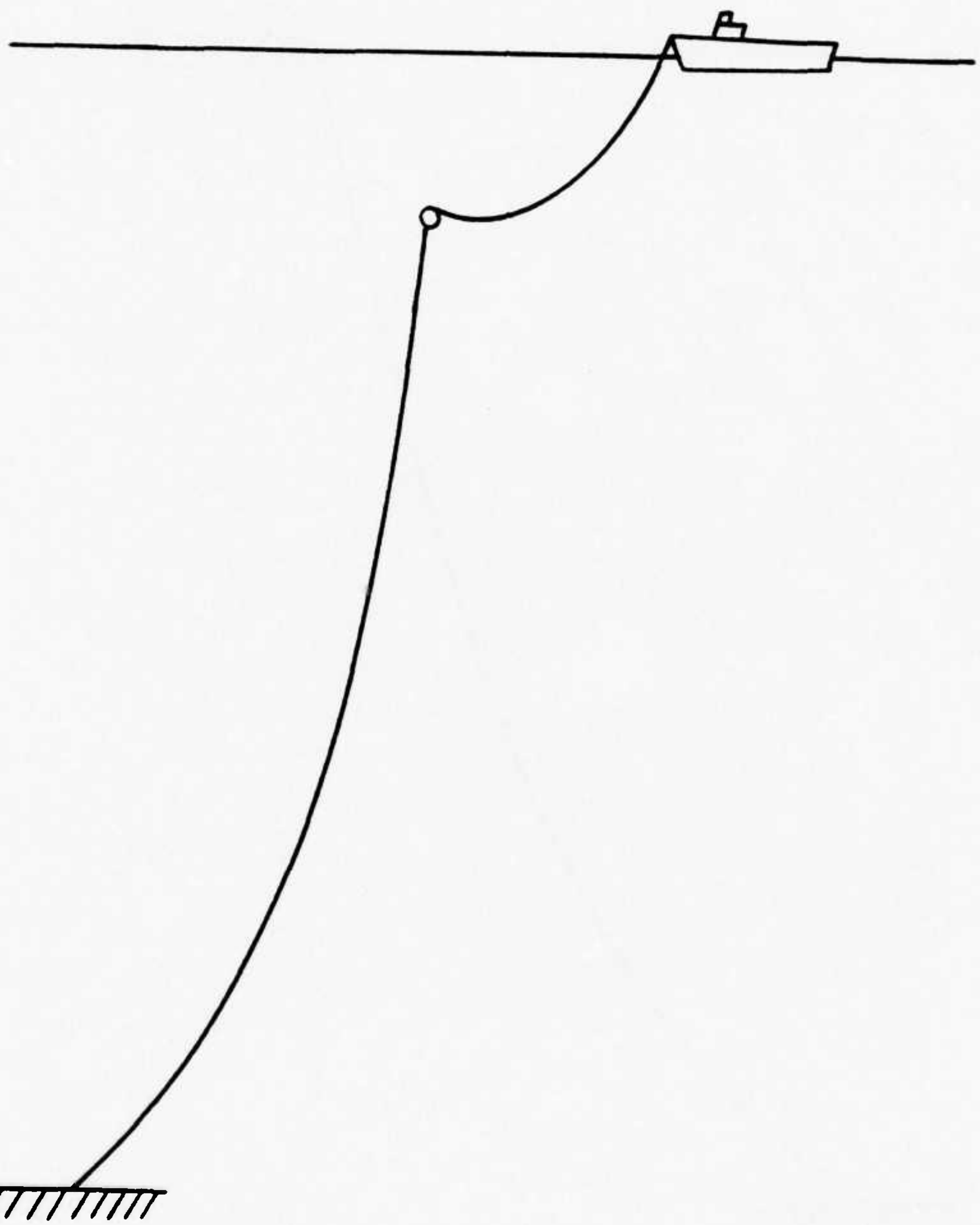

Figure C-6. System With One Buoy

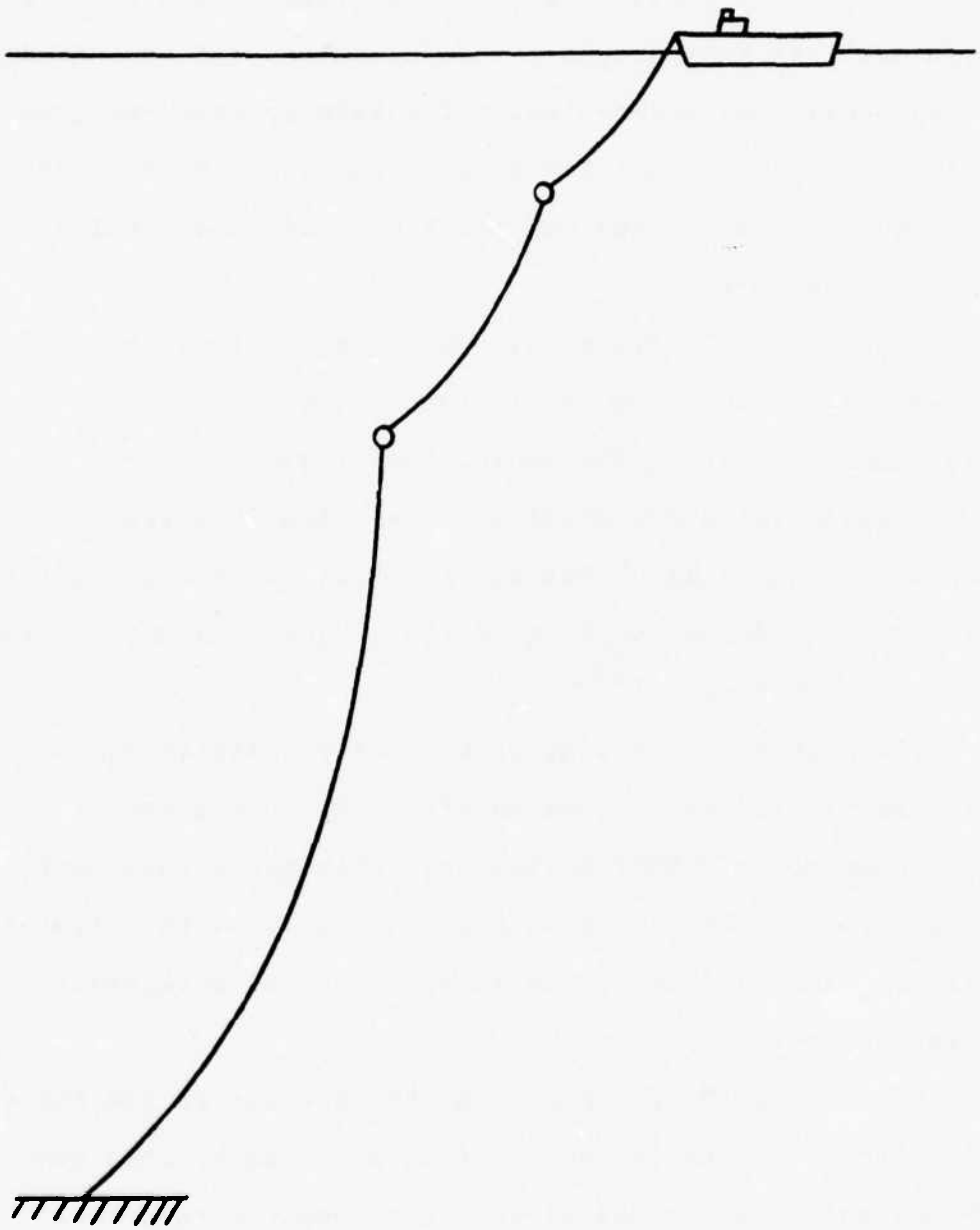

Figure C-7. System With Two Buoys

C.4 Flow Charts

The steady state model is subdivided into a main program and five subroutines. (The dynamic model is included in an additional subroutine.) The main program performs very few calculations; its purpose is to guide the program through the subroutines and print and plot the results. (See figure C-8.)

Subroutine CONFIG specifies the cable equations; it gives the tension, the two angles, and the position at regular intervals along the cable. (See figure C-9.)

Subroutine RUNGE gives a Runge-Kutta numerical solution for the integration of the differential equations. (It is called from CONFIG and from DYMICS.) This subroutine was developed by White.[25]

Subroutine ANGLE simply gets any two angles to be between $-\pi$ and π radians or -180 and 180 degrees.

Subroutine SUBSRF solves the force and moment equilibrium equations of the subsurface buoy to give the tension, angles, and position of the second point of attachment. (See figure C-10.)

Subroutine TENCOR corrects the tensions at the anchor in order to reduce the error between the calculated location of the ship and the actual location.(See figure C-11.)

