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A FORTRAN IV PROGRAM FOR THE THREE-DIMENSIONAL STEADY-STATE CONFIGURATION OF EXTENSIBLE FLEXIBLE CABLE SYSTEMS

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Bethesda, Maryland

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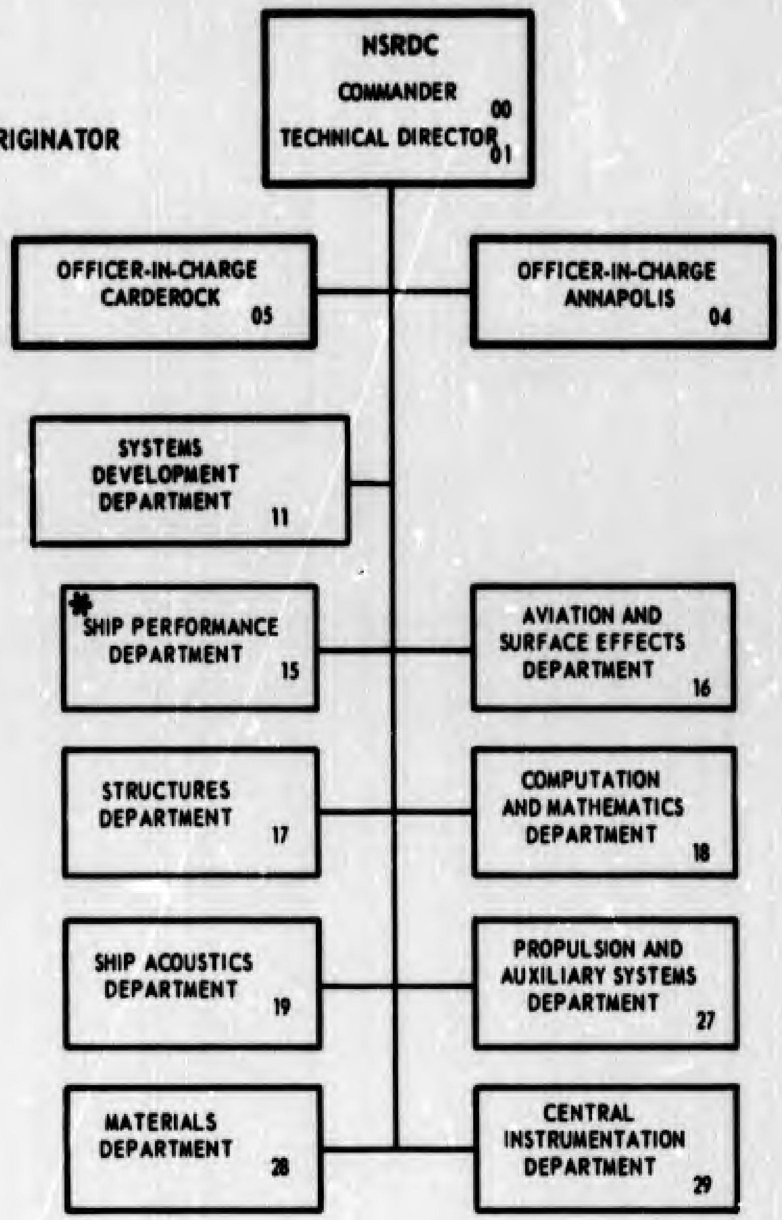

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A detailed description is given of Program CAB3E, a general FORTRAN IV program for predicting the three-dimensional, steady-state configuration of extensible flexible cable systems. The cable system may consist of an arbitrary number of different cable segments and intermediate bodies. All but the initial body are restricted to simple bodies having only weight and

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drag forces. The description includes the equations of equilibrium for the cable and intermediate bodies, the subroutines of the program, and instructions for program usage. Several sample problems are included.