Subroutine DYMICS gives the positions, velocities,

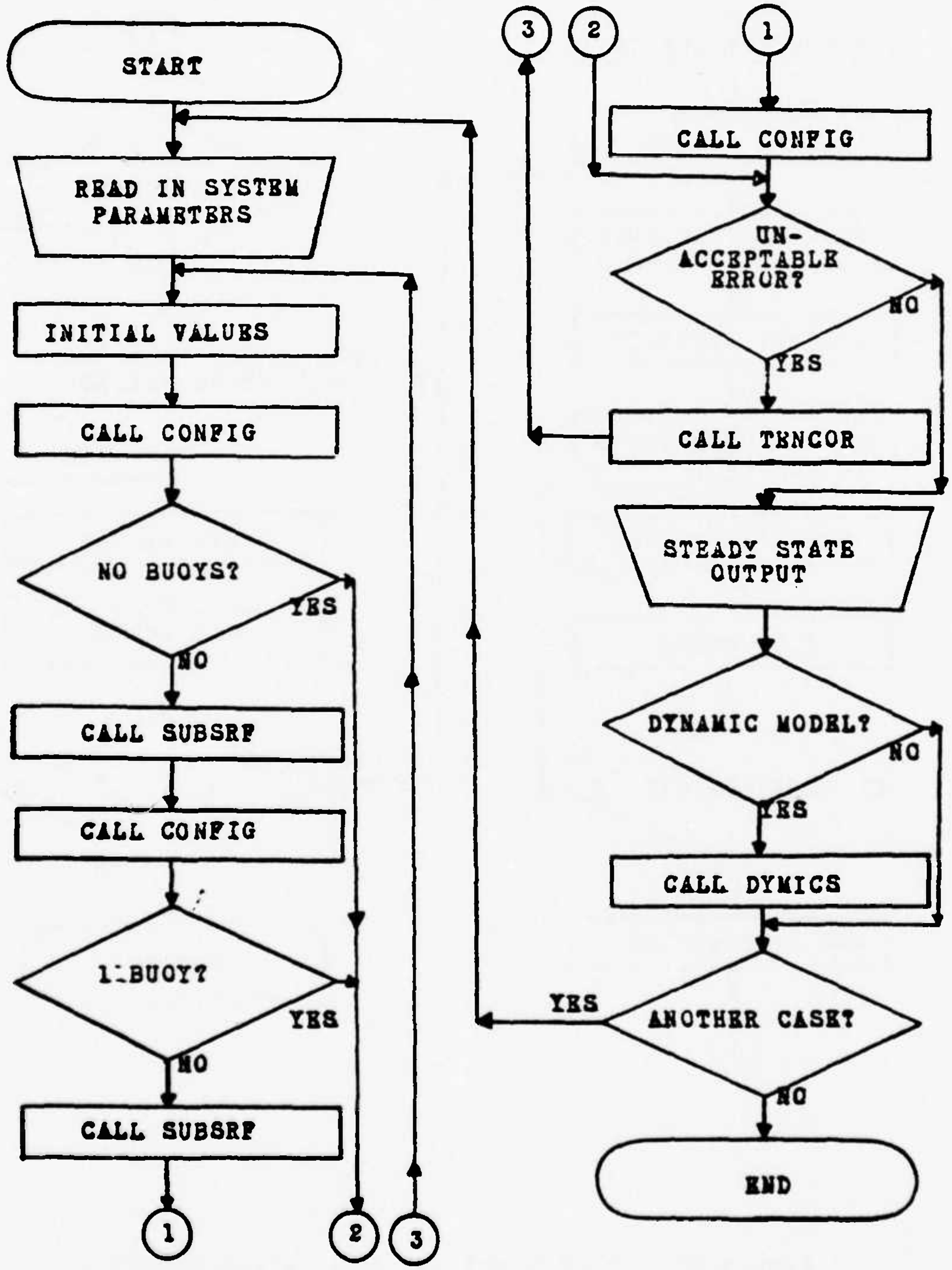

Figure C-8. Flow Chart for Main Program

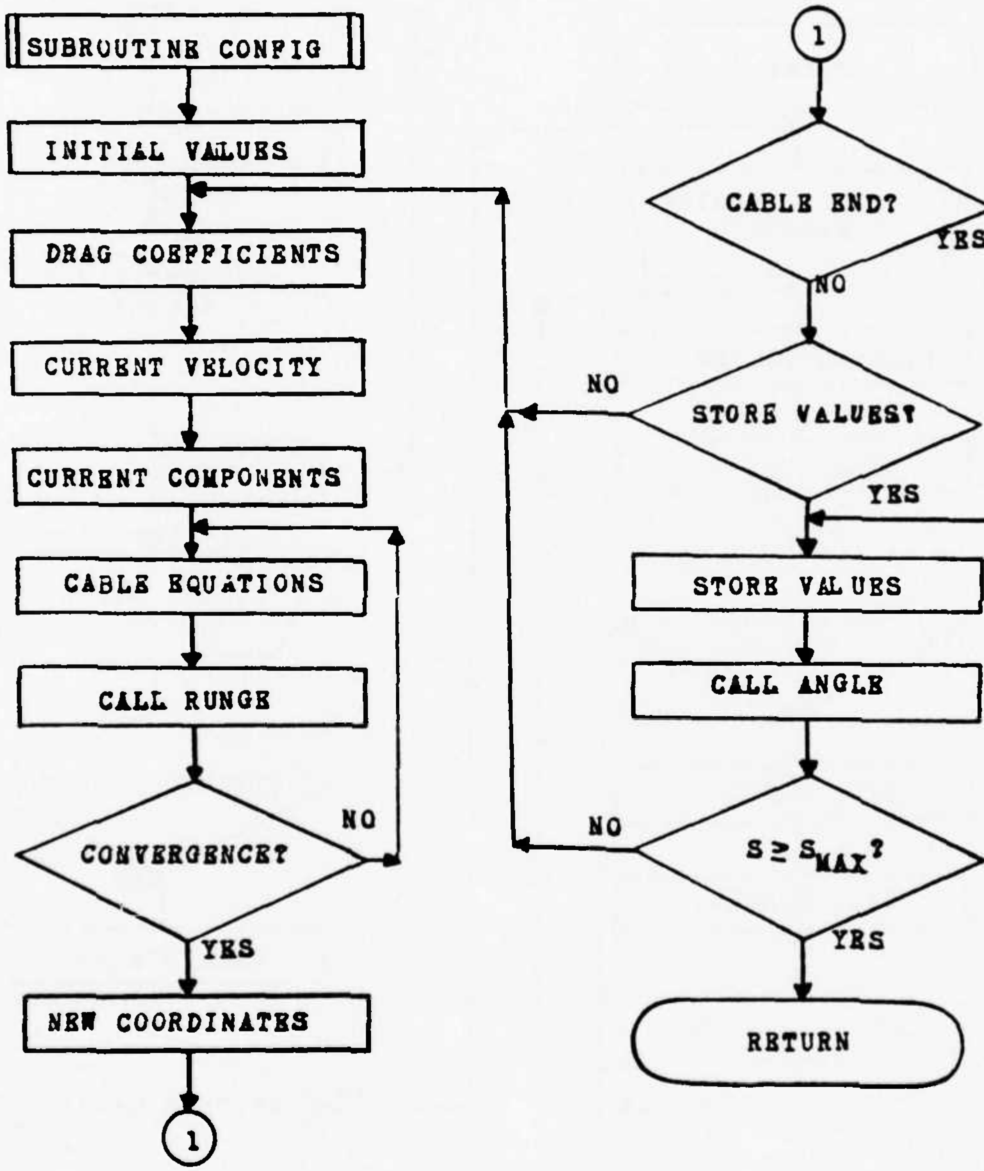

Figure C-9. Flow Chart for Subroutine CONFIG

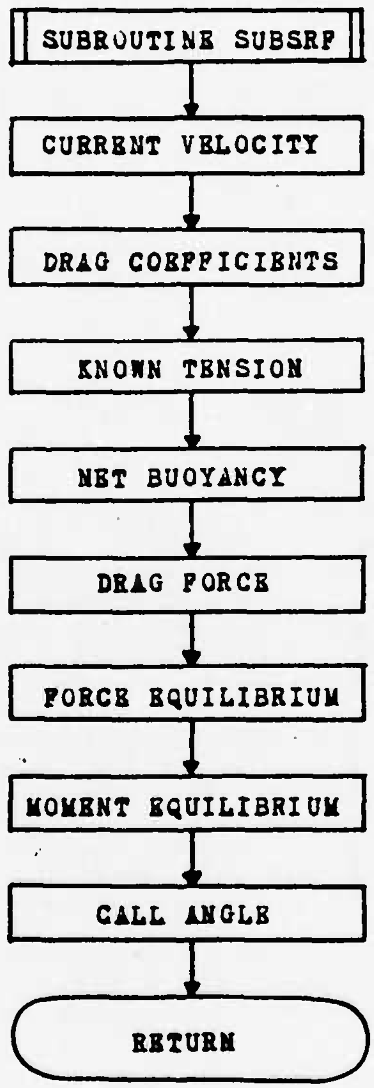

Figure C-10. Flow Chart for Subroutine SUBSRF

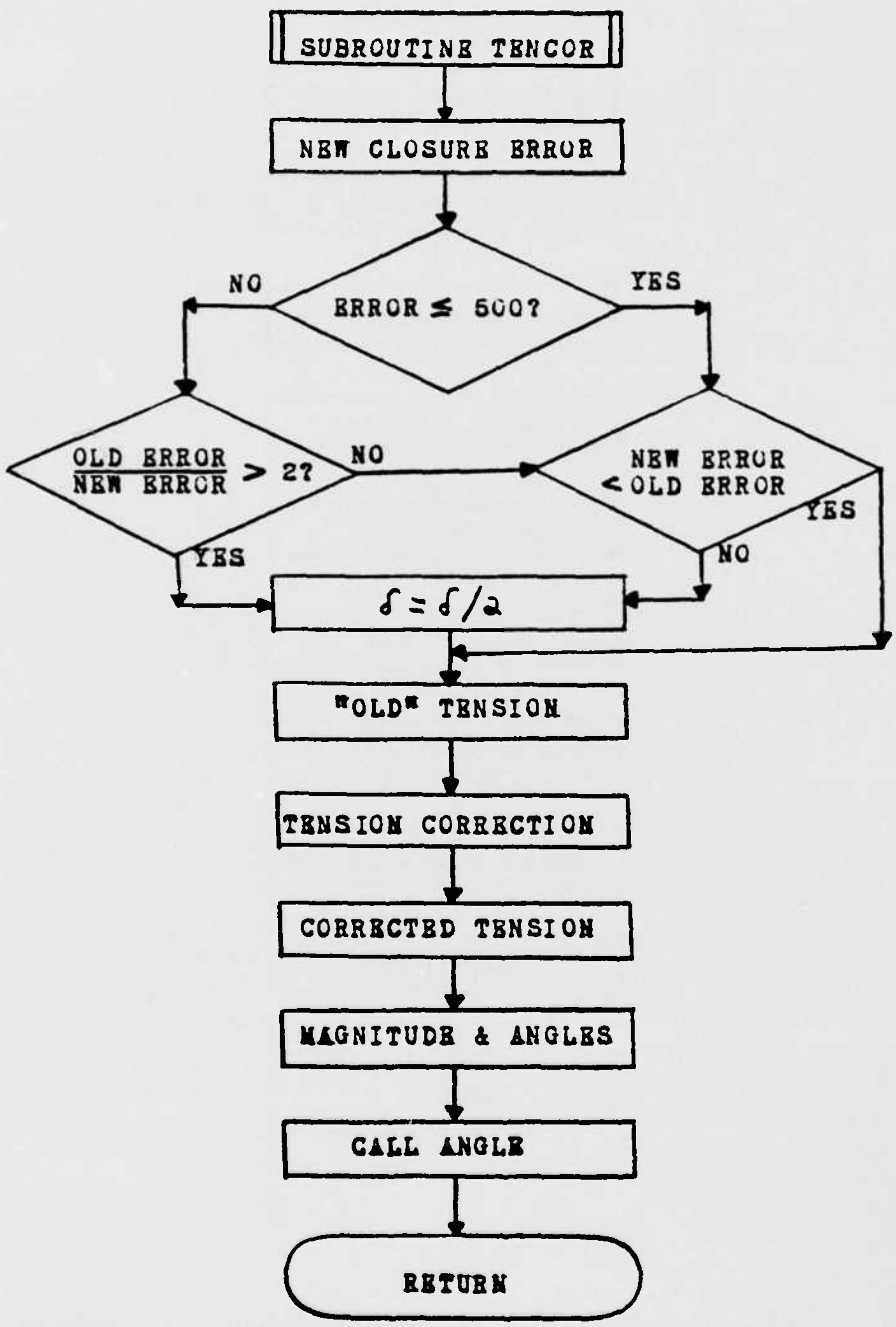

Figure C-11. Flow Chart for Subroutine TENCOR

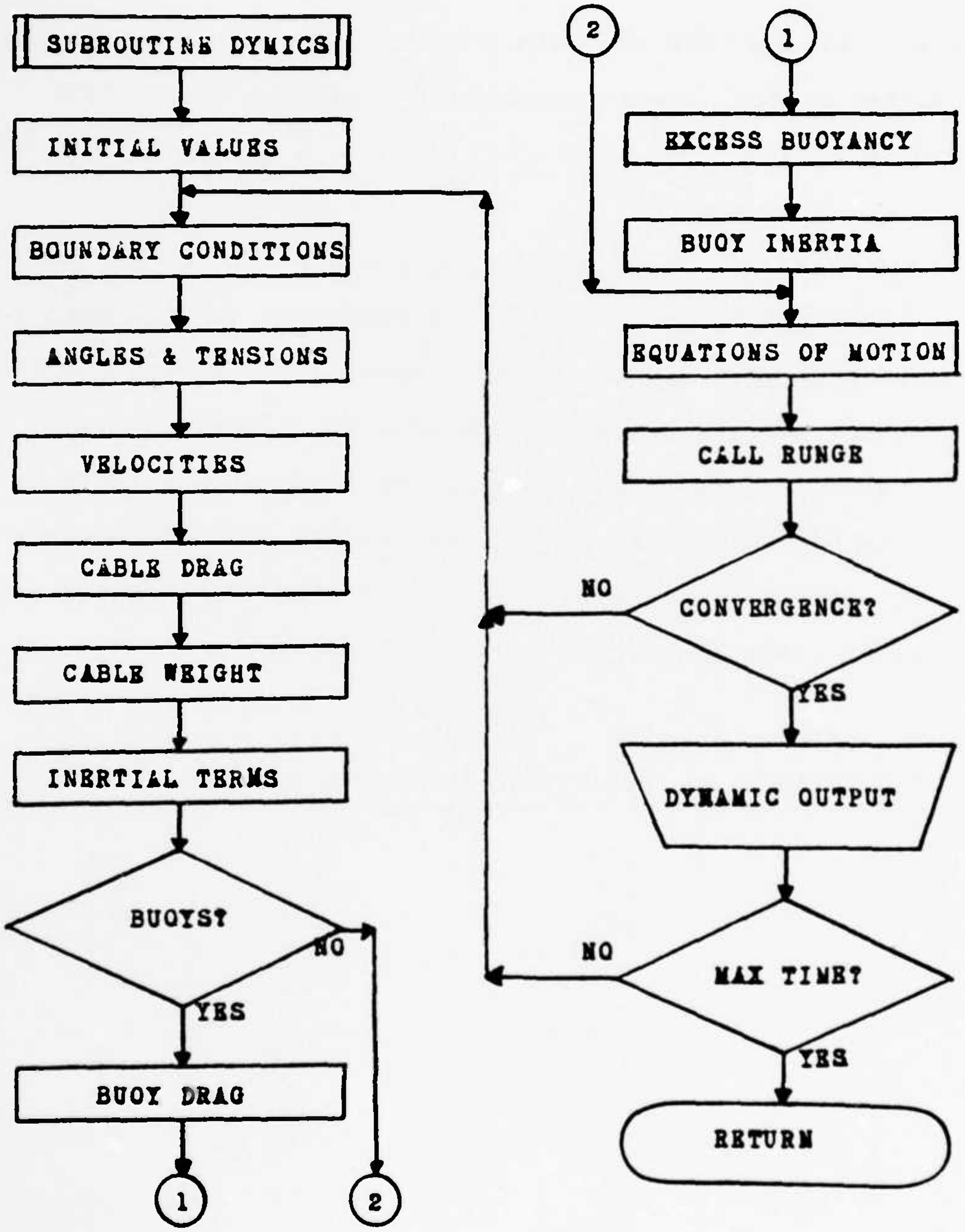

Figure C-12. Flow Chart for Subroutine DYMICS accelerations, and tensions of the system when it is being excited by the dynamic motions of a surface ship. (See figure C-12.)

C.5 Input Data Cards

The program was designed to allow the user as much freedom as possible in choosing various parameters for the system. Thus, maximum use was made of inputting data. The order and format of each parameter of each card required for the steady state model is given below in table C-1. (Do not include cards 3 to 203 if IDYMIC = 0; do not include cards 104 to 203 if BETA = 0 or 180.)

CARD NUMBER	PARAMETER	COLUMNS	FORMAT
1	NCB	1-10	I10
	NCD	11-20	I10
	NCE	21-30	I10
	IDYMIC	31-40	I10
	IPLOT	41-50	I10
2	EPSLNA	1-10	F10.2
	NOITER	11-20	I10
3	BETA	1-10	F10.5
	TMMAX	11-20	F10.5
4-103	AMPZ	1-10	F10.4
	OMEGAZ	11-20	F10.4
	PHANGZ	21-30	F10.4

Table C-1. Order of Input Data Cards

CARD NUMBER	PARAMETER	COLUMNS	FORMAT
104-203	AMPX	1-10	F10.4
	OMEGAX	11-20	F10.4
	PHANGX	21-30	F10.4
204	XCHAR	1-6	A6
	YCHAR	7-12	A6
	ZCHAR	13-18	A6
	XCHRR	19-24	A6
	YCHRR	25-30	A6
	ZCHRR	31-36	A6
	VELX	37-42	A6
	VELY	43-48	A6
	VELZ	49-54	A6
	TEN	55-60	A6
	TIM	61-66	A6
205	CX	1-10	F10.9
	D	11-20	F10.9
	CY	21-30	F10.9
	GB	31-40	F10.9
	THEC	41-50	F10.9
206	IBUOY	1-10	I10
	EA	11-20	F10.2
	PA	21-30	F10.2
	EB	31-40	F10.2
	PB	41-50	F10.2
207	SAD	1-10	F10.3
	EAD	11-20	F10.3
	WAD	21-30	F10.3
	DAD	31-40	F10.3
	DSAD	41-50	F10.3
208	SEG	1-10	F10.3
	EEG	11-20	F10.3
	WEG	21-30	F10.3
	DEG	31-40	F10.3
	DSEG	41-50	F10.3

Table C-1. Order of Input Data Cards (Cont'd)

CARD NUMBER	PARAMETER	COLUMNS	FORMAT
209	SGT	1-10	F10.3
	EGT	11-20	F10.3
	WGT	21-30	F10.3
	DGT	31-40	F10.3
	DSGT	41-50	F10.3
210	TITLE	1-6	A6
211	G	1-10	F10.2
	H	11-20	F10.2
	ICASE	21-30	I10

Table C-1. Order of Input Data Cards (Cont'd)

The parameters used in table C-1 may be described as follows:

NCB = number of times cards 210 and 211 will be repeated for one set of values of cards 1 thru 209.

NCD = number of times cards 206 thru 211 will be repeated for one set of values of cards 1 thru 205.

NCE = number of times card 206 will be repeated for one set of values of cards 1 thru 204.

IDYMIC = 0 if only the steady state model is desired.
= 1 if both the steady state and dynamic models are desired.

IPLOT = 0 if no plots are desired.
= 1 if plots are desired.

EPSLNA = maximum closure error at ship (feet) for steady state model.

NOITER = maximum number of iterations per case for steady state model.

BETA = ship heading in degrees (following seas = 0°, beam seas = 90°, head seas = 180°).

TMMAX = length of time in seconds for which the dynamic simulation is desired.

AMPZ = amplitude in feet of heave of ship at frequency OMEGAZ (in radians) and phase angle PHANGZ (in radians).

AMPX = amplitude in feet of sway of ship at frequency OMEGAX (in radians) and phase angle PHANGX (in radians).

XCHAR,
YCHAR,
ZCHAR = labels on x-axis, y-axis, and z-axis respectively on plots of steady state model.

XCHRR,
YCHRR,
ZCHRR = labels on x-axis, y-axis, and z-axis respectively on plots of dynamic model.

VELX,
VELY,
VELZ = labels for velocity components in x, y, and z directions respectively on plots of dynamic model.

TEN = label for tension on plots of dynamic model.

TIM = label for time on plots of dynamic model.

CX = current speed in knots at the surface.

D = depth in feet above which the current variation is exponential and below which the current variation is linear.

CY = current speed in knots at depth D

CB = current speed in knots at ocean bottom.

THBC = current direction in degrees, measured positive counterclockwise from the y-axis.

IBUOY = total number of buoys (0, 1, or 2).

BA = excess buoyancy in pounds of first buoy (displacement minus buoy air weight).

PA = density of first buoy in pounds per cubic foot.

BB = excess buoyancy in pounds of second buoy.

PB = density of second buoy in pounds per cubic foot.

SAD = unstretched length of cable in feet between the anchor and the first buoy (between the anchor and ship if no buoys); this length of cable is referred to as the first segment.

BAD = modulus of elasticity in pounds per square inch of the first segment.

WAD = weight in water of first segment in pounds per foot.

DAD = outside diameter in inches of first segment.

DSAD = strength member diameter in inches of first segment (See figure 1.).

SBG = unstretched length of cable in feet between the first buoy and the second buoy (between the first buoy and ship if only one buoy); this length of cable is referred to as the second segment
= if no buoys

BBG,
WBG,
DBG,
DSBG -= are analogous to BAD, WAD, DAD, and DSAD respectively, except that they refer to the second segment
= if no buoys

SGT = unstretched length of cable in feet between the second buoy and the ship; this length of cable is referred to as the third segment.
= 0 if no buoys or only one buoy.

EGT,
WGT,
DGT,
DSGT = are analogous to EAD, WAD, DAD, and DSAD respectively except that they refer to the third segment.
= 0 if no buoys or only one buoy.

TITLE = title printed on all plots.

G = projected length in feet in the horizontal plane between the anchor and the ship.

H = water depth in feet.

ICASE = case number.

The order of the cards resembles a large DO loop for the program:

```
          (DATA CARDS 1 THRU 204)
     DO 1 NCBC = 1, NCB
          (DATA CARD 205)
     DO 2 NCDC = 1, NCD
          (DATA CARDS 206 THRU 209)
     DO 3 NCBC = 1, NCB
          (DATA CARDS 210 THRU 211)
   3 CONTINUE
   2 CONTINUE
   1 CONTINUE
```

Thus, there is only one of cards 1 thru 204, there are NCB of card 205, there are NCB X NCD of cards 206 thru 209, and there are NCB X NCD X NCB of cards 210 and 211.

This means that the ship's position and water depth are varied first, then the parameters of the cables and buoys, and finally the current velocity.

C.6 Program Convergence and Limitations

The steady state program has been applied to a number of cases; however, they have not been exhaustive. Convergence for the iteration process which finds the tension at the anchor has been found to take place after about 18 to 26 iterations.

Problems have been encountered with certain configurations. Very high tension cases, where the cable must elongate a good deal, are slow to converge. For example, in one such case, the maximum tensions in the cable reached 30,000 pounds after 70 iterations. (Higher tensions were expected.) For the purposes of this study, though, tensions of this magnitude will not exist. (The maximum allowable steady state tension is 8000 pounds due to material limitations.)

Slack cases have also had problems with convergence. A slack mooring, as used here, is defined to be a configuration in which a portion of the lower section of cable remains on the bottom (that is, it lies in the horizontal plane). For this study, such cases are not of interest for two reasons. First, such tensions will always be in the acceptable range. Second, a slack cable is undesirable because of possible problems with the cable tangling itself.

It should be noted that the program does not account for certain physical constraints on the cable attachment at a subsurface buoy. Certain cases may produce a configuration where the cable "goes inside" the buoy. The program cannot apply this geometrical limitation to the cable angles at the buoy.

This program was run on a UNIVAC 1108 digital computer at the Naval Underwater Systems Center. The approximate CPU time in the steady state was two minutes per case, where the closure error (EPSLNA) was taken to be 10 feet. Approximate CPU time for the dynamic model in minutes was given by

$$\text{CPU time} \simeq 0.004 \left(\frac{\text{TMMAX}}{b}\right)$$

where TMMAX is time in seconds the system is allowed to run and b is the step size in time (seconds).

Appendix D

SHIP DESCRIPTION

The ship used in this study is one of the Agor class. Its parameters are given in tables D-1 and D-2, where the terms are defined to be:

CB	:	block coefficient, defined as volume of the displaced fluid divided by (midship beam • midship draft • ship length between perpendiculars) (nondimensional)
XLBP	:	ship length between perpendiculars (feet)
BEAM	:	midship beam (feet)
DRAFT	:	midship draft (feet)
XCG	:	longitudinal center of gravity measured from the waterline (positive up) (feet)
VCG	:	vertical center of gravity measured from the waterline (positive up) (feet)
GM	:	metacentric height (feet)
RYY	:	radius of gyration about the y-axis (feet)
RXX	:	radius of gyration about the x-axis (feet)
RZZ	:	radius of gyration about the z-axis (feet)
XZI	:	mass moment of inertia about the x-z axis (slug • feet squared)
WSURFA	:	wetted surface (feet squared)
ST	:	station number (F.P.= 0, A.P.= 10) (nondimensional)
XI	:	distance to ship station ST measured from amidship positive forward (feet)

YM : full beam at waterline of station ST (feet)

ZM : draft at station ST (feet)

SIGMA : area coefficient of station ST (defined as section area divided by beam • draft of station ST) (nondimensional)

ZCB : vertical center of buoyancy of station ST measured from the waterline positive up (feet)

GIRTH : girth of ship station ST (feet)

ALPH : angle between ship side and vertical, required only for IWBK = 1 (degrees)

IWBK = 1 : sections with a deep U or V shape and small radius at the keel (typically at the forward portion of the ship)

IWBK = 3 : sections having a triangular shape as the extreme aft section of a cruiser stern ship

IWBK = 4 : sections which are unlikely to produce eddies as the ship rolls

Figure D-1 indicates the coordinate system used at the ship. (This is for the seakeeping program only.)

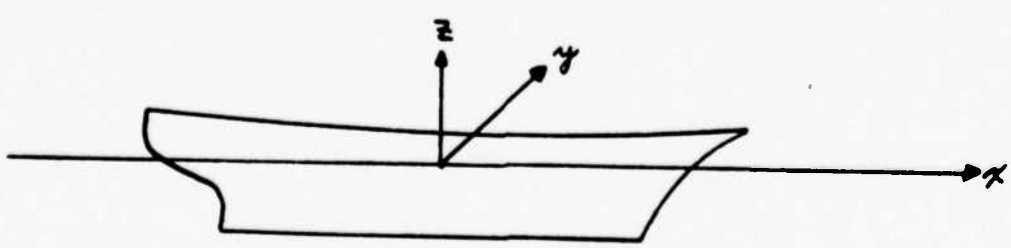

Figure D-1. Coordinate System of Ship

The (x, y, z) coordinates of the point for which motion computations were performed are (98.0, 0, 0). The x coordinate of the origin for motion computations was assumed to be the same as the XCG of the ship. Regular wave frequencies (wave length / ship length) used in this study are given as: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.25, 2.5, 2.75, and 3.0.

CB	=	0.43
XLBP	=	196.0
BEAM	=	39.0
DRAFT	=	14.25
XCG	=	-2.0
VCG	=	3.1
GM	=	1.95
RYY	=	49.0
RXX	=	15.6
RZZ	=	49.0
XZI	=	0.0
WSURFA	=	8073.0

Table D-1. Ship Parameters

ST	XI	YM	ZM	SIGMA	ZCB	GIRTH	ALPH	IWBK
0	98.0	0.0	0.0	0.000	0.0	26.8		4
½	88.2	4.2	13.2	0.538	-4.3	29.8	10.0	1
1	78.4	9.0	13.8	0.598	-4.4	38.7	17.0	1
2	58.8	18.8	13.9	0.678	-4.4	56.6	21.0	1
3	39.2	28.6	14.1	0.736	-4.8	71.5		4
4	19.6	36.0	14.2	0.758	-5.0	84.9		4
5	0.0	39.0	14.2	0.782	-5.1	90.8		4
6	-19.6	39.0	14.2	0.736	-4.9	92.3		4
7	-39.2	36.6	14.1	0.644	-4.6	77.4		4
8	-58.8	31.6	14.0	0.504	-3.9	61.0		3
9	-78.4	20.2	13.9	0.336	-3.0	56.6		3
9½	-88.2	11.6	3.0	0.488	-1.2	23.8		3
10	-98.0	0.0	0.0	0.000	0.0	0.0		4

Table D-2. Ship Station Parameters

Appendix B

COMPUTER PROGRAM LISTING

This appendix contains the program used to simulate the cable-buoy-ship systems described in this study.

```
@FOR,SI STEADY,STEADY
FOR 0E2B-01/11/77-04:56:42 (,0)

   MAIN PROGRAM

   STORAGE USED: CODE(1) 003227; DATA(0) 004370; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   CONF16
    0004   SUBSHF
    0005   TEKLOK
    0006   MOVES6
    0007   SETSMG
    0010   BEGIN3
    0011   OBJCT6
    0012   SUBJ3D
    0013   GRPH3D
    0014   PNT3D
    0015   SHOE3D
    0016   PAGE6
    0017   SUBJEG
    0020   GRAPHG
    0021   POINTG
    0022   LINESG
    0023   EXITG
    0024   DYNICS
    0025   NINTR$
    0026   NRDL$
    0027   NI02$
    0030   ALOG
    0031   CBRT
    0032   NPRT$
    0033   SQRT
    0034   NSTOP$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0000   003706 10F      0001   003106 1030L    0001   001770 1041G    0001   003135 1050L    0001   002027 1076G
    0000   003736 109F     0000   003701 11F      0000   003742 110F     0001   003207 1100L    0001   001407 111L
    0000   003754 112F     0001   002064 1126G    0001   001413 113L     0000   003700 12F      0000   003765 120F
    0001   002320 1226G    0001   002356 1245G    0001   002415 1264G    0001   000033 135G     0001   003022 1360G
    0001   003047 1375G    0001   003075 1412G    0001   003110 1424G    0001   000057 151G     0000   004014 160F
    0001   001436 161L     0000   004027 162F     0001   001442 163L     0001   000072 166G     0000   004041 170F
    0000   004053 176F     0000   004054 180F     0001   001473 195L     0000   003721 20F      0000   003715 21F
    0000   004066 210F     0000   004076 212F     0001   000154 22L      0000   004121 220F     0000   004104 226F
    0001   000155 23L      0001   001637 230L     0000   003714 24F      0000   004142 240F     0001   001633 243L
    0001   001033 244L     0000   003723 25F      0000   004152 250F     0000   003710 26F      0000   004166 260F
    0001   001050 261L     0001   001664 262L     0001   001677 263L     0000   004176 270F     0001   000116 28L
    0000   004205 280F     0001   000451 30L      0001   000076 32L      0000   003712 33F      0001   000070 35L
    0000   004217 350F     0000   004236 360F     0000   004267 361F     0001   001777 362L     0001   000076 37L
    0001   000156 38L      0000   004273 380F     0001   000252 39L      0000   004300 390F     0000   003717 40F
    0000   004304 410F     0000   004313 419F     0001   002110 421L     0000   004310 430F     0000   003725 46F
    0001   000627 48L      0001   000730 49L      0001   001112 491L     0001   001133 492L     0001   001153 493L
    0001   002271 510L     0001   001362 550L     0001   001010 58L      0001   001105 59L      0001   002543 600L
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0001      002645 010L     0001      002747 620L     0001      002447 660L     0000      003702 8F       0000      003704 9F
0001      002760 995L     0000 R 002271 AMPX     0000 R 002436 AMPZ     0000 R 003436 BFTA     0000 R 003460 CR
0000 R 003455 CA       0000 R 003457 CT       0000 R 003462 C2       0000 R 003456 D        0000 R 003476 DAD
0000 R 003503 DEG      0000 R 003656 DELTH    0000 R 003541 DEL10    0000 R 003510 DGT      0000 R 002225 DL
0000 R 003661 DMA      0000 R 003663 DMB      0000 R 002233 DOUT     0000 R 002211 DS       0000 R 003477 DSAD
0000 R 003504 DSEG     0000 R 003511 DSGT     0000 R 003465 EA       0000 R 003474 EAD      0000 R 003467 EB
0000 R 002217 ECG      0000 R 003501 EEG      0000 R 003506 EGT      0000 R 003434 EPSLNA   0000 R 003647 ERS
0000 R 003657 ESH      0000 R 003537 ETA      0000 R 003547 ETAD     0000 R 003655 ETAH     0000 R 002255 EXB
0000 R 003514 G        0000 R 003664 GG       0000 R 003515 H        0000 R 003526 HOOLD    0000 R 003645 HHIA
0000 R 003650 HH1B     0000 R 003646 HH2A     0000 R 003651 HH2B     0000 I 003554 IATCH1   0000 I 003555 IATCH2
0000 I 003464 IDUGT    0000 I 003516 ICASE    0000 I 003546 IDELTA   0000 I 003432 IDYMIC   0000 I 003433 IPLOT
0000 I 003600 IHHOH    0000 I 003531 ISRC1    0000 I 003553 ISRFB    0000 I 003551 ISRF1    0000 I 003552 ISRF2
0000 I 003545 ITEHIS   0000 I 003550 IIRTSS   0000 I 003565 LMENT    0000 I 003577 LS       0000 I 003621 LT
0000 I 003540 LTEPA    0000 I 003532 LTME     0000 I 003533 LTM1     0000 I 003534 LTM2     0000 I 003643 LU
0000 I 003440 N        0000 I 003674 NB       0000 I 003676 NB3      0000 I 003427 NCB      0000 I 003512 NCBC
0000 I 003430 NCD      0000 I 003463 NCDC     0000 I 003431 NCE      0000 I 003454 NCEC     0000 I 003675 NF
0000 I 003677 NE3      0000 I 003435 NOITER   0000 I 003566 NSG1     0000 I 003610 NSG2     0000 I 003632 NSG3
0000 I 003556 NUP      0000 R 002603 OMEGAX   0000 R 002750 OMEGAZ   0000 R 001604 P        0000 R 003466 PA
0000 R 003470 PB       0000 R 003665 PERELG   0000 R 003115 PHANGX   0000 R 003262 PHANGZ   0000 R 003576 PHIF
0000 R 003604 PHIG     0000 R 003620 PHIH     0000 R 003525 PHII     0000 R 003626 PHIII    0000 R 003642 PHIJ
0000 R 003544 PHIPA    0000 R 000226 PHIS     0000 R 000606 PHIT     0000 R 001166 PHIU     0000 R 003654 PHIW
0000 R 002114 PLUI     0000 R 003471 RA       0000 R 002247 RAD      0000 R 003472 RB       0000 R 003601 RPC
0000 R 003623 RBE      0000 R 003522 RHOA     0000 R 003521 RHOW     0000 R 003473 SAD      0000 R 003500 SEG
0000 R 003507 SF       0000 R 003505 SGT      0000 R 003611 SH       0000 R 003570 SIF      0000 R 003612 SIH
0000 R 003634 SIJ      0000 R 000322 SIS      0000 R 000702 SIT      0000 R 001262 SIU      0000 R 003633 SJ
0000 R 003564 SL       0000 R 003560 SOI      0000 R 000264 SS       0000 R 000644 ST       0000 R 003557 STRI
0000 R 001224 SU       0000 R 003452 TEN      0000 R 003574 TF       0000 R 003602 TG       0000 R 003616 TH
0000 R 003461 THEC     0000 R 003575 THETAF   0000 R 003603 THETAG   0000 R 003617 THETAH   0000 R 003524 THETAI
0000 R 003641 THETAJ   0000 R 000170 THETAS   0000 R 000550 THETAT   0000 R 001130 THETAU   0000 R 003653 THETAW
0000 R 003625 THETII   0000 R 003543 THETPA   0000 R 001356 THETVS   0000 R 001452 THETVT   0000 R 001546 THETVU
0000 R 003624 TII      0000 R 003453 TIM      0000 R 003513 TITLE    0000 R 003640 TJ       0000 R 003437 TMMAX
0000 R 003523 TNSONI   0000 R 003542 TPA      0000 R 000132 TS       0000 R 000512 TT       0000 R 001072 TU
0000 R 003652 TW       0000 R 001320 VCS      0000 R 001414 VCT      0000 R 001510 VCU      0000 R 003447 VELX
0000 R 003450 VELY     0000 R 003451 VEL2     0000 R 003517 WA       0000 R 003475 WAD      0000 R 003520 WB
0000 R 002241 WCG      0000 R 003502 WEG      0000 R 003507 WGT      0000 R 002263 WT       0000 R 003441 XCHAR
0000 R 003444 XCHRR    0000 R 003571 XF       0000 R 003605 XG       0000 R 003613 XH       0000 R 003561 XI
0000 R 003627 XII      0000 R 002164 XIX      0000 R 003635 XJ       0000 R 003671 XMAX     0000 R 003666 XMIN
0000 R 000000 XS       0000 R 000360 XT       0000 R 000740 XU       0000 R 003442 YCHAR    0000 R 003445 YCHRR
0000 R 003572 YF       0000 R 003606 YG       0000 R 003614 YH       0000 R 003562 YI       0000 R 003630 YII
0000 R 002173 YIY      0000 R 002636 YJ       0000 R 003672 YMAX     0000 R 003667 YMIN     0000 R 003530 YOLD
0000 R 003535 YOLS     0000 R 000036 YS       0000 R 000416 YT       0000 R 000776 YU       0000 R 003443 ZCHAR
0000 R 003446 ZCHRR    0000 R 003573 ZF       0000 R 003607 ZG       0000 R 003615 ZH       0000 R 003563 ZI
0000 R 003631 ZII      0000 R 002202 ZIZ      0000 R 003637 ZJ       0000 R 003673 ZMAX     0000 R 003670 ZMIN
0000 R 003622 ZOF      0000 R 003644 ZOG      0000 R 003527 ZOLD     0000 R 003536 ZOLS     0000 R 000074 ZS
0000 R 003660 ZSLS     0000 R 000454 ZT       0000 R 003662 ZTLT     0000 R 001034 ZU
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00100     1.    C                                                                        000000
00100     2.    C     STEADY STATE CONFIGURATIONS OF MOORED UMBILICAL CABLE              000000
00100     3.    C                                                                        000000
00101     4.          DIMENSION XS(30),YS(30),ZS(30),TS(30),THETAS(30),PHIS(30),SS(30),S 000000
00101     5.         1IS(30),XT(30),TT(30),ZT(30),TT(30),THETAT(30),PHIT(30),ST(30),SIT( 000000
00101     6.         230),XU(30),YU(30),ZU(30),TU(30),THETAU(30),PHIU(30),SU(30),SIU(30) 000000
00101     7.         3,VCS(30),THETVS(30),VC((30),THETVI(30),VCU(30),THETVU(30),P(200),P 000000
00101     8.         4LOT(40)                                                            000000
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00103      DIMENSION X1X(7),,1Y(7),Z1Z(7),DS(6),ECB(6),HL(6),DOUT(6),,CH(6),      000001
00103     1RAD(6),EXB(6),WT(6)                                                     000001
00104      DIMENSION AMPX(101),AMPZ(101),OMEGAX(101),OMEGAZ(101),PHANGX(101),     000001
00104     1PHANGZ(101)                                                             000001
00104 C                                                                            000001
00104 C                                                                            000001
00104 C    NCB IS NUMBER OF DIFFERENT DISTANCES(HORIZONTAL DISTANCE BETWEEN       000001
00104 C       ANCHOR AND SHIP) TO BE TESTED FOR ALL BUOY CONFIGURATIONS           000001
00104 C    NCD IS NUMBER OF DIFFERENT BUOY CONFIGURATIONS TO BE TESTED            000001
00104 C    IPLOT=1 IF 3D PLOT IS WANTED,  =0 IF 3D PLOT IS NOT WANTED             000001
00104 C                                                                            000001
00105      READ 12,NCB,NCD,NCE,IDYMIC,IPLOT                                        000001
00114   12 FORMAT(5I10)                                                            000012
00115   11 FORMAT(4I10)                                                            000012
00115 C                                                                            000012
00115 C    EPSLNA IS MAXIMUM CLOSURE ERROR AT SHIP IN FEET                        000012
00115 C    NOITER IS THE MAXIMUM NUMBER OF ITERATIONS BEFORE TERMINATION          000012
00115 C       FOR EACH CASE                                                        000012
00115 C                                                                            000012
00116      READ 8,EPSLNA,NOITER                                                    000012
00122    8 FORMAT(F10.2,I10)                                                       000020
00123    9 FORMAT(F10.2)                                                           000020
00124   10 FORMAT(2F10.2)                                                          000020
00124 C                                                                            000020
00124 C    BETA IS SHIP HEADING ANGLE (FOLLOWING SEAS=0 DEG,                      000020
00124 C       BEAM SEAS=90 DEG, HEAD SEAS=180 DEG)                                000020
00124 C    TMMAX IS DESIRED LENGTH OF TIME FOR DYNAMIC CALCULATIONS               000020
00124 C    AMPX AND AMPZ ARE AMPLITUDES                                           000020
00124 C    PHANGX AND PHANGZ ARE PHASE ANGLES                                     000020
00124 C    OMEGAX AND OMEGAZ ARE FREQUENCIES                                      000020
00124 C                                                                            000020
00125      IF(IDYMIC.EQ.0) GO TO 32                                                000020
00127      READ 26,BETA,TMMAX                                                      000022
00133   26 FORMAT(2F10.5)                                                          000033
00134      DO 36 N=1,101                                                           000033
00137      READ 33,AMPZ(N),OMEGAZ(N),PHANGZ(N)                                     000033
00144   36 CONTINUE                                                                000042
00146      IF(BETA.EQ.0..OR.BETA.EQ.180.) GO TO 35                                 000042
00150      DO 34 N=1,101                                                           000057
00153      READ 33,AMPX(N),OMEGAX(N),PHANGX(N)                                     000057
00160   34 CONTINUE                                                                000066
00162   33 FORMAT(3F10.4)                                                          000066
00163      GO TO 37                                                                000066
00164   35 CONTINUE                                                                000072
00165      DO 41 N=1,101                                                           000072
00170      AMPX(N)=0.                                                              000072
00171      OMEGAX(N)=0.                                                            000072
00172      PHANGX(N)=0.                                                            000073
00173   41 CONTINUE                                                                000076
00175   37 CONTINUE                                                                000076
00176   32 CONTINUE                                                                000076
00176 C                                                                            000076
00176 C    3D PLOT AXIS LABELS                                                     000076
00176 C                                                                            000076
00177      READ 24,XCHAR,YCHAR,ZCHAR,XCHRR,YCHRR,ZCHRR,VELX,VELY,,CLZ,TI ,,TIM    000076
00214   24 FORMAT(12A6)                                                            000114
00215      NCEC=0                                                                  000114
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00216      28 CONTINUE                                                              000116
00217         NCEC=NCEC+1                                                           000116
00217    C                                                                          000116
00217    C                                                                          000116
00217    C    CX,D,THEC,AND CZ DESCRIBE THE CURRENT MAGNITUDE AND DIRECTION         000116
00220         READ 21,CX,D,CY,CD,THEC                                               000120
00227      21 FORMAT(5F10.9)                                                        000131
00227    C                                                                          000131
00227    C    CONVERT THEC TO RADIANS                                               000131
00227    C                                                                          000131
00230         THEC=THEC*0.01745                                                     000131
00231         IF(CX.EQ.0.) GO TO 22                                                 000134
00233         IF(CY.EQ.0.) GO TO 22                                                 000136
00235         IF(D.EQ.0.) GO TO 22                                                  000140
00237         CZ=(ALOG(CX/CY))/D                                                    000142
00240         GO TO 23                                                              000152
00241      22 CONTINUE                                                              000154
00242         CZ=0.                                                                 000154
00243      23 CONTINUE                                                              000155
00244         NCDC=0                                                                000155
00245      38 CONTINUE                                                              000156
00246         NCDC=NCDC+1                                                           000156
00246    C                                                                          000156
00246    C    IBUOY IS TOTAL NUMBER OF BUOYS (0,1,OR 2)                             000156
00246    C    EA IS EXCESS BUOYANCY OF FIRST BUOY (DISPLACEMENT MINUS AIR WT)       000156
00246    C    PA IS FIRST BUOY DENSITY IN LBS PER CUBIC FOOT                        000156
00246    C    RA IS FIRST BUOY RADIUS IN FEET                                       000156
00246    C    EB IS EXCESS BUOYANCY OF SECOND BUOY(DISPLACEMENT MINUS AIR WT)       000156
00246    C    PB IS SECOND BUOY DENSITY IN LBS PER CUBIC FOOT                       000156
00246    C    RB IS SECOND BUOY RADIUS IN FEET ( =0 IF NO BUOYS OR 1 BUOY)          000156
00246    C                                                                          000156
00247         READ 40,IBUOY,EA,PA,EB,PB                                             000160
00256      40 FORMAT(I10,4F10.2)                                                    000171
00257         RA=CBRT((EA/(64.4-PA))*(3./(4.*3.14159)))                             000171
00260         RB=CBRT((EB/(64.4-PB))*(3./(4.*3.14159)))                             000203
00260    C                                                                          000203
00260    C    CHARACTERISTICS OF EACH CABLE SEGMENT                                 000203
00260    C                                                                          000203
00260    C    S IS CABLE LENGTH IN FEET                                             000203
00260    C    E IS MODULUS OF ELASTICITY IN LBS PER SQUARE INCH                     000203
00260    C    W IS WEIGHT IN WATER IN LBS PER FOOT                                  000203
00260    C    D IS OUTSIDE DIAMETER IN INCHES                                       000203
00260    C    DS IS STRENGTH MEMBER DIAMETER IN INCHES                              000203
00260    C                                                                          000203
00260    C    SUFFIX AD REFERS TO SECTION OF CABLE FROM ANCHOR TO FIRST BUOY        000203
00260    C       (OR SHIP IF NO BUOYS)                                              000203
00260    C    SUFFIX EG REFERS TO SECTION OF CABLE FROM FIRST BUOY TO SECOND        000203
00260    C       BUOY (OR SHIP IF NO SECOND BUOY)                                   000203
00260    C          (SET ALL PARAMETERS EQUAL TO ZERO IF NO BUOYS)                  000203
00260    C    SUFFIX GT REFERS TO SECTION OF CABLE FROM SECOND BUOY TO SHIP         000203
00260    C       (SET ALL PARAMETERS EQUAL TO ZERO IF THERE ARE NO BUOYS OR ONE)    000203
00260    C                                                                          000203
00261         READ 20,SAD,EAD,WAD,DAD,DSAD                                          000215
00270         READ 20,SEG,EEG,WEG,DEG,DSEG                                          000226
00277         READ 20,SGT,EGT,WGT,DGT,DSGT                                          000237
00306      20 FORMAT(5F10.3)                                                        000250
00307         NCBC=0                                                                000250
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00310        39 CONTINUE                                                           000252
00311           NCUC=NCUC+1                                                        000252
00312           EAU=EAU*144.                                                       000254
00313           EEU=EEU*144.                                                       000257
00314           EGT=EGT*144.                                                       000262
00314     C                                                                        000262
00314     C     3D PLOT TITLE                                                      000262
00314     C                                                                        000262
00315           READ 24,TITLE                                                      000265
00315     C                                                                        000265
00315     C     G IS HORIZONTAL DISTANCE FROM SHIP TO ANCHOR IN FEET               000265
00315     C     H IS WATER DEPTH AT ANCHOR IN FEET                                 000265
00315     C     ICASE IS CASE NUMBER                                               000265
00315     C                                                                        000265
00320           READ 25,G,H,ICASE                                                  000272
00325        25 FORMAT(2F10.2,I10)                                                 000301
00325     C                                                                        000301
00325     C     WA IS FIRST BUOY WEIGHT IN LBS                                     000301
00325     C     WB IS SECOND BUOY WEIGHT IN LBS ( =0 IF NO BUOYS OR 1 BUOY)        000301
00325     C                                                                        000301
00326           WA=(4./3.)*3.14159*RA**3*PA                                        000301
00327           WB=(4./3.)*3.14159*RB**3*PB                                        000310
00327     C                                                                        000310
00327     C     RHOW IS DENSITY OF WATER IN SLUGS PER CUBIC FOOT                   000310
00327     C     RHOA IS DENSITY OF AIR IN SLUGS PER CUBIC FOOT                     000310
00327     C                                                                        000310
00330           RHOW=1.998                                                         000317
00331           RHOA=0.00238                                                       000321
00331     C                                                                        000321
00331     C     SPECIFY TENSION AND ANGLES ESTIMATE AND OTHER PARAMETERS AT ANCHOR 000321
00331     C                                                                        000321
00332        31 CONTINUE                                                           000323
00333           TNSON1=64.4*((4./3.)*3.14159*((RA**3)+(RB**3)))-(WB+WA)            000323
00334           IF(IBUOY.EQ.0) TNSON1=3000.0                                       000332
00336           THETA1=0.                                                          000336
00337           PHI1=45.0*0.01745                                                  000337
00337     C                                                                        000337
00337     C     SPECIFY INITIAL VALUES OF CONSTANTS                                000337
00337     C                                                                        000337
00340           HOOLD=1000.                                                        000341
00341           ZOLD=20000.                                                        000343
00342           YOLD=1000.                                                         000345
00343           ISHCT=1                                                            000346
00344           LTME=0                                                             000350
00345           LTM1=0                                                             000351
00346           LTM2=0                                                             000352
00347           YOLS=YOLD                                                          000353
00350           ZOLS=ZOLD                                                          000354
00351           ETA=10.*TNSON1                                                     000355
00352           LTEPA=0                                                            000360
00353           DELTO=TNSON1                                                       000361
00354           TPA=TNSON1                                                         000363
00355           THETPA=THETA1                                                      000364
00356           PHIPA=PHI1                                                         000366
00357           IIERTS=0                                                           000367
00360           IDELTA=0                                                           000370
00361           ETAU=ETA                                                           000371
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      ITRTSS=0
      ISHF1=0
      ISHF2=0
      ISHFB=0
      IF(IBUOY.EQ.1.AND.IATCH1.EQ.1) ISHF1=1
      IF(IBUOY.EQ.2.AND.IATCH2.EQ.1) ISHF2=1
      IF(ISHF1.EQ.1.OR.ISHF2.EQ.1) ISHFU=1
   30 CONTINUE
      ITERTS=ITERTS+1
      NUP=1
C
C     CALCULATE TENSION AND CONFIGURATION ALONG CABLE FROM ANCHOR TO
C        FIRST BUOY (OR SHIP IF NO BUOYS)
C
      STHI=0
      SOI=0
      XI=0
      YI=0
      ZI=0
      SL=SAD
      XIX(1)=0.
      YIY(1)=0.
      ZIZ(1)=0.
      LMENT=2
      NSG1=3
      IF(IBUOY.EQ.0) NSG1=6
      CALL CONFIG(EAD,DAD,DSAD,WAD,H,STHI,SOI,XI,YI,ZI,THSONI,THETAI,PHI
     1I,SL,RHOW,NUP,SF,SIF,XF,YF,ZF,TF,THETAF,PHIF,SS,SIS,XS,YS,ZS,TS,TH
     2ETAS,PHIS,VCS,THETVS,LS,CX,D,THEC,C2,CD,NSG1,XIX,YIY,ZIZ,LMENT,DLI
C
C     CHECK TO SEE IF THERE IS AT LEAST ONE BUOY
C
      IF(IBUOY.EQ.0) GO TO 491
      IF(ISHF1.EQ.1) GO TO 491
C
C
C     CALCULATE TENSION,ANGLES,AND POSITION OF FIRST BUOY
C
      CALL SUBSHF(IRROR,NUP,A,RA,RHOW,TF,THETAF,PHIF,XF,YF,ZF,G,I,RHC,T
     1G,THETAG,PHIG,XG,YG,ZG,CX,D,THEC,C2,CB)
      IF(IRROR.EQ.0) GO TO 48
      PRINT 46
   46 FORMAT(1H1,'SUBSURFACE BUOY CALCULATIONS ARE NOT WORKING')
      GO TO  999
   48 CONTINUE
C
C     CALCULATE TENSION AND CONFIGURATION ALONG CABLE FROM FIRST BUOY
C        TO SECOND BUOY (OR SHIP IF NO SECOND BUOY)
C
      NUP=1
      SL=SEG
      NSG2=1
      IF(IBUOY.EQ.1) NSG2=3
      CALL CONFIG(EEG,DEG,DSEG,WEG,H,SF,SIF,XG,YG,ZG,TG,THETAG,PHIG,SL,R
     1HOW,NUP,SH,SIH,XH,YH,ZH,TH,THETAH,PHIH,ST,SIT,XT,YT,ZT,TT,THETAT,P
     2HIT,VCT,THETVT,LT,CX,D,THEC,C2,CD,NSG2,XIX,YIY,ZIZ,LMENT,DLI
      ZOLD=ZH
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00440        IF(ISHF1.EQ.0) GO TO 49                                      000722
00442        ITHTSS=ITHTSS+1                                              000724
00443     49 CONTINUE                                                     000730
00444        ZOF=ABS(ZH-H)                                                000730
00444  C                                                                  000730
00444  C                                                                  000730
00444  C     CHECK IF THERE ARE TWO BUOYS                                 000730
00444  C                                                                  000730
00445        IF(IBUOY.EQ.0.OR.IBUOY.EQ.1) GO TO 492                       000733
00445  C                                                                  000733
00445  C     CALCULATE THE TENSION,ANGLES,AND POSITION OF SECOND BUOY     000733
00445  C                                                                  000733
00447        CALL SUBSHF(IRROR,NUP,U,RB,RHOW,TH,THETAH,PHIH,XH,YH,ZH,G,H,RHE,T 000745
00447       1II,THETII,PHIII,XII,YII,ZII,CX,D,THEC,CZ,CB)               000745
00450        IF(IRROR.EQ.0) GO TO 58                                      001000
00452        PRINT 46                                                     001002
00454        GO TO 999                                                    001006
00455     58 CONTINUE                                                     001010
00455  C                                                                  001010
00455  C     CALCULATE TENSION AND CONFIGURATION ALONG CABLE FROM SECOND BUOY 001010
00455  C         TO SHIP                                                  001010
00455  C                                                                  001010
00456        NUP=1                                                        001010
00457        SL=SGT                                                       001011
00460        NSG3=2                                                       001013
00461        CALL CONFIG(EGT,DGT,DSGT,WGT,H,SH,S1H,XII,YII,ZII,TII,THETII,PHIII 001015
00461       1,SL,RHOW,NUP,SJ,SIJ,XJ,YJ,ZJ,TJ,THETAJ,PHIJ,SU,S1U,XU,YU,ZU,TU,THE 001015
00461       2TAU,PHIU,VCU,THETVU,LU,CX,D,THEC,CZ,CB,NSG3,X1X,Y1Y,Z1Z,LMENT,DL) 001015
00462        ZOLD=ZJ                                                      001075
00463        IF(ISHF2.EQ.0) GO TO 59                                      001077
00465        ITHTSS=ITHTSS+1                                              001101
00466     59 CONTINUE                                                     001105
00467        ZOG=ABS(ZJ-H)                                                001105
00467  C                                                                  001105
00470        GO TO 493                                                    001110
00471    491 CONTINUE                                                     001112
00472        SJ=SF                                                        001112
00473        SIJ=SIF                                                      001113
00474        XJ=XF                                                        001115
00475        YJ=YF                                                        001117
00476        ZJ=ZF                                                        001121
00477        TJ=TF                                                        001123
00500        THETAJ=THETAF                                                001125
00501        PHIJ=PHIF                                                    001127
00502        GO TO 493                                                    001131
00503    492 CONTINUE                                                     001133
00504        SJ=SH                                                        001133
00505        SIJ=SIH                                                      001134
00506        XJ=XH                                                        001136
00507        YJ=YH                                                        001140
00510        ZJ=ZH                                                        001142
00511        TJ=TH                                                        001144
00512        THETAJ=THETAH                                                001146
00513        PHIJ=PHIH                                                    001150
00514    493 CONTINUE                                                     001153
00515        HM1A=H-1.2*HA                                                001153
00516        HM2A=H-1.2*HB                                                001157
```

```
00517          IF(ISHF1.EQ.1) H=HH1A                                              001164
00521          IF(ISHF2.EQ.1) H=HH2A                                              001171
00523          ERS=SQRT((XJ)**2+(YJ-G)**2+(ZJ-H)**2)                              001201
00524          HH1U=HH1A+1.2*HA                                                   001217
00525          HH2U=HH2A+1.2*HB                                                   001222
00526          IF(ISHF1.EQ.1) H=HH1B                                              001225
00530          IF(ISHF2.EQ.1) H=HH2B                                              001232
00532          TOLD=YJ                                                            001237
00533          ZOLD=ZJ                                                            001241
00534          IF(ERS.LE.EPSLNA) GO TO 550                                        001243
00536          IF(ERS.GT.200000.) GO TO 550                                       001247
00540          IF(ITERTS.GE.NOITER) GO TO 550                                     001251
00540    C                                                                        001253
00540    C     CORRECT TENSION AND ANGLES AT ANCHOR                               001253
00540    C                                                                        001253
00542          HH1A=H-1.2*HA                                                      001257
00543          HH2A=H-1.2*HB                                                      001262
00544          IF(ISHF1.EQ.1) H=HH1A                                              001265
00546          IF(ISHF2.EQ.1) H=HH2A                                              001272
00550          CALL TENCOR(EPSLNA,G,H,ETA,DELTO,TPA,THETPA,PHIPA,XJ,YJ,ZJ,TW,THET 001277
00550         1AW,PHIW,ETAN,DELTN,LTEPA,ITERTS)                                   001277
00551          HH1U=HH1A+1.2*HA                                                   001323
00552          HH2U=HH2A+1.2*HB                                                   001326
00553          IF(ISHF1.EQ.1) H=HH1B                                              001331
00555          IF(ISHF2.EQ.1) H=HH2B                                              001336
00557          ETA=ETAN                                                           001343
00560          DELTO=DELTN                                                        001345
00561          TPA=TW                                                             001347
00562          THETPA=THETAW                                                      001351
00563          PHIPA=PHIW                                                         001353
00564          TNSON1=TW                                                          001355
00565          THETA1=THETAW                                                      001356
00566          PHI1=PHIW                                                          001357
00567          GO TO 30                                                           001360
00570      550 CONTINUE                                                           001362
00571      560 CONTINUE                                                           001362
00571    C                                                                        001362
00571    C                                                                        001362
00571    C                                                                        001362
00571    C                                                                        001362
00571    C                                                                        001362
00571    C                                                                        001362
00571    C     PRINTED OUTPUT                                                     001362
00571    C                                                                        001362
00571    C                                                                        001362
00572          EAD=EAU/144.                                                       001362
00573          EEG=EEG/144.                                                       001364
00574          EGT=EGT/144.                                                       001367
00576          PRINT 109,ICASE                                                    001372
00600      109 FORMAT(1H1,'CASE NUMBER',I4)                                       001377
00601          IF(IBUOY.EQ.0) GO TO 111                                           001377
00603          PRINT 110                                                          001401
00605      110 FORMAT(1H ,'PARAMETERS OF CABLE FROM ANCHOR TO FIRST BUOY')        001405
00606          GO TO 113                                                          001405
00607      111 CONTINUE                                                           001407
00610          PRINT 112                                                          001407
00612      112 FORMAT(1H ,'PARAMETERS OF CABLE FROM ANCHOR TO SHIP')              001413
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00613        113 CONTINUE                                                                001413
00614            PRINT 120,SAD,LAD,WAD,DAD,DSAD                                          001413
00623        120 FORMAT(1H ,'LENGTH=',F6.1,' FEET     E=',E8.4,' PSI     WT PER FT=',   001423
00623           1F8.5,' LBS     OD=',F8.4,' INCHES     STR MEM DIAM=',F8.4,' INCHES')   001423
00624            IF(IBUOY.EQ.0) GO TO 195                                                001423
00626            IF(IBUOY.EQ.1) GO TO 161                                                001425
00630            PRINT 160                                                               001430
00632        160 FORMAT(//1H ,'PARAMETERS OF CABLE FROM FIRST BUOY TO SECOND BUOY')      001434
00633            GO TO 163                                                               001434
00634        161 CONTINUE                                                                001436
00635            PRINT 162                                                               001436
00637        162 FORMAT(//1H ,'PARAMETERS OF CABLE FROM FIRST BUOY TO SHIP')             001442
00640        163 CONTINUE                                                                001442
00641            PRINT 120,SEG,LEG,WEG,DEG,DSEG                                          001442
00650            IF(IBUOY.EQ.1) GO TO 195                                                001452
00652            PRINT 170                                                               001455
00654        170 FORMAT(//1H ,'PARAMETERS OF CABLE FROM SECOND BUOY TO SHIP')            001461
00655            PRINT 120,SGT,LGT,WGT,DGT,DSGT                                          001461
00655      C                                                                             001461
00664        195 CONTINUE                                                                001473
00665            PRINT 176                                                               001473
00667        176 FORMAT(//)                                                              001476
00670            ESN=ERS                                                                 001476
00671            IF(ISHF1.EQ.1) ERS=ZOF                                                  001500
00673            IF(ISHF2.EQ.1) ERS=ZOG                                                  001505
00675            PRINT 180,ERS                                                           001516
00700        180 FORMAT(//1H ,'POSITION OF SHIP IS ACCURATE TO ',F6.1,' FEET')           001523
00701            ERS=ESN                                                                 001523
00702            PRINT 176                                                               001525
00704            IF(IBUOY.EQ.0) GO TO 230                                                001531
00706            PRINT 210                                                               001533
00710        210 FORMAT(//1H ,'PARAMETERS OF FIRST SPHERICAL BUOY')                      001537
00711            PRINT 212                                                               001537
00713        212 FORMAT(1H ,36X,'(SUBSURFACE BUOY)')                                     001543
00714            ZSLS=H-ZS(LS)                                                           001543
00715            PRINT 226,EA,ZSLS                                                       001547
00721        226 FORMAT(1H ,'EXCESS BUOYANCY=',F8.1,' POUNDS     BUOY DEPTH=',F10.1     001555
00721           1,' FEET')                                                               001555
00722            PRINT 220,RA,WA,PA                                                      001555
00727        220 FORMAT(1H ,'RADIUS=',F7.2,' FEET     WEIGHT=',F8.1,' POUNDS     DEN   001564
00727           1SITY=',F7.2,' LBS PER CUB FT')                                         001564
00730            DMA=2.*RA                                                               001564
00731            IF(IBUOY.EQ.1) GO TO 230                                                001567
00733            PRINT 240                                                               001572
00735        240 FORMAT(//1H ,'PARAMETERS OF SECOND SPHERICAL BUOY')                     001576
00736            PRINT 212                                                               001576
00740            ZTLT=H-ZT(LT)                                                           001602
00741            PRINT 226,EB,ZTLT                                                       001606
00745            PRINT 220,RB,WB,PB                                                      001614
00752            DMB=2.*RB                                                               001623
00753            IF(LTM2.EQ.1) GO TO 243                                                 001626
00755            GO TO 244                                                               001631
00756        243 CONTINUE                                                                001633
00757        244 CONTINUE                                                                001633
00760            PRINT 176                                                               001633
00762        230 CONTINUE                                                                001637
00763            GG=G                                                                    001637
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      IF(ISHF1.EQ.1) GO TO 261                                        001640
      IF(ISHF2.EQ.1) GO TO 262                                        001643
      GO TO 263                                                       001646
  261 CONTINUE                                                        001650
      G=SQRT((XT(LT))**2+(YT(LT))**2)                                 001650
      GO TO 263                                                       001662
  262 CONTINUE                                                        001664
      G=SQRT((XU(LU))**2+(YU(LU))**2)                                 001664
  263 CONTINUE                                                        001677
      PRINT 250,G                                                     001677
      G=GG                                                            001703
  250 FORMAT(//1H ,'HORIZONTAL DISTANCE FROM ANCHOR TO SHIP =',F9.1,' FE 001705
     1ET')                                                            001705
      PRINT 260,H                                                     001705
  260 FORMAT(1H ,'WATER DEPTH AT ANCHOR=',F9.1,' FEET')               001712
      PRINT 270,ITERTS                                                001712
  270 FORMAT(///1H ,'NUMBER OF ITERATIONS =',I3)                      001717
      PRINT 280,DELIN                                                 001717
  280 FORMAT(1H ,'DELTA OF ITERATION PROCESS=',F12.3,' AT ANCHOR')    001724
      PRINT 176                                                       001724
C                                                                     001724
  342 CONTINUE                                                        001730
      PRINT 350                                                       001736
  350 FORMAT(1H1,'ALL LENGTHS ARE FEET,TENSION IS LBS,ANGLES ARE DEGREES 001745
     1,AND CURRENT IS KNOTS')                                         001745
      PRINT 176                                                       001745
      PRINT 176                                                       001751
      PRINT 360                                                       001755
  360 FORMAT(5X,'LENGTH',3X,'ELONG LNTH',3X,'PCT ELONG',8X,'X',11X,'Y',1 001761
     11X,'Z',8X,'TENSION',7X,'THETA',8X,'PHI',6X,'CURRENT',5X,'CUR DIR') 001761
      PRINT 361                                                       001761
  361 FORMAT(///1H ,61X,'ANCHOR'/)                                    001770
C     PERELG IS PERCENT ELONGATION OF THE CABLE((TOTAL ELONGATED LENGTH 001770
C        MINUS TOTAL UNSTRETCHED LENGTH) DIVIDED BY UNSTRETCHED LENGTH) 001770
      DO 370 N=1,LS                                                   001770
      PERELG=0.                                                       001770
      IF(SIS(N).EQ.0.) GO TO 362                                      001770
      PERELG=(SS(N)-SIS(N))/SIS(N)                                    001772
  362 CONTINUE                                                        001777
      PRINT 380,SIS(N),SS(N),PERELG,XS(N),YS(N),ZS(N),TS(N),THETAS(N),PH 001777
     1IS(N),VCS(N),THETVS(N)                                          001777
  370 CONTINUE                                                        002016
  380 FORMAT(2F12.1,F12.3,4F12.1,4F12.2)                              002016
      IF(IBUOY.EQ.0) GO TO 421                                        002016
      PRINT 390                                                       002020
  390 FORMAT(/60X,'FIRST BUOY'/)                                      002027
      DO 400 N=1,LT                                                   002027
      PERELG=(ST(N)-SIT(N))/SIT(N)                                    002027
      PRINT 380,SIT(N),ST(N),PERELG,XT(N),YT(N),ZT(N),TT(N),THETAT(N),PH 002032
     1IT(N),VCT(N),THETVT(N)                                          002032
  400 CONTINUE                                                        002052
      IF(IBUOY.EQ.1) GO TO 421                                        002052
      PRINT 410                                                       002055
  410 FORMAT(/59X,'SECOND BUOY'/)                                     002064
      DO 422 N=1,LU                                                   002064
      PERELG=(SU(N)-SIU(N))/SIU(N)                                    002064
      PRINT 380,SIU(N),SU(N),PERELG,XU(N),YU(N),ZU(N),TU(N),THETAU(N),PH 002067
```