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NOTATION

$[A]$	Transformation matrix = $[\theta]\,[\phi_V]$
$[A_f]$	Transformation matrix = $[\psi + \gamma]\,[A]$
A_{nm}	Numerical coefficient
A_{n0}	Numerical coefficient
A_{tm}	Numerical coefficient
A_{t0}	Numerical coefficient
B	Buoyancy per unit length
B_{nm}	Numerical coefficient
B_{tm}	Numerical coefficient
C_D	Drag coefficient
$C_D A$	Drag area
C_L	Side force coefficient
C_c	Camber lift coefficient factor
C_γ	Side force coefficient slope
c	Velocity of fluid relative to cable
D	Drag force
d	Cable thickness
E	Drag force per unit length in the Z-direction
e	Cable strain = $(ds - ds_0)/ds_0$
F	Force
F_n	Drag force per unit length normal to the cable
f	Ratio of maximum camber to chord
G	Drag force per unit length tangential to the cable
h	Cable fairing chord
I	Drag force per unit length in the X-direction
$\vec{i}_c$	Unit vector in the X-direction
$\vec{j}_c$	Unit vector in the Y-direction

K_s	Experimental constant for stranded cables
$\vec{k}_c$	Unit vector in the Z-direction
L	Side force per unit length
p	Poisson's ratio
R	Drag force per unit length when the cable segment is normal to the stream = $(1/2)\ \rho\ C_D\ dc^2$
Re	Reynolds number = cd/ν
S	Total cable length
s	Distance measured along the cable, or scope
T	Cable tension
Wa	Weight per unit length in vacuum
X	One of the two coordinate directions normal to a cable segment
X_f	Coordinate direction parallel to the nose-tail line of the fairing
x	Horizontal direction positive to the right
x^1	Intermediate coordinate direction
Y	Coordinate direction tangential to a cable segment
y	Vertical direction positive downward
y^1	Intermediate coordinate direction
Z	One of the two coordinate directions normal to a cable segment
Z_f	Coordinate direction in the fairing section plane normal to the nose-tail line
z	Horizontal direction positive into the paper
z^1	Intermediate coordinate direction
α	Angle which the current makes with the x-direction
γ	Angle of attack in fairing section plane between $\vec{c}_n$ and X_f
θ	Angular rotation about the x^1-axis
$[\theta]$	Transformation matrix associated with θ
ν	Fluid kinematic viscosity
ρ	Fluid mass density
ϕ_r	Angle between the current and the cable segment

ϕ_V	Angular rotation about the z-axis
$[\phi_V]$	Transformation matrix associated with ϕ_V
ϕ_y	Angle between the tangent to the cable and the vertical y-axis
ψ	Angle in fairing section plane between $\vec{c}_n$ and X
$(\psi + \gamma)$	Angular rotation about the Y-axis
$[\psi + \gamma]$	Transformation matrix associated with $(\psi + \gamma)$

Subscripts

B	Intermediate body
c	Camber
F	Faired cable
n	Normal to the cable
0	Reference state
p	Angle of attack
S	Stranded cable
t	Tangential to the cable
X	X-direction
x	x-direction
Y	Direction tangent to the cable
y	Vertical direction
Z	Z-direction
Z_f	Z_f-direction
z	z-direction

ABSTRACT

A detailed description is given of Program CAB3E, a general FORTRAN IV program for predicting the three-dimensional, steady-state configuration of extensible flexible cable systems. The cable system may consist of an arbitrary number of different cable segments and intermediate bodies. All but the initial body are restricted to simple bodies having only weight and drag forces. The description includes the equations of equilibrium for the cable and intermediate bodies, the subroutines of the program, and instructions for program usage. Several sample problems are included.

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INTRODUCTION

This report presents a detailed description of Program CAB3E, a general FORTRAN IV program for predicting the three-dimensional, steady-state configuration of extensible flexible cable systems. Program CAB3E allows the cable to take any configuration and is a generalization of earlier versions[1,2] which were restricted to moored cables. Other major generalizations include (1) the addition of side forces which act on stranded cables and faired cables with camber or angle of attack and (2) allowance for the cable to lie in two fluid media, e.g., as in a helicopter towing situation. Program CAB3E is believed to be one of the most comprehensive and general flexible cable programs available in the open literature. Various versions of this program have been used extensively throughout the U.S. Navy and in a

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[1] Wang, H.T., "Effect of Nonplanar Current Profiles on the Configuration of Moored Cable Systems," NSRDC Report 3692 (Oct 1971). A complete listing of references is given on page 68.

[2] Wang, H.T. and B.L. Webster, "Current Profiles Which Give Rise to Nonunique Solutions of Moored Cable Systems," Paper OTC-1538, Fourth Annual Offshore Technology Conference, Houston, Texas (May 1972).

number of industrial organizations. The present program represents a significant extension of the capabilities of the Cuthill Program,[3] a two-dimensional cable program which has been used extensively at the Naval Ship Research and Development Center and elsewhere.