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     1U(N),VCU(N),THET,U(N)                                          002067
 420 CONTINUE                                                        002110
 441 CONTINUE                                                        002110
     PRINT 430                                                       002110
 430 FORMAT(/62X,'SHIP')                                             002113
     IF(IPLOT.EQ.0) GO TO 999                                        002113
     PRINT 419                                                       002115
 419 FORMAT(1H1)                                                     002121
C                                                                    002121
C    3D PLOT OF POSITION OF SYSTEM                                   002121
C                                                                    002121
     CALL MODE3D(P,0)                                                002121
     CALL SETSMG(P,93,0.)                                            002125
     CALL BEGIN3(PLOT)                                               002132
     PLOT(1)=-4000.                                                  002135
     PLOT(2)=14000.                                                  002137
     PLOT(3)=0.                                                      002141
     PLOT(4)=18000.                                                  002142
     PLOT(5)=0.                                                      002144
     PLOT(6)=10000.                                                  002145
     PLOT(9)=0.                                                      002146
     PLOT(25)=2.                                                     002147
     PLOT(26)=2.                                                     002151
     PLOT(29)=1.                                                     002152
     PLOT(30)=1.                                                     002154
     PLOT(31)=1.                                                     002155
     PLOT(32)=1.                                                     002156
     CALL SETSMG(P,14,0.)                                            002157
     CALL OBJCTG(P,200.,200.,3600.,2900.)                            002164
     CALL SUBJ3D (P,PLOT)                                            002173
     CALL GRPH3D(P,PLOT,XS,YS,ZS,LS,6,XCHAR,6,YCHAR,6,ZCHAR,6,TITLE) 002177
     IF(IBUOY.EQ.0) GO TO 510                                        002217
     CALL PNT3D(P,PLOT,XT,YT,ZT,LT)                                  002221
     CALL SHOE3D(P,PLOT,LT,XT,YT,ZT,1,0)                             002231
     IF(IBUOY.EQ.1) GO TO 510                                        002243
     CALL PNT3D(P,PLOT,XU,YU,ZU,LU)                                  002246
     CALL SHOE3D(P,PLOT,LU,XU,YU,ZU,1,0)                             002256
 510 CONTINUE                                                        002271
     CALL PAGEG(P,0,1,1)                                             002271
C                                                                    002271
C    OTHER PLOTS                                                     002271
C                                                                    002271
     XMIN=0.                                                         002276
     YMIN=0.                                                         002277
     ZMIN=0.                                                         002300
     XMAX=1.                                                         002301
     YMAX=1.                                                         002303
     ZMAX=1.                                                         002304
     DO 630 N=1,LS                                                   002320
     IF(XS(N).LT.XMIN) XMIN=XS(N)                                    002320
     IF(XS(N).GE.XMAX) XMAX=XS(N)                                    002325
     IF(YS(N).GE.YMAX) YMAX=YS(N)                                    002333
     IF(ZS(N).GE.ZMAX) ZMAX=ZS(N)                                    002341
 630 CONTINUE                                                        002351
     IF(IBUOY.EQ.0) GO TO 660                                        002351
     DO 640 N=1,LT                                                   002356
     IF(XT(N).LT.XMIN) XMIN=XT(N)                                    002356
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01251          IF(XT(N).GE.XMAX) XMAX=XT(N)                          002363
01253          IF(YT(N).GE.YMAX) YMAX=YT(N)                          002371
01255          IF(ZT(N).GE.ZMAX) ZMAX=ZT(N)                          002377
01257      640 CONTINUE                                              002407
01261          IF(IBUOY.EQ.1) GO TO 660                              002407
01263          DO 650 N=1,LU                                         002415
01266          IF(XU(N).LE.XMIN) XMIN=XU(N)                          002415
01270          IF(XU(N).GE.XMAX) XMAX=XU(N)                          002422
01272          IF(YU(N).GE.YMAX) YMAX=YU(N)                          002430
01274          IF(ZU(N).GE.ZMAX) ZMAX=ZU(N)                          002436
01276      650 CONTINUE                                              002447
01300      660 CONTINUE                                              002447
01301          CALL SUBJEG(P,XMIN,YMIN,XMAX,YMAX)                    002447
01302          CALL GRAPHG(P,0,XS,YS,6,XCHAR,6,YCHAR,6,TITLE)        002455
01303          CALL POINTG(P,LS,XS,YS)                               002471
01304          CALL LINESG(P,LS,XS,YS)                               002477
01305          IF(IBUOY.EQ.0) GO TO 600                              002505
01307          CALL POINTG(P,LT,XT,YT)                               002507
01310          CALL LINESG(P,LT,XT,YT)                               002515
01311          IF(IBUOY.EQ.1) GO TO 600                              002523
01313          CALL POINTG(P,LU,XU,YU)                               002526
01314          CALL LINESG(P,LU,XU,YU)                               002534
01315      600 CONTINUE                                              002543
01316          CALL PAGEG(P,0,1,1)                                   002543
01317          CALL SUBJEG(P,YMIN,ZMIN,YMAX,ZMAX)                    002550
01320          CALL GRAPHG(P,0,YS,ZS,6,YCHAR,6,ZCHAR,6,TITLE)        002557
01321          CALL POINTG(P,LS,YS,ZS)                               002573
01322          CALL LINESG(P,LS,YS,ZS)                               002601
01323          IF(IBUOY.EQ.0) GO TO 610                              002607
01325          CALL POINTG(P,LT,YT,ZT)                               002611
01326          CALL LINESG(P,LT,YT,ZT)                               002617
01327          IF(IBUOY.EQ.1) GO TO 610                              002625
01331          CALL POINTG(P,LU,YU,ZU)                               002630
01332          CALL LINESG(P,LU,YU,ZU)                               002636
01333      610 CONTINUE                                              002645
01334          CALL PAGEG(P,0,1,1)                                   002645
01335          CALL SUBJEG(P,XMIN,ZMIN,XMAX,ZMAX)                    002652
01336          CALL GRAPHG(P,0,XS,ZS,6,XCHAR,6,ZCHAR,6,TITLE)        002661
01337          CALL POINTG(P,LS,XS,ZS)                               002675
01340          CALL LINESG(P,LS,XS,ZS)                               002703
01341          IF(IBUOY.EQ.0) GO TO 620                              002711
01343          CALL POINTG(P,LT,XT,ZT)                               002713
01344          CALL LINESG(P,LT,XT,ZT)                               002721
01345          IF(IBUOY.EQ.1) GO TO 620                              002727
01347          CALL POINTG(P,LU,XU,ZU)                               002732
01350          CALL LINESG(P,LU,XU,ZU)                               002740
01351      620 CONTINUE                                              002747
01352          CALL PAGEG(P,0,1,1)                                   002747
01353          CALL EXITG(P)                                         002754
01354      999 CONTINUE                                              002760
01354    C                                                           002760
01354    C                                                           002760
01354    C                                                           002760
01354    C     DYNAMIC SIMULATION IF IDYMIC=1                        002760
01354    C                                                           002760
01355          IF(IDYMIC.NE.1) GO TO 1100                            002760
01357          DO 1030 N=1,NSGI                                      003022
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01302           DS(N)=USAD/12.                                          003022
01303           DOUT(N)=DAD/12.                                         003023
01304           ECB(N)=EAD*144.                                         003025
01305           WCB(N)=WAD                                              003027
01306      1000 CONTINUE                                                003032
01370           IF(IBUOY.EQ.0) GO TO 1030                               003032
01372           NB=NSG1+1                                               003034
01373           NE=NSG1+NSG2                                            003037
01374           DO 1010 N=NB,NE                                         003042
01377           DS(N)=USEG/12.                                          003047
01400           DOUT(N)=DEG/12.                                         003050
01401           ECB(N)=EEG*144.                                         003052
01402           WCB(N)=WEG                                              003054
01403      1010 CONTINUE                                                003057
01405           IF(IBUOY.EQ.1) GO TO 1030                               003057
01407           NB3=NE+1                                                003062
01410           NE3=NE+NSG3                                             003065
01411           DO 1020 N=NB3,NE3                                       003070
01414           DS(N)=USGT/12.                                          003075
01415           DOUT(N)=DGT/12.                                         003076
01416           ECB(N)=EGT*144.                                         003100
01417           WCB(N)=WGT                                              003102
01420      1020 CONTINUE                                                003110
01422      1030 CONTINUE                                                003110
01423           DO 1040 N=1,6                                           003110
01426           RAD(N)=0.                                               003110
01427           EXB(N)=0.                                               003110
01430           WT(N)=0.                                                003111
01431      1040 CONTINUE                                                003113
01433           IF(IBUOY.EQ.0) GO TO 1050                               003113
01435           RAD(4)=RA                                               003115
01436           EXB(4)=EA                                               003117
01437           WT(4)=WA                                                003121
01440           IF(IBUOY.EQ.1) GO TO 1050                               003123
01442           RAD(5)=RB                                               003126
01443           EXB(5)=EB                                               003130
01444           WT(5)=WB                                                003132
01445      1050 CONTINUE                                                003135
01446           CALL DYMICS(XIX,YIY,ZIZ,DS,ECB,DL,G,H,CX,CZ,CD,D,THEC,  003135
01446          1DOUT,RHOW,WCB,IBUOY,RAD,EXB,WT,TMMAX,XCHAR,YCHAR,ZCHAR,XCHRR  003135
01446          2,YCHRR,ZCHRR,VELX,VELY,VELZ,TEN,TIM,TITLE,IPLOT,AMPX,AMPZ,OMEGAX,  003135
01446          3OMEGAZ,PHANGX,PHANGZ)                                   003135
01447      1100 CONTINUE                                                003207
01447     C                                                             003207
01447     C     GO BACK TO BEGINNING OF PROGRAM TO READ IN NEW VALUES FOR NEXT  003207
01447     C        CASE OR END PROGRAM                                  003207
01447     C                                                             003207
01450           IF(NCBC.LT.NCB) GO TO 39                                003207
01452           IF(NCDC.LT.NCD) GO TO 38                                003212
01454           IF(NCEC.LT.NCE) GO TO 28                                003216
01456           STOP                                                    003222
01457           END                                                     003226

   END OF COMPILATION:       NO DIAGNOSTICS.
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FOR,SI CONFIG,CONFIG
FOR UE28-01/11/77-04:57:16 (,0)

   SUBROUTINE CONFIG    ENTRY POINT 001277

   STORAGE USED: CODE(1) 001467; DATA(0) 000321; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   RUNGE
    0004   ANGLE
    0005   EXP
    0006   COS
    0007   SIN
    0010   NERR2$
    0011   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001     000104 100L      0001     000107 110L      0001     000737 120L      0001     000771 130L      0001     001107 18L
    0001     000243 19L       0001     000247 20L       0001     000255 30L       0001     000652 40L       0001     000172 49L
    0001     000172 50L       0001     000161 60L       0001     001031 64L       0001     000164 70L       0001     000166 80L
    0001     001221 90L       0000 R 000137 B         0000 R 000152 CON       0000 R 000147 CON1      0000 R 000150 CON2
    0000 R 000151 CON3      0000 R 000154 CDT       0000 R 000153 CDT1      0000 R 000163 COOS      0000 R 000052 D
    0000 R 000165 DS        0000 R 000166 DX        0000 R 000167 DY        0000 R 000170 DZ        0000 I 000136 IC
    0000 I 000130 IKEEP     0000   000223 INJP$     0000 I 000142 K         0000 I 000141 M         0000 I 000140 N
    0000 R 000000 R         0000 R 000146 RE        0000 R 000132 S         0000 R 000124 SEG       0000 R 000127 SLL
    0000 R 000125 STEST     0000 R 000131 STR       0000 R 000155 U         0000 R 000160 UCC       0000 R 000156 V
    0000 R 000145 VC        0000 R 000161 VCC       0000 R 000157 W         0000 R 000162 WCC       0000 R 000164 WCCA
    0000 R 000126 WCCC      0000 R 000133 X         0000 R 000134 Y         0000 R 000135 Z         0000 R 000143 ZAP
    0000 R 000144 ZAPH


 00101      1*          SUBROUTINE CONFIG(E,DM,DD,WC,H,S1,SO1,X1,Y1,Z1,T1,TH1,PH11,SL,RHOW       000063
 00101      2*         1,NUP,SF,SIF,XF,YF,ZF,TF,THF,PHIF,SS,SIS,XS,YS,ZS,TS,THS,PHIS,VCS,T      000063
 00101      3*         2HCS,L,CXX,DXX,THEC,CZZ,CB,NSEG,X1X,Y1Y,Z1Z,LMENT,DL)                    000063
 00103      4*          DIMENSION SS(30),SIS(30),XS(30),YS(30),ZS(30),TS(30),THS(30),PHIS(      000063
 00103      5*         130),VCS(30),THCS(30),R(42),C(42),X1X(7),Y1Y(7),Z1Z(7),DL(6)              000063
 00103      6*    C                                                                              000063
 00103      7*    C     INITIAL VALUES OF PARAMETERS                                             000063
 00103      8*    C                                                                              000063
 00104      9*          SEG=NSEG                                                                 000063
 00105     10*          STEST=SO1+SL/SEG                                                         000066
 00106     11*          WCCC=WC                                                                  000072
 00107     12*          IF(NUP.EQ.2) GO TO 100                                                   000074
 00111     13*          SLL=SO1+SL                                                               000077
 00112     14*          GO TO 110                                                                000102
 00113     15*      100 CONTINUE                                                                 000104
 00114     16*          SLL=SO1-SL                                                               000104
 00115     17*      110 CONTINUE                                                                 000107
 00116     18*          L=2                                                                      000107
```

```
00117           IKELP=0                                          000110
00120           SS(1)=S1                                         000111
00121           SIS(1)=SO1                                       000113
00122           XS(1)=X1                                         000115
00123           YS(1)=Y1                                         000117
00124           ZS(1)=Z1                                         000121
00125           TS(1)=T1                                         000123
00126           THS(1)=TH1/C.01745                               000125
00127           PHIS(1)=PHI1/0.01745                             000130
00130           STR=S1                                           000133
00131           S=SO1                                            000134
00132           X=X1                                             000135
00133           Y=Y1                                             000136
00134           Z=Z1                                             000137
00135           R(1)=T1                                          000140
00136           R(2)=TH1                                         000141
00137           R(3)=PHI1                                        000143
00140           IC=0                                             000145
00140     C                                                      000145
00140     C      CONVERT DM AND DO FROM INCHES TO FEET           000145
00140     C                                                      000145
00141           DM=DM/12.                                        000146
00142           DO=DO/12.                                        000151
00142     C                                                      000151
00142     C     CONSTANTS FOR SUBROUTINE RUNGE                   000151
00142     C                                                      000151
00143           IF(NUP.EQ.1) GO TO 60                            000154
00145           GO TO 70                                         000157
00146        60 CONTINUE                                         000161
00147           B=20.0                                           000161
00150           GO TO 80                                         000162
00151        70 CONTINUE                                         000164
00152           B=-20.0                                          000164
00153        80 CONTINUE                                         000166
00154           N=3                                              000166
00155           M=0                                              000167
00156           K=0                                              000170
00157        49 CONTINUE                                         000172
00160        50 CONTINUE                                         000172
00160     C                                                      000172
00160     C     CALCULATE CURRENT MAGNITUDE AND DIRECTION        000172
00160     C                                                      000172
00161           ZAP=H-Z                                          000172
00162           IF(ZAP.GE.DXX) ZAP=DXX                           000175
00164           ZAPM=-ZAP*CZZ                                    000203
00165           ZAP=H-Z                                          000206
00166           IF(Z.GT.H) ZAPM=0.                               000210
00170           VC=(CXX*EXP(ZAPM))*1.689                         000220
00171           IF(ZAP.LE.DXX) GO TO 19                          000226
00173           VC=CB*1.689+(Z/(H-DXX))*(VC-CD*1.689)            000232
00174        19 CONTINUE                                         000243
00175           IF(Z.EQ.Z1) GO TO 20                             000243
00177           GO TO 30                                         000245
00200        20 CONTINUE                                         000247
00201           VCS(1)=VC/1.689                                  000247
00202           THCS(1)=THEC/0.01745                             000251
00203        30 CONTINUE                                         000255
```

```
00203      C                                                                    000255
00203      C     SPECIFY OR CALCULATE NORMAL AND TANGENTIAL DRAG COEFFICIENTS   000255
00203      C        FOR CABLE                                                   000255
00203      C     RE IS REYNOLDS NUMBER                                          000255
00203      C                                                                    000255
00204            RE=VC*DM/1.6E-5                                                000255
00205            CDN1=1.2*(EXP(-((RE-2.0E2)/8.0E3)))                            000260
00206            CDN2=0.9*(EXP((RE-2.5E3)/4.3E4))                               000270
00207            CDN3=1.2                                                       000301
00210            IF(RE.GE.2.0E2.AND.RE.LT.2.5E3) CDN=CDN1                       000303
00212            IF(RE.GE.2.5E3.AND.RE.LT.1.5E4) CDN=CDN2                       000323
00214            IF(RE.GE.1.5E4.AND.RE.LT.2.0E5) CDN=CDN3                       000371
00216            CDT1=0.006*(EXP(-((RE-2.0E3)/2.2E5)))                          000411
00217            IF(RE.GE.2.0E3.AND.RE.LE.2.0E5) CDT=CDT1                       000422
00217      C                                                                    000422
00217      C     CALCULATE CURRENT COMPONENTS IN INERTIAL COORDINATES           000422
00217      C                                                                    000422
00221            U=-VC*SIN(THEC)                                                000446
00222            V=VC*COS(THEC)                                                 000453
00223            W=0.                                                           000460
00223      C                                                                    000460
00223      C     CALCULATE CURRENT COMPONENTS IN CABLE COORDINATES              000460
00223      C                                                                    000460
00224            UCC=U*COS(R(2))+V*SIN(R(2))                                    000461
00225            VCC=-U*SIN(R(2))*COS(R(3))+V*COS(R(2))*COS(R(3))+W*SIN(R(3))   000466
00226            WCC=U*SIN(R(2))*SIN(R(3))-V*COS(R(2))*SIN(R(3))+W*COS(R(3))    000503
00226      C                                                                    000503
00226      C     STEADY STATE EQUATIONS                                         000503
00226      C                                                                    000503
00227            IF(R(1).EQ.0.) R(1)=1.                                         000514
00231            COOS=COS(R(3))                                                 000520
00232            IF(COOS.EQ.0.) COOS=0.0001                                     000524
00234            WCCA=WC+(64.4*3.14159*((DM/12.)**2)/4.))                       000530
00235            IF(Z.GE.H) WC=WCCA                                             000536
00237            IF(Z.LE.0.) WC=0.                                              000544
00241            IF(Z.GT.0..AND.Z.LT.H) WC=WCCC                                 000550
00243            D(1)=WC*SIN(R(3))-0.5*RHOW*3.14159*DM*CDT*VCC*ABS(VCC)         000567
00244            D(2)=0.5*RHOW*DM*CDN*UCC*ABS(UCC)/(R(1)*COOS)                  000605
00245            D(3)=(WC*COS(R(3))-0.5*RHOW*DM*CDN*WCC*ABS(WCC))/R(1)          000615
00245      C                                                                    000615
00245      C      SOLVE ABOVE SIMULTANEOUS DIFFERENTIAL EQUATIONS               000615
00245      C                                                                    000615
00246            CALL RUNGE(N,R,D,S,H,M,K)                                      000631
00247            GO TO (50,40),K                                                000642
00250         40 CONTINUE                                                       000652
00250      C                                                                    000652
00250      C     CALCULATE COMPONENTS OF ELEMENT AND STRETCH                    000652
00250      C                                                                    000652
00251            IF(R(1).LE.0.) R(1)=0.                                         000652
00253            DS=D*(1.+(4.*R(1))/(3.14159*(DD**2)*E))                        000655
00254            STR=STR+DS                                                     000667
00255            DX=-DS*SIN(R(2))*COS(R(3))                                     000671
00256            DY=DS*COS(R(2))*COS(R(3))                                      000703
00257            DZ=DS*SIN(R(3))                                                000711
00257      C                                                                    000711
00257      C     CALCULATE NEW COORDINATES                                      000711
00257      C                                                                    000711
```

```
      X=X+DX                                                         000716
      Y=Y+DY                                                         000721
      Z=Z+DZ                                                         000724
C                                                                    000724
C     IC IS A COUNTER SO THAT THE COORDINATES AND TENSION WILL BE    000724
C        STORED ONLY AT SPECIFIC INTERVALS                           000724
C                                                                    000724
      IF(S.GE.SLL) GO TO 120                                         000726
      IF(S.LT.STEST) GO TO 130                                       000732
  120 CONTINUE                                                       000737
      XIX(LMENT)=X                                                   000737
      YIY(LMENT)=Y                                                   000742
      ZIZ(LMENT)=Z                                                   000746
      DL(LMENT-1)=S-SOI                                              000752
      SOI=S                                                          000757
      STEST=S+SL/SEG                                                 000761
      LMENT=LMENT+1                                                  000765
  130 CONTINUE                                                       000771
      IC=IC+1                                                        000771
      IF(S.GE.SLL.AND.NUP.EQ.1) GO TO 64                             000773
      IF(S.LE.SLL.AND.NUP.EQ.2) GO TO 64                             001010
      IF(IC.LT.50) GO TO 49                                          001025
   64 CONTINUE                                                       001031
      CALL ANGLE(R(2),R(3),1)                                        001031
C                                                                    001031
      ZAP=H-Z                                                        001035
      IF(ZAP.GE.DXX) ZAP=DXX                                         001041
      ZAPM=-ZAP*CZZ                                                  001047
      ZAP=H-Z                                                        001052
      IF(Z.GT.H) ZAPM=0.                                             001054
      VC=(CXX*EXP(ZAPM))*1.689                                       001064
      IF(ZAP.LE.DXX) GO TO 18                                        001072
      VC=CB*1.689+(Z/(H-DXX))*(VC-CB*1.689)                          001076
   18 CONTINUE                                                       001107
      IC=0                                                           001107
C                                                                    001107
      SS(L)=STR                                                      001107
      SIS(L)=S                                                       001113
      XS(L)=X                                                        001117
      YS(L)=Y                                                        001123
      ZS(L)=Z                                                        001127
      TS(L)=R(1)                                                     001133
      THS(L)=R(2)/0.01745                                            001137
      PHIS(L)=R(3)/0.01745                                           001144
      VCS(L)=VC/1.689                                                001151
      THCS(L)=THEC/0.01745                                           001156
C                                                                    001156
C     RETURN TO MAIN PROGRAM IF END OF CABLE SEGMENT HAS BEEN REACHED  001156
C                                                                    001156
      IF(S.GE.SLL.AND.NUP.EQ.1) GO TO 90                             001163
      IF(S.LE.SLL.AND.NUP.EQ.2) GO TO 90                             001177
      L=L+1                                                          001214
      GO TO 49                                                       001217
   90 CONTINUE                                                       001221
      SF=STR                                                         001221
      SIF=S                                                          001222
      XF=X                                                           001224
```

```
00352   190*        YF=Y                      001226
00353   191*        ZF=Z                      001230
00354   192*        TF=R(1)                   001232
00355   193*        THF=R(2)                  001234
00356   194*        PHIF=R(3)                 001236
00357   195*        DM=DM*12.0                001240
00360   196*        DD=DD*12.0                001243
00361   197*        WC=WCCC                   001246
00362   198*        RETURN                    001250
00363   199*        END                       001466

     END OF COMPILATION:       NO  DIAGNOSTICS.
```

```
@FOR,SI RUNGE,RUNGE
FOR OE20-01/11/77-04:57:19 (,0)

   SUBROUTINE RUNGE     ENTRY POINT 000133

   STORAGE USED: CODE(1) 000162; DATA(0) 000104; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR2$
    0004   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000020 1L        0001   000120 10L       0001   000022 107G      0001   000053 120G      0001   000101 130G
    0001   000027 3L        0001   000031 4L        0001   000035 5L        0001   000073 7L        0001   000116 9L
    0000 R 000053 A         0000 I 000052 I         0000   000066 INJP$     0000 R 000000 Q


00101      1*          SUBROUTINE RUNGE(N,Y,D,X,H,M,K)                                      000002
00103      2*          DIMENSION Y(42),D(42),Q(42)                                          000002
00104      3*          M=M+1                                                                000002
00105      4*          GO TO (1,4,5,3,7),M                                                  000005
00106      5*        1 DO 2 I=1,N                                                           000022
00111      6*        2 Q(I)=0.                                                              000022
00113      7*          A=.5                                                                 000023
00114      8*          GO TO 9                                                              000025
00115      9*        3 A=1.707107                                                           000027
00116     10*        4 X=X+.5*H                                                             000031
00117     11*        5 DO 6 I=1,N                                                           000035
00122     12*          Y(I)=Y(I)+A*(D(I)*H-Q(I))                                            000053
00123     13*        6 Q(I)=2.*A*H*D(I)+(1.-3.*A)*Q(I)                                      000060
00125     14*          A=.2928932                                                           000067
00126     15*          GO TO 9                                                              000071
00127     16*        7 DO 8 I=1,N                                                           000101
00132     17*        8 Y(I)=Y(I)+H*D(I)/6.-Q(I)/3.                                          000101
00134     18*          M=0                                                                  000111
00135     19*          K=2                                                                  000112
00136     20*          GO TO 10                                                             000114
00137     21*        9 K=1                                                                  000116
00140     22*       10 RETURN                                                               000120
00141     23*          END                                                                  000161

      END OF COMPILATION:        NO DIAGNOSTICS.
```

```
WFOR,SI ANGLE,ANGLE
FOR 0E26-01/11/77-04:57:21 (,0)

   SUBROUTINE ANGLE     ENTRY POINT 000063

   STORAGE USED: CODE(1) 000075; DATA(0) 000017; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000023 115G      0001   000023 409L      0001   000034 410L      0001   000040 411L      0001   000044 412L
    0000 R 000000 A         0000   000011 INJP$     0000 I 000005 N         0000 R 000002 SEMI      0000 R 000004 SEMID
    0000 R 000003 SEMIM


00101      1*             SUBROUTINE ANGLE(THETA,PHI,NRAD)                              000000
00101      2*      C                                                                    000000
00101      3*      C      THIS SUBROUTINE GETS THETA AND PHI TO BE BETWEEN -3.14 AND +3.14  000000
00101      4*      C         RADIANS IF NRAD=1 OR BETWEEN -180 AND +180 DEGREES IF NRAD=0   000000
00101      5*      C                                                                    000000
00103      6*             DIMENSION A(2)                                                000000
00104      7*             A(1)=THETA                                                    000000
00105      8*             A(2)=PHI                                                      000001
00106      9*             IF(NRAD.EQ.1) SEMI=3.141592654                                000003
00110     10*             IF(NRAD.EQ.0) SEMI=180.0                                      000010
00112     11*             SEMIM=-SEMI                                                   000014
00113     12*             SEMID=2.0*SEMI                                                000016
00114     13*             DO 10 N=1,2                                                   000023
00117     14*         409 CONTINUE                                                      000023
00120     15*             IF(A(N).LT.SEMIM) GO TO 410                                   000023
00122     16*             IF(A(N).GT.SEMI) GO TO 411                                    000026
00124     17*             GO TO 412                                                     000032
00125     18*         410 CONTINUE                                                      000034
00126     19*             A(N)=A(N)+SEMID                                               000034
00127     20*             GO TO 409                                                     000036
00130     21*         411 CONTINUE                                                      000040
00131     22*             A(N)=A(N)-SEMID                                               000040
00132     23*             GO TO 409                                                     000042
00133     24*         412 CONTINUE                                                      000045
00134     25*          10 CONTINUE                                                      000045
00136     26*             THETA=A(1)                                                    000045
00137     27*             PHI=A(2)                                                      000047
00140     28*             RETURN                                                        000051
00141     29*             END                                                           000074

      END OF COMPILATION:        NO  DIAGNOSTICS.
```

```
WFOR,S1 SUBSRF,SUBSRF
FOR 0E26-01/11/77-04157:22 (,0)

   SUBROUTINE SUBSRF    ENTRY POINT 000637

   STORAGE USED: CODE(1) 000736; DATA(0) 000120; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   ANGLE
    0004   EXP
    0005   COS
    0006   SIN
    0007   ATAN
    0010   SQRT
    0011   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001    000056 19L      0001    000443 50L      0001    000502 55L      0001    000626 99L      0000 R 000023 AEX
    0000 R 000024 AEY       0000 R 000025 AEZ       0000 R 000020 B         0000 R 000014 C         0000 R 000013 CDS
    0000 R 000007 CDS1      0000 R 000010 CDS2      0000 R 000011 CDS3      0000 R 000012 CDS4      0000 R 000034 C1
    0000 R 000035 C2        0000 R 000036 C3        0000 R 000021 DFX       0000 R 000022 DFY       0000 R 000037 DS
    0000 I 000030 IERROR    0000    000065 INJP$    0000 R 000006 RE        0000 R 000031 TBDEX     0000 R 000032 TBDEY
    0000 R 000033 TBDEZ     0000 R 000015 TBEDX     0000 R 000016 TBEDY     0000 R 000017 TBEDZ     0000 R 000027 THBN
    0000 R 000026 THBP      0000 R 000005 VC        0000 R 000000 X         0000 R 000042 XDB       0000 R 000001 Y
    0000 R 000041 YDB       0000 R 000002 Z         0000 R 000003 ZAP       0000 R 000004 ZAPM      0000 R 000040 ZDB