The present report describes the equations which form the basis of the program. Equations which have been given previously[1] are simply summarized. Those which are new to the present report are given in greater detail. Determination of the angle of attack of faired cables is considered in some detail in Appendix A. Two linearized algebraic equations which greatly simplify the cable twisting problem are derived and their applicability is briefly discussed.

A description of each of the subroutines of the program is also given. A considerable portion of the report is devoted to instructions on use of the program. Each of the input variables, by means of which data are entered into the program, is defined and the output is described. Several sample problems are presented to illustrate program usage. The listing of the program is given in Appendix B.

The manner in which the program is to be used depends on a number of factors, including the particular application being considered, the accuracy desired, the user's knowledge of computer programming, and his knowledge of the mechanical behavior and properties of the particular cable system under consideration. In the form indicated in Appendix B, the program can conveniently solve a wide range of initial-value cable problems. These problems are characterized by the fact that conditions at one end of the cable are known in advance. The hydrodynamic loading along the cable can be given in a somewhat more general form by changing a few cards in Subroutine DAUX and the side forces along a faired cable can be calculated more accurately by specifying the values for several fairing variables in Subroutine TWIST. For boundary-value problems where one or more conditions must be iterated before prescribed conditions at both ends are satisfied, the user may choose one of two alternatives: (1) he may either read into the program a parametric variation of the required conditions or (2) he may program an iteration scheme into Subroutine ITERA. Finally, the user may program a more accurate modeling of the cable system, e.g., by adding one or more moment differential equations of equilibrium for the cable or by formulating a more general description of the forces acting on the intermediate bodies which are presently restricted to be simple bodies having only weight and drag forces. Fundamental changes of this type will, of course, add to the complexity of the program logic with a resultant increase in computer time and input variables. This is illustrated by Appendix A which discusses the complexity added by introduction of the differential equation for twist.

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[3]Cuthill, E., "A FORTRAN IV Program for the Calculation of the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," NSRDC Report 2531 (Feb 1968).

DERIVATION OF EQUATIONS

Figure 1 shows the coordinate systems used in the present study. The directions of the (x,y,z) spatial coordinate system are fixed, with the y-axis positive in the direction of gravity. As shown in Figure 1, the origin of this coordinate system lies directly above or below the initial point of the cable, which is defined as the point at which conditions are prescribed in order to start the integration of the equations. In other words, x = z = 0 at the initial point while y = SUBM, as shown in Figure 1. For towed and moored cable systems, the initial point respectively corresponds to the point of attachment of the cable to the towed body and to the moored buoy. For these systems, the variable SUBM may conveniently be taken to represent the distance of the body or buoy from the ocean surface.

The differential equations are derived for a coordinate system attached to the cable and called the cable coordinate system. This coordinate system is denoted by (X,Y,Z), with the Y-axis directed along the cable. As shown in Figure 1, the cable coordinate system may be obtained from the spatial coordinate system by first rotating the spatial system by an angle ϕ_V about the z-axis and then rotating the intermediate (x^1, y^1, z^1) system by an angle θ about the x^1-axis. The direction cosines between the spatial and cable coordinate systems, derived earlier,[1] are shown in Figure 1. Since the orientation of the cable changes along the cable, the angles θ and ϕ_V are functions of the cable scope s.

The following three differential equations of equilibrium are obtained for the cable in an arbitrary stretched condition by using the transformation matrix [A] given in Appendix A:

$$- T \cos \theta \frac{d\phi_V}{ds} + I + L_X + \sin \phi_V \, W = 0 \tag{1}$$

$$\frac{dT}{ds} + G + \cos \theta \cos \phi_V \, W = 0 \tag{2}$$

$$T \frac{d\theta}{ds} + E + L_Z - \sin \theta \cos \phi_V \, W = 0 \tag{3}$$

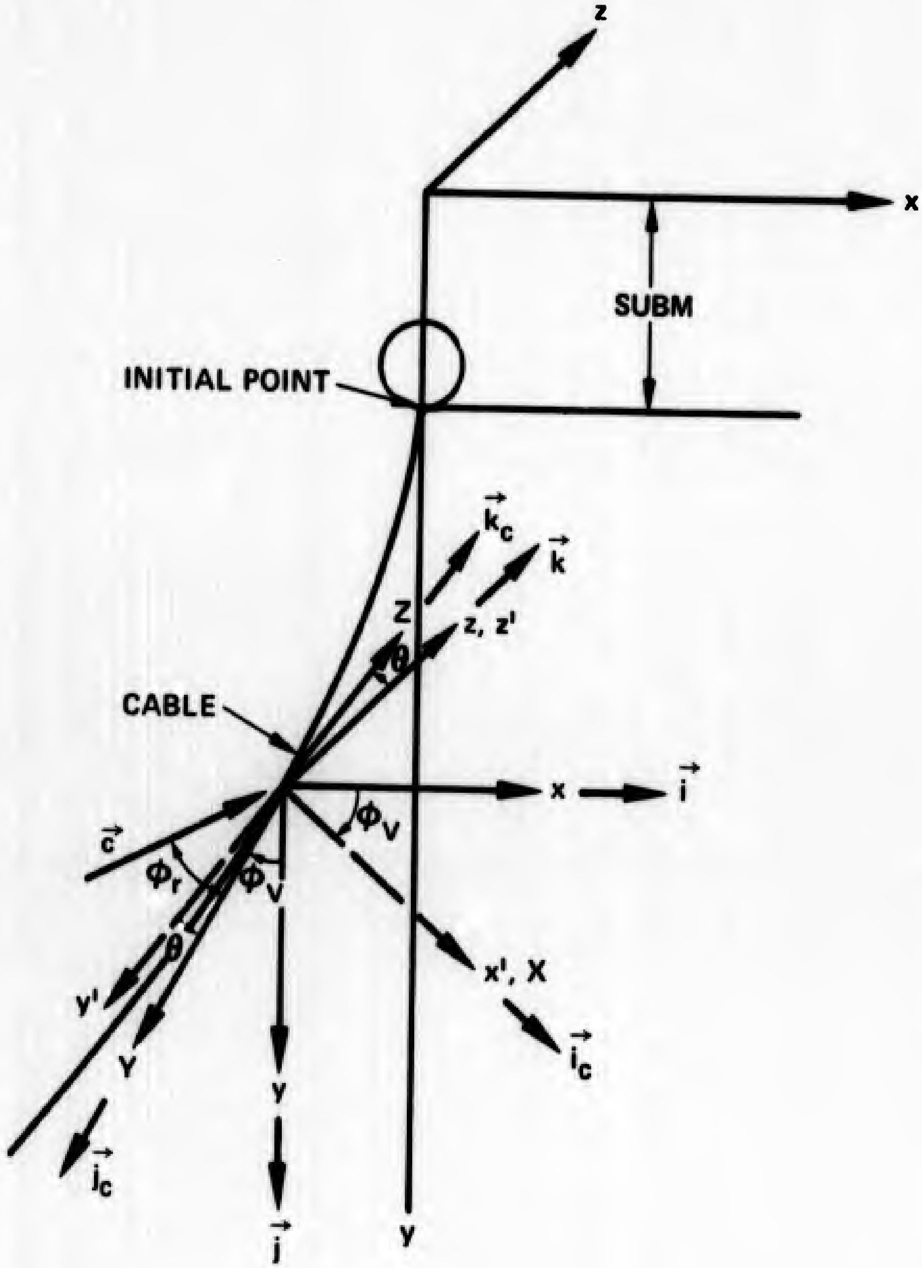
where s = stretched cable scope

W = weight per unit length in fluid of the stretched cable

T = cable tension

I,G,E = fluid drag forces per unit length acting on the stretched cable in the X,Y,Z directions, respectively

L_X, L_Z = fluid side forces per unit length acting on the stretched cable in the X,Z directions, respectively



$\cos(X, x) = \cos\phi_V$	$\cos(X, y) = \sin\phi_V$	$\cos(X, z) = 0$
$\cos(Y, x) = -\cos\theta\sin\phi_V$	$\cos(Y, y) = \cos\theta\cos\phi_V$	$\cos(Y, z) = \sin\theta$
$\cos(Z, x) = \sin\theta\sin\phi_V$	$\cos(Z, y) = -\sin\theta\cos\phi_V$	$\cos(Z, z) = \cos\theta$

Figure 1 – Geometrical Configuration of Cable System

The above equations are similar to the three differential equations of equilibrium given earlier[1] except that the side forces L_X and L_Z have been added.