00101      1*          SUBROUTINE SUBSRF(IRROR,NUP,WS,RS,RHOW,TBED,THBED,PHBED,XED,YED,ZE         000000
00101      2*         1D,G,H,RHC,TBDE,THBDE,PHBDE,XDDE,YDDE,ZDDE,LXX,DXX,THEC,CZZ,CD)             000000
00101      3*      C                                                                              000000
00101      4*      C                                                                              000000
00101      5*      C   CALCULATE CURRENT MAGNITUDE AND DIRECTION                                  000000
00101      6*      C                                                                              000000
00103      7*          X=XED                                                                      000000
00104      8*          Y=YED                                                                      000003
00105      9*          Z=ZED                                                                      000005
00106     10*          ZAP=H-Z                                                                    000007
00107     11*          IF(ZAP.GE.DXX) ZAP=DXX                                                     000013
00111     12*          ZAPM=-ZAP*CZZ                                                              000021
00112     13*          ZAP=H-Z                                                                    000024
00113     14*          IF(Z.GT.H) ZAPM=0.                                                         000026
00115     15*          VC=(CXX*EXP(ZAPM))*1.689                                                   000033
00116     16*          IF(ZAP.LE.DXX) GO TO 19                                                    000041
00120     17*          VC=CD*1.689+(Z/(H-DXX))*(VC-CD*1.689)                                      000045
00121     18*       19 CONTINUE                                                                   000056
00121     19*      C                                                                              000056
00121     20*      C   SPECIFY COEFFICIENT OF DRAG FOR SPHERE                                     000056
00121     21*      C   RE IS REYNOLDS NUMBER                                                      000056
00121     22*      C                                                                              000056
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00122      RE=VC*(2.*RS)/1.6E-5                                              000056
00123      CDS1=0.5                                                          000062
00124      CDS2=0.5*(EXP(-((RE-2.0E5)/4.9E4)))                               000064
00125      CDS3=0.16*(EXP((RE-2.5E5)/1.4E6))                                 000074
00126      CDS4=0.2                                                          000105
00127      IF(RE.GE.3.0E4.AND.RE.LT.2.0E5) CDS=CDS1                          000107
00131      IF(RE.GE.2.0E5.AND.RE.LT.2.5E5) CDS=CDS2                          000127
00133      IF(RE.GE.2.5E5.AND.RE.LT.4.0E5) CDS=CDS3                          000166
00135      IF(RE.GE.4.0E5.AND.RE.LT.1.0E7) CDS=CDS4                          000206
00135   C                                                                    000206
00135   C  C=1 IF GOING TOWARD SHIP. =-1 IF GOING TOWARD ANCHOR              000206
00135   C                                                                    000206
00137      IF(NUP.EQ.1) C=1.                                                 000226
00141      IF(NUP.EQ.2) C=-1.                                                000242
00141   C                                                                    000242
00141   C  CALCULATE TENSION COMPONENTS IN INERTIAL SYSTEM                   000242
00141   C                                                                    000242
00143      TBEDX=-TBED*SIN(THBED)*COS(PHBED)                                 000247
00144      TBEDY=TBED*COS(THBED)*COS(PHBED)                                  000255
00145      TBEDZ=TBED*SIN(PHBED)                                             000263
00145   C                                                                    000263
00145   C  CALCULATE NET BUOYANCY                                            000263
00145   C                                                                    000263
00146      B=(64.4*(4./3.)*3.14159*RS**3)-WS                                 000270
00146   C                                                                    000270
00146   C  CALCULATE DRAG COMPONENTS IN INERTIAL SYSTEM                      000270
00146   C                                                                    000270
00147      DFX=0.5*RHOW*CDS*1.*3.14159*RS**2*(-VC)*SIN(THEC)*ABS((-VC)*SIN(TH 000275
00147     1EC))                                                              000275
00150      DFY=0.5*RHOW*CDS*1.*3.14159*RS**2*VC*COS(THEC)*ABS(VC*COS(THEC))  000304
00150   C                                                                    000304
00150   C  CALCULATE CONSTANTS FOR SOLUTION TO UNKNOWN TENSION AND ANGLES    000304
C0150   C                                                                    000304
00151      AEX=-TBEDX+(C*DFX)                                                000313
00152      AEY=TBEDY-(C*DFY)                                                 000316
00153      AEZ=TBEDZ-(C*B)                                                   000321
00154      THBP=90.*0.01745                                                  000324
00155      THBN=-90.*0.01745                                                 000326
00156      IF(AEY.EQ.0..AND.AEX.GE.0.) THBDE=THBP                            000327
00160      IF(AEY.EQ.0..AND.AEX.LE.0.) THBDE=THBN                            000343
00162      IF(AEY.EQ.0..AND.AEZ.GE.0.) PHBDE=THBP                            000357
00164      IF(AEY.EQ.0..AND.AEZ.LE.0.) PHBDE=THBN                            000373
00164   C                                                                    000373
00164   C  CALCULATE TENSION AND ANGLES AT UNKNOWN POINT                      000373
00164   C                                                                    000373
00166      IF(AEY.EQ.0..AND.AEX.GE.0.) GO TO 50                              000407
00170      IF(AEY.EQ.0..AND.AEX.LE.0.) GO TO 50                              000421
00172      THBDE=ATAN(AEX/AEY)                                               000433
00173   50 CONTINUE                                                          000443
00174      IF(AEY.EQ.0..AND.AEZ.LE.0.) GO TO 55                              000443
00176      IF(AEY.EQ.0..AND.AEZ.GE.0.) GO TO 55                              000454
00200      PHBDE=ATAN((AEZ/AEY)*COS(THBDE))                                  000466
00201   55 CONTINUE                                                          000502
00202      IF(PHBDE.EQ.0.000) IERROR=1                                       000502
00204      IF(PHBDE.EQ.0.000) GO TO 99                                       000505
00206      TBDE=AEZ/SIN(PHBDE)                                               000507
00207      IF(TBDE.LE.0.) TBDE=0.                                            000515
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00207      C                                                                       000515
00207      C     CALCULATE TENSION COMPONENTS AT UNKNOWN POINT IN INERTIAL SYSTEM  000515
00207      C                                                                       000515
00211            TBDEX=-TBDE*SIN(THBDE)*COS(PHBDE)                                 000525
00212            TBDEY=TBDE*COS(THBDE)*COS(PHBDE)                                  000533
00213            TBDEZ=TBDE*SIN(PHBDE)                                             000541
00213      C                                                                       000541
00213      C     CALCULATE COORDINATES OF UNKNOWN POINT                            000541
00213      C                                                                       000541
00214            C1=(B/2.)+TBDEZ                                                   000546
00215            C2=(DFY/2.)+TBDEY                                                 000552
00216            C3=(DFX/2.)+TBDEX                                                 000556
00217            DS=2.*RS                                                          000562
00217      C                                                                       000562
00220            ZDB=DS/(SQRT((C2/C1)**2+(C3/C1)**2+1.))                           000565
00221            YDB=(C2/C1)*ZDB                                                   000603
00222            XDB=(C3/C1)*ZDB                                                   000605
00222      C                                                                       000605
00223            XBDE=XLD+XDB                                                      000610
00224            YBDE=YED+YDB                                                      000612
00225            ZBDE=ZED+ZDB                                                      000614
00225      C                                                                       000614
00226            IERROR=0                                                          000617
00227            CALL ANGLE(THBDE,PHBDE,1)                                         000620
00230         99 CONTINUE                                                          000626
00231            RETURN                                                            000626
00232            END                                                               000735

     END OF COMPILATION:         NO DIAGNOSTICS.
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```
@FOR,SI TENCOR,TENCOR
FOR 0E2B-01/11/77-04157124 (,0)

   SUBROUTINE TENCOR     ENTRY POINT 000226

   STORAGE USED: CODE(1) 000321; DATA(0) 000043; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   ANGLE
    0004   SQRT
    0005   COS
    0006   SIN
    0007   ATAN
    0010   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   000056 100L      0001   000211 110L      0001   000057 190L      0001   000102 230L      0001   000067 270L
    0001   000077 200L      0001   000102 300L      0001   000207 500L      0001   000043 70L       0001   000053 80L
    0000 R 000004 DELX      0000 R 000005 DELY      0000 R 000006 DELZ      0000 R 000000 ERRR      0000   000017 INJP$
    0000 R 000007 TTNX      0000 R 000010 TTNY      0000 R 000011 TTNZ      0000 R 000001 TTX       0000 R 000002 TTY
    0000 R 000003 TTZ

00101      1*             SUBROUTINE TENCOR(EPS,Y,Z,ERRORP,DELTAP,TNSONT,THETAT,PHIT,XT,YT,Z                000000
00101      2*            1T,TNSONN,THETAN,PHIN,ERRORN,DELTAN,LTEP,ITERTS)                                   000000
00101      3*       C                                                                                      000000
00101      4*       C     CALCULATE NEW CLOSURE ERROR                                                      000000
00101      5*       C                                                                                      000000
00103      6*             ERRORN=(0.-XT)**2+(Y-YT)**2+(Z-ZT)**2                                            000000
00104      7*             ERRORN=SQRT(ERRORN)                                                              000012
00104      8*       C                                                                                      000012
00104      9*       C     IS CLOSURE ERROR IN ACCEPTABLE RANGE                                             000012
00104     10*       C                                                                                      000012
00105     11*             IF(ERRORN.LT.EPS) GO TO 500                                                      000016
00106     12*       C                                                                                      000016
00107     13*             DELTAN=DELTAP                                                                    000021
00110     14*             LTEP=0                                                                           000023
00110     15*       C                                                                                      000023
00110     16*       C     DECREASE DELTA IF CLOSURE ERROR IS INCREASING                                    000023
00110     17*       C        OR IF OLD ERROR IS MORE THAN 2 TIMES NEW ERROR                                000023
00110     18*       C                                                                                      000023
00111     19*             ERRR=ERRORP/ERRORN                                                               000024
00112     20*             IF(ITERTS.GE.30) GO TO 190                                                       000027
00112     21*             IF(ERRORN.LE.500.0) GO TO 70                                                     000033
00112     22*             IF(ERRR.GT.2.0) GO TO 80                                                         000037
00120     23*          70 CONTINUE                                                                         000043
00121     24*             IF(ERRORN.LT.ERRORP) GO TO 100                                                   000043
00123     25*             DELTAN=DELTAN/2.                                                                 000046
00124     26*             GO TO 100                                                                        000051
```

```
00125          80 CONTINUE                                                        000053
00126             DELTAN=DELTAN/2.                                                000053
00127         100 CONTINUE                                                        000056
00130             GO TO 230                                                       000056
00131         190 CONTINUE                                                        000057
00132             IF(ERRORN.LE.500.) GO TO 270                                    000057
00134             IF(ERRR.GT.2.0) GO TO 280                                       000062
00136         270 CONTINUE                                                        000067
00137             IF(ERRORN.LT.ERRORP) GO TO 300                                  000067
00141             DELTAN=DELTAN/1.2                                               000072
00142             GO TO 300                                                       000075
00143         280 CONTINUE                                                        000077
00144             DELTAN=DELTAN/1.2                                               000077
00145         300 CONTINUE                                                        000102
00146         230 CONTINUE                                                        000102
00146       C                                                                     000102
00146       C     CALCULATE TENSION COMPONENTS IN INERTIAL SYSTEM                 000102
00146       C                                                                     000102
00147             TTX=-TNSONT*SIN(THETAT)*COS(PHIT)                               000102
00150             TTY=TNSONT*COS(THETAT)*COS(PHIT)                                000113
00151             TTZ=TNSONT*SIN(PHIT)                                            000121
00151       C                                                                     000121
00151       C     CALCULATE TENSION CORRECTIONS                                   000121
00151       C                                                                     000121
00152             DELX=(DELTAN/ERRORN)*(XT)*(-1.)                                 000126
00153             DELY=(DELTAN/ERRORN)*(YT-Y)*(-1.)                               000133
00154             DELZ=(DELTAN/ERRORN)*(ZT-Z)*(-1.)                               000137
00154       C                                                                     000137
00154       C     CALCULATE CORRECTED TENSION COMPONENTS                          000137
00154       C                                                                     000137
00155             TTNX=TTX+DELX                                                   000143
00156             TTNY=TTY+DELY                                                   000145
00157             TTNZ=TTZ+DELZ                                                   000147
00157       C                                                                     000147
00157       C     CONVERT TENSION COMPONENTS INTO TENSION MAGNITUDE AND ANGLES    000147
00157       C                                                                     000147
00160             TNSONN=SQRT(TTNX**2+TTNY**2+TTNZ**2)                            000151
00161             PHIN=ATAN(TTNZ/(SQRT(TTNX**2+TTNY**2)))                         000164
00162             THETAN=ATAN(-(TTNX)/TTNY)                                       000176
00163             GO TO 110                                                       000205
00164         500 CONTINUE                                                        000207
00165             LTEP=1                                                          000207
00166         110 CONTINUE                                                        000211
00167             CALL ANGLE(THETAN,PHIN,1)                                       000211
00170             RETURN                                                          000215
00171             END                                                             000320

     END OF COMPILATION:        NO DIAGNOSTICS.
```

```
@FOR,SI DYNICS,DYNICS
FOR 0E2B-01/11/77-04:57:25 (,0)

   SUBROUTINE DYNICS    ENTRY POINT 003726

   STORAGE USED: CODE(1) 004111; DATA(0) 022143; BLANK COMMON(2) 000000

   EXTERNAL REFERENCES (BLOCK, NAME)

    0003   RUNGE
    0004   MODESG
    0005   SETSMG
    0006   SUBJEG
    0007   GRAPHG
    0010   POINTG
    0011   LINESG
    0012   PAGEG
    0013   EXITG
    0014   SIN
    0015   COS
    0016   ATAN
    0017   SQRT
    0020   EXP
    0021   NERR2$
    0022   NPRT$
    0023   NIO2$
    0024   NIO1$
    0025   NERR3$

   STORAGE ASSIGNMENT  (BLOCK, TYPE, RELATIVE LOCATION, NAME)

    0001   003061 1037G    0001   003141 1053G    0001   003221 1067G    0001   003310 1105G    0001   003376 1132G
    0001   003466 1150G    0001   003544 1163G    0001   003622 1176G    0001   002337 118L     0001   000072 120G
    0001   002316 120L     0001   002563 125L     0001   000120 132G     0001   002520 134L     0000   021652 135F
    0000   021657 136F     0001   002550 140L     0001   002554 141L     0001   002560 142L     0000   021666 143F
    0001   002564 144L     0000   021676 145F     0001   000164 145G     0001   002570 146L     0000   021672 147F
    0000   021726 150F     0000   021753 160F     0001   000211 161G     0001   000134 20L      0001   000342 203G
    0000   021760 211F     0001   000512 225G     0001   003273 245L     0001   000603 251G     0001   003672 285L
    0001   003677 301L     0001   001002 302G     0000   021625 34F      0001   001414 350G     0001   001433 357G
    0001   001722 415G     0001   001756 427G     0000   021644 499F     0001   002226 505G     0001   002407 510L
    0000   021646 512F     0001   002320 532G     0001   002353 557G     0001   000571 58L      0001   002441 613G
    0001   002531 646G     0001   002611 713G     0001   002677 755G     0001   002735 777G     0001   001713 79L
    0001   002206 99L      0000 R 000334 ACC      0000 R 021513 ACX      0000 R 021514 ACZ      0000 R 021500 B
    0000 R 021543 CDN      0000 R 021540 CDN1     0000 R 021541 CDN2     0000 R 021542 CDN3     0000 R 021570 CDS
    0000 R 021564 CDS1     0000 R 021565 CDS2     0000 R 021566 CDS3     0000 R 021567 CDS4     0000 R 021545 CDT
    0000 R 021544 CDT1     0000 R 021532 CPH      0000 R 021536 CPI      0000 R 021534 CTE      0000 R 021530 CTH
    0000 R 021164 C1       0000 R 021330 C2       0000 R 000262 D        0000 R 021572 DPA      0000 R 021573 DPX
    0000 R 021574 DBY      0000 R 021575 DBZ      0000 R 010504 DISP     0000 R 021507 DISX     0000 R 021510 DISZ
    0000 R 000202 DRGX     0000 R 021546 DRGX1    0000 R 021551 DRGX2    0000 R 000210 DRGY     0000 R 021547 DRGY1
    0000 R 021552 DRGY2    0000 R 000216 DRGZ     0000 R 021550 DRGZ1    0000 R 021553 DRGZ2    0000 R 021554 EMU
    0000 R 021576 EMUB     0000 R 021555 EMV      0000 R 000232 ERTIAX   0000 R 000240 ERTIAY   0000 R 000246 ERTIAZ
    0000 R 021577 HYDB     0000 R 021556 HYDRMX   0000 R 021557 HYDRMY   0000 R 021560 HYDRMZ   0000 R 021561 HYDRNX
    0000 R 021562 HYDRNY   0000 R 021563 HYDRNZ   0000 I 000254 IB       0000 I 021602 IMAX     0000   022035 INJP$
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0000 I 021601 IIM     0000 I 021605 IIMAX   0000 I 021603 J       0000 I 021476 K       0000 I 021506 L
0000 I 021502 LAST    0000 I 021477 M       0000 I 021505 N       0000 I 021604 NTME    0000 R 020654 P
0000 R 000061 PHI     0000 R 000000 R       0000 R 021537 RE      0000 R 021531 SPH     0000 R 021535 SPI
0000 R 021520 SPRCHT  0000 R 021533 STE     0000 R 021527 STH     0000 R 000070 T       0000 R 000052 THETA
0000 R 021503 TLAST   0000 R 021475 TM      0000 R 021501 TMCNT   0000 R 021504 TMCT    0000 R 021624 TMMIN
0000 R 021474 TMSTOR  0000 R 021623 TNMAX   0000 R 021617 TNMIN   0000 R 014570 TNS     0000 R 000106 TX
0000 R 000114 TY      0000 R 000122 TZ      0000 R 021523 U       0000 R 000130 UR      0000 R 021525 UXN
0000 R 021524 V       0000 R 000077 VC      0000 R 004420 VEL     0000 R 021600 VIRM    0000 R 021511 VLX
0000 R 021512 VLZ     0000 R 000146 VR      0000 R 021620 VXMAX   0000 R 021614 VXMIN   0000 R 021621 VYMAX
0000 R 021615 VYMIN   0000 R 021526 VYN     0000 R 021622 VZMAX   0000 R 021616 VZMIN   0000 R 000164 WR
0000 R 000224 WTHK    0000 R 021571 WZN     0000 R 021611 XMAX    0000 R 021606 XMIN    0000 R 021515 XND
0000 R 021612 YMAX    0000 R 021607 YMIN    0000 R 021516 YND     0000 R 021521 ZAP     0000 R 021522 ZAPM
0000 R 021613 ZMAX    0000 R 021610 ZMIN    0000 R 021517 ZND
```

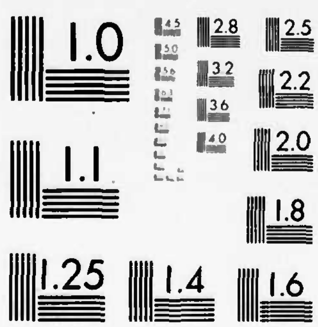
```
00101          SUBROUTINE DYMICS(X1,Y1,Z1,DS,EC,DL,G,H,CAX,CZZ,CB,                000043
00101         1DXX,THEC,DCUT,RHOW,WC,IBUOY,RAD,EXB,WT,TMMAX,XCHAR,YCHAR,          000043
00101         2ZCHAR,XCHRR,YCHRR,ZCHRR,VELX,VELY,VELZ,TFN,TIM,TITLE,IPLOT,SHX,    000043
00101         3SHZ,OMEGAX,OMEGAZ,PHAX,PHAZ)                                       000043
00103          DIMENSION X1(7),Y1(7),Z1(7),R(42),THETA(7),PHI(7),DS(6),EC(6),DL(6 000043
00103         1),T(7),VC(7),TX(6),TY(6),TZ(6),UR(7,2),VR(7,2),WR(7,2),DOUT(6),    000043
00103         2DRGX(6),DRGY(6),DRGZ(6),WC(6),WTRM(6),ERTIAX(6),ERTIAY(6),ERTIAZ(6 000043
00103         3),IB(6),RAD(6),EXB(6),WT(6),D(42),ACC(7,3,100),VEL(7,3,100),DISP(7 000043
00103         4,3,100),TNS(7,3,100)                                               000043
00104          DIMENSION P(200),C1(100),C2(100)                                   000043
00105          DIMENSION SHX(101),SHZ(101),OMEGAX(101),OMEGAZ(101),PHAX(101),     000043
00105         1PHAZ(101)                                                          000043
00105    C                                                                        000043
00105    C     INITIAL VALUES AT TIME=0                                           000043
00105    C                                                                        000043
00106          TMSTOR=TMMAX                                                       000043
00107          TM=0.                                                              000045
00110          K=0                                                                000046
00111          M=0                                                                000047
00112          B=0.1                                                              000050
00113          TMCNT=10.                                                          000052
00114          LAST=50                                                            000054
00115          TLAST=LAST                                                         000056
00116          TMCT=TMMAX-TLAST                                                   000061
00117          DO 10 N=1,7                                                        000072
00122          L=N*6                                                              000072
00123          R(L-5)=0.                                                          000076
00124          R(L-4)=X1(N)                                                       000077
00125          R(L-3)=0.                                                          000101
00126          R(L-2)=Y1(N)                                                       000102
00127          R(L-1)=0.                                                          000104
00130          R(L)=Z1(N)                                                         000105
00131          DO 5 K=1,7                                                         000120
00134          DISP(K,1,1)=X1(K)                                                  000120
00135          DISP(K,2,1)=Y1(K)                                                  000121
00136          DISP(K,3,1)=Z1(K)                                                  000123
00137        5 CONTINUE                                                           000134
00141       10 CONTINUE                                                           000134
00143       20 CONTINUE                                                           000134
00143    C                                                                        000134
```

AD-A039 831 NAVAL UNDERWATER SYSTEMS CENTER NEW LONDON CONN NEW --ETC F/G 13/10
A STEADY STATE AND DYNAMIC ANALYSIS OF A MOORING SYSTEM.(U)
MAR 77 J P RADOCHIA
UNCLASSIFIED NUSC-TR-5597 NL

3 OF 3
ADA039 831

END
DATE
FILMED
6-77

039



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
00143   C        BOUNDARY CONDITIONS                                        000134
00143   C                                                                   000134
00144            DO 30 N=1,6                                                000134
00147            R(N)=0.                                                    000164
00150         30 CONTINUE                                                   000165
00150   C                                                                   000165
00150   C        SHIP MOTIONS                                               000165
00150   C                                                                   000165
00152            DISX=0.                                                    000165
00153            DISZ=0.                                                    000166
00154            VLX=0.                                                     000167
00155            VLZ=0.                                                     000170
00156            ACX=0.                                                     000171
00157            ACZ=0.                                                     000172
00160            DO 35 N=1,101                                              000211
00163            DISX=DISX+(SHX(N)*SIN(OMEGAX(N)*TM+PHAX(N)))               000211
00164            DISZ=DISZ+(SHZ(N)*SIN(OMEGAZ(N)*TM+PHAZ(N)))               000222
00165            VLX=VLX+(SHX(N)*OMEGAX(N)*COS(OMEGAX(N)*TM+PHAX(N)))       000234
00166            VLZ=VLZ+(SHZ(N)*OMEGAZ(N)*COS(OMEGAZ(N)*TM+PHAZ(N)))       000250
00167            ACX=ACX-(SHX(N)*OMEGAX(N)**2*SIN(OMEGAX(N)*TM+PHAX(N)))    000264
00170            ACZ=ACZ-(SHZ(N)*OMEGAZ(N)**2*SIN(OMEGAZ(N)*TM+PHAZ(N)))    000301
00171         35 CONTINUE                                                   000317
00173            DISZ=DISZ+H                                                000317
00174            R(37)=VLX                                                  000322
00175            R(38)=DISX                                                 000324
00176            R(39)=0.                                                   000326
00177            R(40)=0                                                    000327
00200            R(41)=VLZ                                                  000331
00201            R(42)=DISZ                                                 000333
00201   C                                                                   000333
00201   C        CABLE ANGLES,TENSIONS,AND TENSION COMPONENTS               000333
00201   C                                                                   000333
00202            DO 40 N=1,6                                                000342
00205            L=N+6                                                      000342
00206            XND=R(L+2)-R(L-4)                                          000346
00207            YND=R(L+4)-R(L-2)                                          000351
00210            ZND=R(L+6)-R(L)                                            000354
00211            THETA(N)=ATAN(-(XND)/YND)                                  000357
00212            PHI(N)=ATAN(ZND/(SQRT(XND**2+YND**2)))                     000365
00213            SPRCNT=(3.14159*DS(N)**2*EC(N))/(4.*DL(N))                 000404
00214            T(N)=SPRCNT*(SQRT(XND**2+YND**2+ZND**2)-DL(N))             000414
00215            IF(T(N).LE.0.) T(N)=0.                                     000433
00217            TX(N)=-T(N)*SIN(THETA(N))*COS(PHI(N))                      000437
00220            TY(N)=T(N)*COS(THETA(N))*COS(PHI(N))                       000455
00221            TZ(N)=T(N)*SIN(PHI(N))                                     000473
00222         40 CONTINUE                                                   000512
00222   C                                                                   000512
00222   C        CURRENT VELOCITY IN INERTIAL COORDINATES                   000512
00222   C                                                                   000512
00224            DO 50 N=1,7                                                000512
00227            L=N*6                                                      000512
00230            ZAP=H-R(L)                                                 000516
00231            IF(ZAP.GE.DXX) ZAP=DXX                                     000522
00233            ZAPM=-ZAP*CZZ                                              000530
00234            ZAP=H-R(L)                                                 000533
00235            IF(R(L).GT.H) ZAPM=0.                                      000537
00237            VC(N)=(CXA*EXP(ZAPM))*1.689                                000545
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```
      IF(ZAP.LE.DXX) GO TO 58
      VC(N)=CB*1.689+(R(L)/(H-DXX))*(VC(N)-CB*1.689(
   58 CONTINUE
      U=-VC(N)*SIN(THEC)
      V=VC(N)*COS(THEC)
   50 CONTINUE
C
C     CURRENT COMPONENTS IN INERTIAL COORDINATES
C
      DO 59 N=2,7
      L=N+6
      UR(1)=0.
      VR(1)=0.
      WR(1)=0.
      UXN=U-R(L-5)
      VYN=V-R(L-3)
      STH=SIN(THETA(N-1))
      CTH=COS(THETA(N-1))
      SPH=SIN(PHI(N-1))
      CPH=COS(PHI(N-1))
      STE=SIN(THETA(N))
      CTE=COS(THETA(N))
      SPI=SIN(PHI(N))
      CPI=COS(PHI(N))
C
C     CURRENT COMPONENTS IN CABLE COORDINATES
C
      UR(N,1)=UXN*CTH+VYN*STH
      VR(N,1)=-UXN*STH*CPH+VYN*CTH*CPH-R(L-1)*SPH
      WR(N,1)=UXN*STH*SPH-VYN*CTH*SPH-R(L-1)*CPH
      UR(N,2)=UXN*CTE+VYN*STE
      VR(N,2)=-UXN*STE*CPI+VYN*CTE*CPI-R(L-1)*SPI
      WR(N,2)=UXN*STE*SPI-VYN*CTE*SPI-R(L-1)*CPI
   59 CONTINUE
      DO 60 N=2,6
C
C     CABLE DRAG COEFFICIENTS FOR REYNOLDS NUMBER RE
C
      RE=VC(N)*DOUT(N-1)/1.6E-5
      CDN1=1.2*(EXP(-((RE-2.0E2)/8.0E3)))
      CDN2=0.9*(EXP((RE-2.5E3)/4.3E4))
      CDN3=1.2
      IF(RE.GE.2.0E2.AND.RE.LT.2.5E3) CDN=CDN1
      IF(RE.GE.2.5E3.AND.RE.LT.1.5E4) CDN=CDN2
      IF(RE.GE.1.5E4.AND.RE.LT.2.0E5) CDN=CDN3
      CDT1=0.006*(EXP(-((RE-2.0E3)/2.2E5)))
      IF(RE.GE.2.0E3.AND.RE.LE.2.0E5) CDT=CDT1
C
C     DRAG COMPONENTS IN CABLE COORDINATES
C
      DRGX(1)=0.
      DRGY(1)=0.
      DRGZ(1)=0.
      DRGX1=0.5*RHOW*DOUT(N-1)*CDN*UR(N,1)*ABS(UR(N,1))
      DRGY1=0.5*RHOW*3.14159*DOUT(N-1)*CDT*VR(N,1)*ABS(VR(N,1))
      DRGZ1=0.5*RHOW*DOUT(N-1)*CDN*WR(N,1)*ABS(WR(N,1))
      DRGX2=0.5*RHOW*DOUT(N)*CDN*UR(N,2)*ABS(UR(N,2))
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```
00330        DRGY2=0.5*RHOW*3.14159*DOUT(N)*CDI*VR(N,2)*ABS(VR(N,2))         001200
00331        DRGZ2=0.5*RHOW*DOUT(N)*CDN*WR(N,2)*ABS(WR(N,2))                 001207
00332        STH=SIN(THETA(N))                                               001216
00333        CTH=COS(THETA(N))                                               001224
00334        SPH=SIN(PHI(N))                                                 001232
00335        CPH=COS(PHI(N))                                                 001240
00336        STE=SIN(THETA(N-1))                                             001246
00337        CTE=COS(THETA(N-1))                                             001254
00340        SP1=SIN(PHI(N-1))                                               001262
00341        CP1=COS(PHI(N-1))                                               001270
00341  C                                                                     001270
00341  C     DRAG COMPONENTS IN INERTIAL COORDINATES                         001270
00341  C                                                                     001270
00342        DRGX(N)=(DRGX1*CTE-DRGY1*STE*CP1+DRGZ1*STE*SP1)*(DL(N-1)/2.)+   001276
00342       1(DRGX2*CTH-DRGY2*STH*CPH+DRGZ2*STH*SPH)*(DL(N)/2.)              001276
00343        DRGT(N)=(DRGX1*STE+DRGY1*CTE*CP1-DRGZ1*CTE*SP1)*(DL(N-1)/2.)+   001326
00343       1(DRGX2*STH+DRGT2*CTH*CPH-DRGZ2*CTH*SPH)*(DL(N)/2.)              001326
00344        DRGZ(N)=(DRGT1*SP1+DRGZ1*CP1)*(DL(N-1)/2.)+(DRGY2*SPH+DRGZ2*CPH)*   001362
00344       1(DL(N)/2.)                                                      001362
00345     60 CONTINUE                                                        001414
00345  C                                                                     001414
00345  C     CABLE WEIGHT IN INERTIAL COORDINATES                            001414
00345  C                                                                     001414
00347        DO 70 N=2,6                                                     001414
00352        WTRM(1)=0.                                                      001414
00353        WTRM(N)=(WC(N-1)*(DL(N-1)/2.))+(WC(N)*(DL(N)/2.))               001414
00354     70 CONTINUE                                                        001433
00354  C                                                                     001433
00354  C     STRUCTURAL MASS                                                 001433
00354  C                                                                     001433
00356        DO 80 N=2,6                                                     001433
00361        EMU=(((3.14159*(DOUT(N)/2.)**2*64.4)+WC(N))/32.2)*(DL(N)/2.)    001441
00362        EMV=(((3.14159*(DOUT(N-1)/2.)**2*64.4)+WC(N-1))/32.2)*(DL(N-1)/2.)   001453
00362  C                                                                     001453
00362  C     HYDRODYNAMIC MASS                                               001453
00362  C                                                                     001453
00363        HYDRMX=(3.14159*RHOW*(DOUT(N)/2.)**2)*(DL(N)/2.)                001465
00364        HYDRMY=0.                                                       001474
00365        HYDRMZ=HYDRMX                                                   001475
00366        HYDRNX=(3.14159*RHOW*(DOUT(N-1)/2.)**2)*(DL(N-1)/2.)            001476
00367        HYDRNY=0.                                                       001505
00370        HYDRNZ=HYDRNX                                                   001506
00370  C                                                                     001506
00370  C     INERTIAL TERMS                                                  001506
00370  C                                                                     001506
00371        ERTIAX(1)=0.                                                    001507
00372        ERTIAY(1)=0.                                                    001510
00373        ERTIAZ(1)=0.                                                    001511
00374        IF(N.EQ.1) GO TO 79                                             001512
00376        STH=SIN(THETA(N))                                               001515
00377        CTH=COS(THETA(N))                                               001523
00400        SPH=SIN(PHI(N))                                                 001531
00401        CPH=COS(PHI(N))                                                 001537
00402        STE=SIN(THETA(N-1))                                             001545
00403        CTE=COS(THETA(N-1))                                             001553
00404        SP1=SIN(PHI(N-1))                                               001561
00405        CP1=COS(PHI(N-1))                                               001567
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00406         ERTIAX(N)=EMV+ABS(HYDRNX*CTE)+ABS(HYDRNY*STE*CPI)+ABS(HYDRNZ*STE*S   001575
00406        1PI)+EMU+ABS(HYDRMX*CTH)+ABS(HYDRMY*STH*CPH)+ABS(HYDRMZ*STH*SPH)       001575
00407         ERTIAY(N)=EMV+ABS(HYDRNX*STE)+ABS(HYDRNY*CTE*CPI)+ABS(HYDRNZ*CTE*S   001632
00407        1PI)+EMU+ABS(HYDRMX*STH)+ABS(HYDRMY*CTH*CPH)+ABS(HYDRMZ*CTH*SPH)       001632
00410         ERTIAZ(N)=EMV+ABS(HYDRNY*SPI)+ABS(HYDRNZ*CPI)+EMU+ABS(HYDRMY*SPH)+    001670
00410        1ABS(HYDRMZ*CPH)                                                       001670
00411      79 CONTINUE                                                              001722
00412      80 CONTINUE                                                              001722
00412  C                                                                            001722
00412  C      CHECK FOR BUOYS                                                       001722
00412  C                                                                            001722
00414         DO 90 N=1,6                                                           001722
00417         IB(N)=0                                                               001722
00420      90 CONTINUE                                                              001724
00422         IF(IBUOY.EQ.1.OR.IBUOY.EQ.2) IB(4)=1                                  001724
00424         IF(IBUOY.EQ.2) IB(5)=1                                                001742
00426         DO 100 N=2,6                                                          001756
00431         IF(IB(N).EQ.0) GO TO 99                                               001756
00431  C                                                                            001756
00431  C      COEFFICIENT OF DRAG FOR SPHERE AT REYNOLDS NUMBER RE                  001756
00431  C                                                                            001756
00433         RE=VC(N)*(2.*RAD(N))/1.6E-5                                           001757
00434         CDS1=0.5                                                              001764
00435         CDS2=0.5*(EXP(-((RE-2.0E5)/4.9E4)))                                   001766
00436         CDS3=0.18*(EXP((RE-2.5E5)/1.4E6))                                     001776
00437         CDS4=0.2                                                              002007
00440         IF(RE.GE.3.0E4.AND.RE.LT.2.0E5) CDS=CDS1                              002011
00442         IF(RE.GE.2.0E5.AND.RE.LT.2.5E5) CDS=CDS2                              002031
00444         IF(RE.GE.2.5E5.AND.RE.LT.4.0E5) CDS=CDS3                              002051
00446         IF(RE.GE.4.0E5.AND.RE.LT.1.0E7) CDS=CDS4                              002071
00446  C                                                                            002071
00446  C      DRAG TERMS FOR SPHERE                                                 002071
00446  C                                                                            002071
00450         U=-VC(N)*SIN(THEC)                                                    002111
00451         V=VC(N)*COS(THEC)                                                     002114
00452         UXN=U-R(L-5)                                                          002117
00453         VYN=V-R(L-3)                                                          002121
00454         WZN=-R(L-1)                                                           002123
00455         DBA=0.5*RHOW*CDS*3.14159*(RAD(N))**2                                  002125
00456         DBX=DBA*UXN*ABS(UXN)                                                  002134
00457         DBY=DBA*VYN*ABS(VYN)                                                  002140
00460         DBZ=DBA*WZN*ABS(WZN)                                                  002145
00461         DRGX(N)=DRGX(N)+DBX                                                   002152
00462         DRGY(N)=DRGY(N)+DBY                                                   002154
00463         DRGZ(N)=DRGZ(N)+DBZ                                                   002156
00463  C                                                                            002156
00463  C      BUOY WEIGHT IN WATER                                                  002156
00463  C                                                                            002156
00464         WTWN(N)=WTRM(N)-EXB(N)                                                002160
00464  C                                                                            002160
00464  C      STRUCTURAL MASS OF BUOY                                               002160
00464  C                                                                            002160
00465         EMUB=WT(N)/32.2                                                       002163
00465  C                                                                            002163
00465  C      HYDRODYNAMIC MASS OF BUOY                                             002163
00465  C                                                                            002163
00466         HYDB=(2./3.)*3.14159*RHOW*RAD(N)**3                                   002166
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00466   C                                                                    002166
00466   C     VIRTUAL MASS OF BUOY                                           002166
00466   C                                                                    002166
00467         VIRM=HYDB+LMUB                                                 002173
00470         ERTIAX(N)=ERTIAX(N)+VIRM                                       002175
00471         ERTIAY(N)=ERTIAY(N)+VIRM                                       002177
00472         ERTIAZ(N)=ERTIAZ(N)+VIRM                                       002202
00473      99 CONTINUE                                                       002212
00474     100 CONTINUE                                                       002212
00474   C                                                                    002212
00474   C     DYNAMIC CABLE EQUATIONS                                        002212
00474   C                                                                    002212
00474   C     ANCHOR                                                         002212
00476         D(1)=0.                                                        002212
00477         D(2)=R(1)                                                      002213
00500         D(3)=0.                                                        002215
00501         D(4)=R(3)                                                      002216
00502         D(5)=0.                                                        002220
00503         D(6)=R(5)                                                      002221
00503   C     CABLE ELEMENTS                                                 002221
00504         DO 110 N=2,6                                                   002226
00507         L=N*6                                                          002226
00510         D(L-5)=(DRGX(N)+TX(N)-TX(N-1))/ERTIAX(N)                       002232
00511         D(L-4)=R(L-5)                                                  002237
00512         D(L-3)=(DRGY(N)+TY(N)-TY(N-1))/ERTIAY(N)                       002241
00513         D(L-2)=R(L-3)                                                  002246
00514         D(L-1)=(-WIRM(N)+DRGZ(N)+TZ(N)-TZ(N-1))/ERTIAZ(N)              002250
00515         D(L)=R(L-1)                                                    002256
00516     110 CONTINUE                                                       002262
00516   C     SHIP                                                           002262
00520         D(37)=ACX                                                      002262
00521         D(38)=R(37)                                                    002264
00522         D(39)=0.                                                       002266
00523         D(40)=R(39)                                                    002267
00524         D(41)=ACZ                                                      002271
00525         D(42)=R(41)                                                    002273
00525   C                                                                    002273
00525   C     INTEGRATE EQUATIONS                                            002273
00525   C                                                                    002273
00526         CALL RUNGE(42,R,D,TM,B,M,K)                                    002275
00527         GO TO(20,120),K                                                002306
00530     120 CONTINUE                                                       002320
00530   C                                                                    002320
00530   C     CHECK IF MAXIMUM TENSION HAS BEEN EXCEEDED                     002320
00530   C                                                                    002320
00531         DO 119 N=1,6                                                   002320
00534         IF(T(N).LE.60000.) GO TO 118                                   002320
00536         PRINT 34,T(N),N,TM                                             002324
00543      34 FORMAT(1H1,'CABLE BREAKS AT',F20.5,' LBS AT SEGMENT NUMBER',I5,' A  002333
00543        1T',F10.3,' SECONDS')                                           002333
00544         TMMAX=TM                                                       002333
00545         GO TO 134                                                      002335
00546     118 CONTINUE                                                       002340
00547     119 CONTINUE                                                       002340
00547   C                                                                    002340
00547   C     STORE VALUES EVERY SECOND                                      002340
00547   C                                                                    002340
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00547      C                                                                      002340
00547      C                                                                      002340
00551            IF(TM.LT.TMCH1) GO TO 510                                        002340
00553            PRINT 499                                                        002344
00555        499 FORMAT('     ')                                                  002353
00556            DO 511 N=1,7                                                     002353
00561            L=N*6                                                            002353
00562            PRINT 512,TM,D(L-5),D(L-3),D(L-1),D(L-4),D(L-2),D(L),R(L-4),R(L-2)  002356
00562           1,R(L),T(N),THETA(N),PHI(N)                                       002356
00601        511 CONTINUE                                                         002403
00603            TMCNT=TMCNT+10.                                                  002403
00604        512 FORMAT(7F10.4,4F10.1,2F10.2)                                     002407
00605        510 CONTINUE                                                         002407
00605      C                                                                      002407
00605      C                                                                      002407
00606            IF(TM.LT.TMCT) GO TO 20                                          002407
00610            TMCT=TMCT+1.                                                     002412
00611            ITM=TMCT-TMMAX-TLAST)                                            002415
00612            DO 130 N=1,7                                                     002427
00615            L=N*6                                                            002441
00616            ACC(N,1,ITM)=D(L-5)                                              002444
00617            ACC(N,2,ITM)=D(L-3)                                              002447
00620            ACC(N,3,ITM)=D(L-1)                                              002451
00621            VEL(N,1,ITM)=D(L-4)                                              002453
00622            VEL(N,2,ITM)=D(L-2)                                              002455
00623            VEL(N,3,ITM)=D(L)                                                002457
00624            DISP(N,1,ITM)=R(L-4)                                             002461
00625            DISP(N,2,ITM)=R(L-2)                                             002463
00626            DISP(N,3,ITM)=R(L)                                               002465
00627            IF(N.EQ.7) GO TO 125                                             002467
00631            TNS(N,1,ITM)=T(N)                                                002472
00632            TNS(N,2,ITM)=THETA(N)*57.3                                       002474
00633            TNS(N,3,ITM)=PHI(N)*57.3                                         002477
00634        125 CONTINUE                                                         002503
00635            TNS(7,1,ITM)=TNS(6,1,ITM)                                        002503
00636            TNS(7,2,ITM)=TNS(6,2,ITM)                                        002504
00637            TNS(7,3,ITM)=TNS(6,3,ITM)                                        002506
00640        130 CONTINUE                                                         002513
00642            IF(TM.LT.TMMAX) GO TO 20                                         002513
00642      C                                                                      002513
00642      C     PRINTED OUTPUT                                                   002513
00642      C                                                                      002513
00644        134 CONTINUE                                                         002520
00645            DO 210 N=1,7                                                     002520
00650            L=N*6                                                            002531
00651            PRINT 135,N                                                      002534
00654        135 FORMAT(1H1,'ELEMENT NUMBER',I2)                                  002541
00655            IF(IB(N).EQ.0) GO TO 140                                         002541
00657            PRINT 136                                                        002543
00661        136 FORMAT(1H+,18X,'(INCLUDES SUBSURFACE BUOY)')                     002550
00662        140 CONTINUE                                                         002550
00663            IF(N.EQ.1) GO TO 141                                             002550
00665            GO TO 142                                                        002552
00666        141 CONTINUE                                                         002554
00667            PRINT 143                                                        002554
00671        143 FORMAT(1H+,18X,'(ANCHOR)')                                       002560
00672        142 CONTINUE                                                         002560
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00673         IF(N.EQ.7) GO TO 144                                                       002561
00675         GO TO 146                                                                  002562
00676     144 CONTINUE                                                                   002564
00677         PRINT 147                                                                  002564
00701     147 FORMAT(1H+,13X,'(SHIP)')                                                   002570
00702     146 CONTINUE                                                                   002570
00703         PRINT 145                                                                  002570
00705     145 FORMAT(//1H ,' TIME(SEC)',3X,'ACCELERATION (FT/SEC**2)',10X,               002573
00705        1'VELOCITY (FT/SEC)',13X,'DISPLACEMENT (FT)',6X,'TENSN(LBS)',5X,            002573
00705        2'ANGLES(DEG)')                                                             002573
00706         PRINT 150                                                                  002573
00710     150 FORMAT(/1H ,15X,'X',9X,'Y',9X,'Z',9X,'X',9X,'Y',9X,'Z',9X,'X',9X,'         002577
00710        1Y',9X,'Z',9X,'T',6X,'THETA',7X,'PHI')                                      002577
00711         IMAX=LAST+1                                                                002577
00712         DO 200 J=1,IMAX                                                            002603
00715         NTME=(TMMAX-(TLAST+1.))+J                                                  002611
00716     155 CONTINUE                                                                   002624
00717         PRINT 160,NTME,ACC(N,1,J),ACC(N,2,J),ACC(N,3,J),VEL(N,1,J),VEL(N,2         002624
00717        1,J),VEL(N,3,J),DISP(N,1,J),DISP(N,2,J),DISP(N,3,J),TNS(N,1,J),TNS(         002624
00717        2N,2,J),TNS(N,3,J)                                                          002624
00736     160 FORMAT(I10,6F10.4,4F10.1,2F10.2)                                           002651
00737     200 CONTINUE                                                                   002651
00741     210 CONTINUE                                                                   002651
00743         IF(IPLOT.EQ.0) GO TO 301                                                   002651
00743   C                                                                                002651
00743   C     PLOTS                                                                      002651
00743   C                                                                                002651
00745         PRINT 211                                                                  002653
00747     211 FORMAT(1H1)                                                                002657
00750         CALL MODESG(P,0)                                                           002657
00751         CALL SETSMG(P,93,0.)                                                       002663
00752         ITMAX=LAST+1                                                               002670
00753         TMMAX=TMSTOR                                                               002672
00754         DO 300 N=1,7                                                               002677
00757         XMIN=1.0E5                                                                 002710
00760         YMIN=1.0E5                                                                 002712
00761         ZMIN=1.0E5                                                                 002713
00762         XMAX=-1.0E5                                                                002714
00763         YMAX=-1.0E5                                                                002715
00764         ZMAX=-1.0E5                                                                002716
00765         VXMIN=1.0E5                                                                002717
00766         VYMIN=1.0E5                                                                002720
00767         VZMIN=1.0E5                                                                002721
00770         TNMIN=1.0E5                                                                002722
00771         VXMAX=-1.0E5                                                               002723
00772         VYMAX=-1.0E5                                                               002724
00773         VZMAX=-1.0E5                                                               002725
00774         TNMAX=-1.0E5                                                               002726
00775         TMMIN=TMMAX-TLAST                                                          002727
00776         DO 247 K=20,ITMAX                                                          002735
01001         IF(DISP(N,1,K).LE.XMIN) XMIN=DISP(N,1,K)                                   002735
01003         IF(DISP(N,2,K).LE.YMIN) YMIN=DISP(N,2,K)                                   002742
01005         IF(DISP(N,3,K).LE.ZMIN) ZMIN=DISP(N,3,K)                                   002750
01007         IF(DISP(N,1,K).GE.XMAX) XMAX=DISP(N,1,K)                                   002756
01011         IF(DISP(N,2,K).GE.YMAX) YMAX=DISP(N,2,K)                                   002764
01013         IF(DISP(N,3,K).GE.ZMAX) ZMAX=DISP(N,3,K)                                   002772
01015         IF(VEL(N,1,K).LE.VXMIN) VXMIN=VEL(N,1,K)                                   003000
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01017        IF(VEL(N,2,K).LE.,YMIN) VYMIN=VEL(N,2,K)          003006
01021        IF(VEL(N,3,K).LE.,ZMIN) VZMIN=VEL(N,3,K)          003014
01023        IF(VEL(N,1,K).GE.,VXMAX) VXMAX=VEL(N,1,K)         003022
01025        IF(VEL(N,2,K).GE.,YMAX) VYMAX=VEL(N,2,K)          003030
01027        IF(VEL(N,3,K).GE.,ZMAX) VZMAX=VEL(N,3,K)          003036
01031    247 CONTINUE                                          003046
01033        IF(N.EQ.1) GO TO 245                              003046
01035        ITMAX=26                                          003051
01036        DO 220 K=1,ITMAX                                  003053
01041        C1(K)=DISP(N,1,K)                                 003061
01042        C2(K)=VEL(N,1,K)                                  003062
01043    220 CONTINUE                                          003065
01045        CALL SUBJEG(P,XMIN,VXMIN,XMAX,VXMAX)              003065
01046        CALL GRAPHG(P,0,C1,C2,6,XCHRR,6,VELX,6,TITLE)     003074
01047        CALL POINTG(P,ITMAX,C1,C2)                        003110
01050        CALL LINESG(P,ITMAX,C1,C2)                        003116
01051        CALL PAGEG(P,0,1,1)                               003124
01052        DO 230 K=1,ITMAX                                  003132
01055        C1(K)=DISP(N,2,K)                                 003141
01056        C2(K)=VEL(N,2,K)                                  003142
01057    230 CONTINUE                                          003145
01061        CALL SUBJEG(P,YMIN,VYMIN,YMAX,VYMAX)              003145
01062        CALL GRAPHG(P,0,C1,C2,6,YCHRR,6,VELY,6,TITLE)     003154
01063        CALL POINTG(P,ITMAX,C1,C2)                        003170
01064        CALL LINESG(P,ITMAX,C1,C2)                        003176
01065        CALL PAGEG(P,0,1,1)                               003204
01066        DO 240 K=1,ITMAX                                  003212
01071        C1(K)=DISP(N,3,K)                                 003221
01072        C2(K)=VEL(N,3,K)                                  003222
01073    240 CONTINUE                                          003225
01075        CALL SUBJEG(P,ZMIN,VZMIN,ZMAX,VZMAX)              003225
01076        CALL GRAPHG(P,0,C1,C2,6,ZCHRR,6,VELZ,6,TITLE)     003234
01077        CALL POINTG(P,ITMAX,C1,C2)                        003250
01100        CALL LINESG(P,ITMAX,C1,C2)                        003256
01101        CALL PAGEG(P,0,1,1)                               003264
01102    245 CONTINUE                                          003273
01103        ITMAX=LAST+1                                      003273
01106        DO 219 K=1,ITMAX                                  003301
01107        IF(DISP(N,1,K).LE.XMIN) XMIN=DISP(N,1,K)          003310
01111        IF(DISP(N,2,K).LE.YMIN) YMIN=DISP(N,2,K)          003315
01113        IF(DISP(N,3,K).LE.ZMIN) ZMIN=DISP(N,3,K)          003323
01115        IF(DISP(N,1,K).GE.XMAX) XMAX=DISP(N,1,K)          003331
01117        IF(DISP(N,2,K).GE.YMAX) YMAX=DISP(N,2,K)          003337
01121        IF(DISP(N,3,K).GE.ZMAX) ZMAX=DISP(N,3,K)          003345
01123        IF(TNS(N,1,K).LE.TNMIN) TNMIN=TNS(N,1,K)          003353
01125        IF(TNS(N,1,K).GE.TNMAX) TNMAX=TNS(N,1,K)          003361
01127    219 CONTINUE                                          003376
01131        DO 250 K=1,ITMAX                                  003376
01134        C1(K)=(TMMAX-(ILAST+1.))*K                        003376
01135        C2(K)=TNS(N,1,K)                                  003403
01136    250 CONTINUE                                          003407
01140        CALL SUBJEG(P,TMMIN,TNMIN,TMMAX,TNMAX)            003407
01141        CALL GRAPHG(P,0,C1,C2,6,TIM,6,TEN,6,TITLE)        003416
01142        CALL POINTG(P,ITMAX,C1,C2)                        003432
01143        CALL LINESG(P,ITMAX,C1,C2)                        003440
01144        CALL PAGEG(P,0,1,1)                               003446
01145        IF(N.EQ.1) GO TO 285                              003456
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01147   497*        DO 260 K=1,ITMAX                                              003466
01152   498*        C2(K)=DISP(N,1,K)                                             003466
01153   499*    260 CONTINUE                                                      003470
01155   500*        CALL SUBJEG(P,TMMIN,XMIN,TMMAX,XMAX)                          003470
01156   501*        CALL GRAPHG(P,0,C1,C2,6,TIM,6,XCHRR,6,TITLE)                  003477
01157   502*        CALL POINTG(P,ITMAX,C1,C2)                                    003513
01160   503*        CALL LINESG(P,ITMAX,C1,C2)                                    003521
01161   504*        CALL PAGEG(P,0,1,1)                                           003527
01162   505*        DO 270 K=1,ITMAX                                              003535
01165   506*        C2(K)=DISP(N,2,K)                                             003544
01166   507*    270 CONTINUE                                                      003546
01170   508*        CALL SUBJEG(P,TMMIN,YMIN,TMMAX,YMAX)                          003546
01171   509*        CALL GRAPHG(P,0,C1,C2,6,TIM,6,YCHRR,6,TITLE)                  003555
01172   510*        CALL POINTG(P,ITMAX,C1,C2)                                    003571
01173   511*        CALL LINESG(P,ITMAX,C1,C2)                                    003577
01174   512*        CALL PAGEG(P,0,1,1)                                           003605
01175   513*        DO 280 K=1,ITMAX                                              003613
01200   514*        C2(K)=DISP(N,3,K)                                             003622
01201   515*    280 CONTINUE                                                      003624
01203   516*        CALL SUBJEG(P,TMMIN,ZMIN,TMMAX,ZMAX)                          003624
01204   517*        CALL GRAPHG(P,0,C1,C2,6,TIM,6,ZCHRR,6,TITLE)                  003633
01205   518*        CALL POINTG(P,ITMAX,C1,C2)                                    003647
01206   519*        CALL LINESG(P,ITMAX,C1,C2)                                    003655
01207   520*        CALL PAGEG(P,0,1,1)                                           003663
01210   521*    285 CONTINUE                                                      003673
01211   522*    300 CONTINUE                                                      003673
01213   523*        CALL EXITG(P)                                                 003673
01214   524*    301 CONTINUE                                                      003677
01215   525*        TMMAX=TMSTOR                                                  003677
01215   526*  C                                                                   003677
01216   527*        RETURN                                                        003700
01217   528*        END                                                           004110

     END OF COMPILATION:        NO DIAGNOSTICS.

GPHLP
FURPUR 0026-01/11-04:57
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Appendix F

VALUES OF EACH ELEMENT OF THE TIME SERIES USED TO DESCRIBE SHIP'S VERTICAL AND LATERAL MOTIONS

This appendix lists all of the values of ω_1, $S_{h_{x_1}}$, ϵ_{x_1}, $S_{h_{z_1}}$, and ϵ_{z_1} used in equations (68), (69), and (70). Three ship headings; BETA = 90°, 135°, 180°; are used for cases 12, 13, and 14 respectively. (See chapter 4.) Thus, three sets of values will be given, one for each heading.

BETA = 90°

w_i	$S_{\ell z_i}$	ε_{z_i}	$S_{\ell x_i}$	ε_{x_i}	w_{i+1}	$S_{\ell z_{i+1}}$	$\varepsilon_{z_{i+1}}$	$S_{\ell x_{i+1}}$	$\varepsilon_{x_{i+1}}$
.4831	.0000	.0125	.0000	.0505	.4833	.0029	2.5799	.0028	2.6179
.4839	.0053	5.8041	.0051	5.8421	.4848	.0074	3.1236	.0071	3.1616
.4862	.0096	2.0287	.0092	2.0667	.4879	.0120	3.8681	.0115	3.9061
.4901	.0146	5.9648	.0140	6.0028	.4926	.0175	2.7121	.0168	2.7501
.4955	.0207	3.4010	.0198	3.4390	.4968	.0240	2.5886	.0230	2.6266
.5024	.0276	2.5731	.0264	2.6111	.5065	.0314	5.8544	.0299	5.8964
.5109	.0353	.4097	.0337	.4527	.5158	.0395	4.9092	.0377	4.9542
.5210	.0438	3.6396	.0418	3.6896	.5266	.0523	3.4171	.0495	3.4671
.5326	.0634	2.9653	.0595	3.0203	.5389	.0743	6.0026	.0694	6.0606
.5457	.0851	2.4352	.0793	2.4972	.5529	.0960	6.1445	.0893	6.2105
.5604	.1070	.2604	.0993	.3304	.5683	.1228	2.7663	.1132	2.8413
.5766	.1414	3.7703	.1296	3.8463	.5853	.1597	2.0789	.1457	2.1589
.5944	.1778	5.8207	.1617	5.9107	.6039	.1959	5.2773	.1777	5.3693
.6137	.2185	2.2562	.1967	2.3512	.6240	.2408	.5995	.2155	.7015
.6346	.2630	4.1710	.2344	4.2790	.6456	.2853	.6435	.2533	.7535
.6570	.3078	1.3917	.2718	1.5077	.6688	.3303	3.7592	.2903	3.8802
.6810	.3521	4.1661	.3078	4.2941	.6935	.3727	.3518	.3234	.4858
.7065	.3935	6.0620	.3393	6.2020	.7198	.4118	2.3342	.3522	2.4792
.7335	.4297	4.3366	.3646	4.4966	.7476	.4446	.8059	.3740	.9809
.7621	.4589	4.5459	.3826	4.7259	.7770	.4713	5.0016	.3890	5.1876
.7923	.4820	4.6990	.3936	4.8910	.8079	.4911	3.5674	.3964	3.7674
.8239	.4965	3.4918	.3974	3.7068	.8404	.5042	2.2141	.3967	2.4441
.8572	.5079	3.0519	.3944	3.2919	.8744	.5110	2.9042	.3908	3.1592
.8920	.5129	2.7346	.3858	3.0046	.9099	.5138	4.4963	.3797	4.7813
.9283	.5138	1.6860	.3726	1.9860	.9470	.5124	5.3313	.3645	5.6563

BETA = 135°

W_i	$S_{\ell z i}$	$E_{z i}$	$S_{\ell x i}$	$E_{x i}$	W_{i+1}	$S_{\ell z i+1}$	$E_{z i+1}$	$S_{\ell x i+1}$	$E_{x i+1}$
.4831	.0000	.0125	.0000	.4125	.4833	.0032	2.5799	.0021	2.9799
.4839	.0059	5.8041	.0038	6.2041	.4848	.0083	3.1236	.0054	3.5236
.4862	.0109	2.0287	.0070	2.4287	.4879	.0137	3.8681	.0088	4.2681
.4901	.0168	5.9648	.0107	6.3648	.4926	.0202	2.7121	.0128	3.1121
.4955	.0238	3.4010	.0151	3.8030	.4988	.0277	2.5886	.0176	2.9916
.5024	.0319	2.5731	.0202	2.9781	.5065	.0363	5.8544	.0229	6.2644
.5109	.0409	.4097	.0258	.8247	.5158	.0458	4.9092	.0288	5.3292
.5210	.0508	3.6396	.0320	4.0696	.5266	.0613	3.4171	.0380	3.8571
.5326	.0752	2.9653	.0459	3.4153	.5389	.0888	6.0026	.0536	6.4626
.5457	.1022	2.4352	.0613	2.9052	.5529	.1157	6.1445	.0691	6.6245
.5604	.1293	.2604	.0769	.7504	.5683	.1503	2.7663	.0881	3.2663
.5766	.1756	3.7703	.1014	4.2803	.5853	.2002	2.0789	.1144	2.5989
.5944	.2244	5.8207	.1274	6.3607	.6039	.2486	5.2773	.1403	5.8373
.6137	.2827	2.2562	.1566	2.8262	.6240	.3160	.5995	.1728	1.1995
.6346	.3490	4.1710	.1888	4.7810	.6456	.3823	.6435	.2051	1.2735
.6570	.4198	1.3917	.2222	2.0317	.6688	.4570	3.7592	.2393	4.4342
.6810	.4948	4.1661	.2557	4.8561	.6935	.5335	.3518	.2710	1.0668
.7065	.5721	6.0620	.2864	6.7920	.7198	.6103	2.3342	.3000	3.1042
.7335	.6483	4.3366	.3132	5.1366	.7476	.6847	.8059	.3247	1.6459
.7621	.7205	4.5459	.3354	5.4059	.7770	.7548	5.0016	.3441	5.9016
.7923	.7875	4.6990	.3513	5.6490	.8079	.8185	3.5674	.3568	4.5474
.8239	.8475	3.4918	.3608	4.5168	.8404	.8749	2.2141	.3633	3.2841
.8572	.9012	3.0519	.3646	4.1719	.8744	.9237	2.9042	.3639	4.0792
.8920	.9433	2.7346	.3615	3.9646	.9099	.9608	4.4963	.3578	5.7663
.9283	.9762	1.6860	.3528	3.0060	.9470	.9895	5.3313	.3462	6.7213

BETA = 135°

W_i	S_{lzi}	E_{zi}	S_{lxi}	E_{xi}	W_{i+1}	S_{lzi+1}	E_{zi+1}	S_{lxi+1}	E_{xi+1}
.9661	1.0028	4.3333	.3389	5.7733	.9857	1.0075	2.1606	.3301	3.6606
1.0056	1.0118	2.4800	.3203	4.0400	1.0259	1.0107	5.1920	.3096	6.8020
1.0465	1.0088	1.5916	.2978	3.2616	1.0676	1.0041	1.8399	.2855	3.5799
1.0890	.9977	3.6154	.2719	5.4154	1.1109	.9812	.0295	.2588	1.8695
1.1331	.9631	5.8990	.2445	7.7690	1.1557	.9431	2.4066	.2298	4.3086
1.1787	.9164	4.9127	.2150	6.8427	1.2021	.8814	.9350	.2003	2.8950
1.2258	.8399	.8681	.1871	2.7681	1.2500	.7928	.2159	.1732	2.0739
1.2745	.7397	3.8145	.1574	4.9845	1.2995	.6820	2.9536	.1425	4.7136
1.3248	.6190	3.7743	.1303	5.3843	1.3505	.5451	.2900	.1162	1.7530
1.3765	.4692	4.6000	.1019	5.7300	1.4030	.4137	4.6010	.0921	5.7610
1.4299	.3462	1.1285	.0805	2.0935	1.4571	.2748	3.5946	.0688	4.3946
1.4848	.2293	2.3799	.0616	2.9799	1.5128	.1692	.6888	.0530	1.1488
1.5412	.1111	3.4924	.0455	3.8424	1.5700	.0925	6.0899	.0418	6.3199
1.5991	.0678	.0560	.0374	.1870	1.6287	.0541	4.5323	.0348	4.6523
1.6586	.0517	2.6680	.0333	2.7730	1.6890	.0491	3.9707	.0317	4.0627
1.7197	.0463	1.6688	.0303	1.7548	1.7508	.0432	5.2955	.0287	5.3755
1.7823	.0396	.1910	.0268	.2660	1.8142	.0349	5.4516	.0245	5.5166
1.8465	.0292	3.3601	.0219	3.4051	1.8791	.0246	5.6802	.0196	5.7022
1.9122	.0194	.0065	.0172	.0185	1.9456	.0141	1.6000	.0147	1.5900
1.9794	.0107	5.4180	.0127	5.3780	2.0136	.0052	4.3815	.0101	4.3415
2.0482	.0050	1.4546	.0087	1.4146	2.0832	.0047	5.0626	.0071	5.0226
2.1185	.0046	.9919	.0067	.9619	2.1543	.0046	2.3343	.0070	2.3043
2.1904	.0047	.8976	.0068	.8776	2.2269	.0047	5.5249	.0061	5.5099
2.2638	.0046	4.2004	.0054	4.2114	2.3011	.0042	4.6728	.0050	4.6628
2.3388	.0038	2.5547	.0047	2.5447	2.3768	.0034	3.2059	.0043	3.1959
2.4153	.0028	2.9858	.0039	2.9758					

BETA = 180°

W_i	Sl_{zi}	E_{zi}	W_{i+1}	Sl_{zi+1}	E_{zi+1}
.4831	.0000	.0125	.4833	.0035	2.5799
.4839	.0064	5.8041	.4848	.0091	3.1236
.4862	.0119	2.0287	.4879	.0151	3.8661
.4901	.0185	5.9648	.4926	.0223	2.7121
.4955	.0263	3.4010	.4988	.0307	2.5886
.5024	.0353	2.5731	.5065	.0402	5.8544
.5109	.0453	.4097	.5158	.0507	4.9092
.5210	.0563	3.6396	.5266	.0683	3.4171
.5326	.0843	2.9653	.5389	.0998	6.0026
.5457	.1152	2.4352	.5529	.1305	6.1445
.5604	.1460	.2604	.5683	.1704	2.7663
.5766	.1998	3.7703	.5853	.2284	2.0769
.5944	.2565	5.8207	.6039	.2845	5.2773
.6137	.3247	2.2562	.6240	.3639	.5995
.6346	.4025	4.1710	.6456	.4418	.6435
.6570	.4868	1.3917	.6688	.5314	3.7592
.6810	.5760	4.1661	.6935	.6208	.3518
.7065	.6656	6.0620	.7198	.7089	2.3342
.7335	.7520	4.3366	.7476	.7948	.8059
.7621	.8354	4.5459	.7770	.8710	5.0016
.7923	.9031	4.6990	.8079	.9316	3.5674
.8239	.9564	3.4918	.8404	.9786	2.2141
.8572	1.0008	3.0519	.8744	1.0125	2.9042
.8920	1.0161	2.7346	.9099	1.0192	4.4963
.9283	1.0156	1.6860	.9470	1.0070	5.3313

BETA = 180°

W_i	$S_{\ell z i}$	$E_{z i}$	W_{i+1}	$S_{\ell z i+1}$	$E_{z i+1}$
.9661	.9971	4.3333	.9857	.9747	2.1606
1.0056	.9497	2.4800	1.0259	.9165	5.1920
1.0465	.8792	1.5916	1.0676	.8350	1.8399
1.0890	.7855	3.6154	1.1109	.7335	.0295
1.1331	.6736	5.8990	1.1557	.6025	2.4086
1.1787	.5322	4.9127	1.2021	.4652	.9350
1.2258	.4064	.8681	1.2500	.3428	.2159
1.2745	.2595	3.8145	1.2995	.1865	2.9536
1.3248	.1606	3.7743	1.3505	.1278	.2900
1.3765	.0962	4.6000	1.4030	.0926	4.6010
1.4299	.0887	1.1285	1.4571	.0876	3.5946
1.4848	.0938	2.3799	1.5128	.0999	.6888
1.5412	.0983	3.4924	1.5700	.0839	6.0899
1.5991	.0655	.0560	1.6287	.0507	4.5323
1.6586	.0365	2.6680	1.6890	.0186	3.9707
1.7197	.0149	1.6688	1.7508	.0127	5.2955
1.7823	.0107	.1910	1.8142	.0100	5.4516
1.8465	.0093	3.3601	1.8791	.0085	5.6802
1.9122	.0075	.0065	1.9456	.0064	1.6000
1.9794	.0052	5.4180	2.0136	.0037	4.3815
2.0482	.0028	1.4546	2.0832	.0013	5.0626
2.1185	.0021	.9919	2.1543	.0033	2.3343
2.1904	.0038	.8976	2.2269	.0038	5.5249
2.2638	.0038	4.2004	2.3011	.0039	4.6728
2.3388	.0038	2.5547	2.3768	.0034	3.2059
2.4153	.0028	2.9658			

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