Wang[1] relates the incremental cable length ds and the forces per unit length for the stretched cable to the respective quantities at a reference state where all the cable parameters are known. This reference state is taken to occur at $T = T_0$, where T_0 need not be equal to zero. The use of the reference tension concept is particularly useful for highly extensible cables which undergo large changes in cable dimensions for relatively small changes in tension. In these cases, the reading in of reference parameters corresponding to a tension in the neighborhood of the actual tensions in the cable will result in a more accurate definition of the steady-state dimensions of the cable. For nearly inextensible cables, it is probably most convenient to take the reference tension as zero. From the relations given in Wang,[1] the relationships among ds, I, G, E, L_X, and L_Z in terms of these quantities at the reference state $T = T_0$ are given by

$$ds = (1 + e)\, ds_0 \tag{4}$$

$$I = (1 - pe)\, I_0 \tag{5a}$$

$$G = (1 - pe)\, G_0 \tag{5b}$$

$$E = (1 - pe)\, E_0 \tag{5c}$$

$$L_X = (1 - pe)\, L_{X0} \tag{5d}$$

$$L_Z = (1 - pe)\, L_{Z0} \tag{5e}$$

Subscript 0 denotes quantities for the reference state where $T = T_0$. In the above, e is cable strain and is a measured function of $(T - T_0)$ and p is Poisson's ratio. Equations (5a) to (5e) are based on the assumption that when the cable stretches from ds_0 to $ds_0\ (1 + e)$, the cross-sectional dimensions of the cable contract by the factor $(1 - pe)$.

Wang[1] breaks the weight per unit length W into a weight per unit length in vacuum and a buoyancy force per unit length. The calculations of the buoyancy force, which basically depends on the volume of the cable segment, require a knowledge of the cross-sectional area of the cable. This area is sometimes inconvenient to obtain precisely for cables with non-circular cross sections. Also, in actual practice, the reference-state cable weight in fluid W_0 is usually given. Accordingly, W_0 is considered to be an input into the program. W is given in terms of W_0 by assuming that the weight in fluid of a given cable segment does not change as it stretches to a new length ds, i.e.,

$$W ds = W_0 \, ds_0 \tag{6}$$

The above formula is strictly correct only if the cable preserves its volume while stretching or if the cable is inextensible. For cases where the cable stretches appreciably with an appreciable change in volume, it is more accurate to use the formulation given earlier.[1] On using Equation (4), the above equation becomes

$$W = \frac{W_0}{1 + e} \tag{7}$$

When Equations (4), (5), and (7) are substituted into Equations (1)–(3) and Equation (4) is rewritten as a differential equation, the following four differential equations are obtained in which all of the cable parameters are expressed in terms of known cable parameters for the reference state:

$$-T \cos\theta \frac{d\phi_V}{ds_0} + I_0 (1 - pe)(1 + e) + L_{X0} (1 - pe)(1 + e) + \sin\phi_V \, W_0 = 0 \tag{8}$$

$$\frac{dT}{ds_0} + G_0 (1 - pe)(1 + e) + \cos\theta \cos\phi_V \, W_0 = 0 \tag{9}$$

$$T \frac{d\theta}{ds_0} + E_0 (1 - pe)(1 + e) + L_{Z0} (1 - pe)(1 + e) - \sin\theta \cos\phi_V \, W_0 = 0 \tag{10}$$

$$\frac{ds}{ds_0} = 1 + e \tag{11}$$

The differential equations for cable displacements are obtained from the direction cosines given in Figure 1. Noting that ds = dY and using Equation (4), we can obtain the following three differential equations for x, y, and z in terms of ds_0:

$$\frac{dx}{ds_0} = -(1 + e) \cos\theta \sin\phi_V \tag{12}$$

$$\frac{dy}{ds_0} = (1 + e) \cos\theta \cos\phi_V \tag{13}$$

$$\frac{dz}{ds_0} = (1 + e) \sin \theta \qquad (14)$$

Since e is a given function of $(T - T_0)$, Equations (8)–(14) represent seven differential equations for the seven dependent variables T, θ, ϕ_V, s, x, y, and z.

EQUATIONS FOR FLUID FORCES

The fluid drag forces I_0, G_0, and E_0 as well as the fluid side forces L_{X0} and L_{Z0} arise due to the fluid velocity relative to the cable system. In the present study, the relative fluid velocity $\vec{c}$ is assumed to have components in only the horizontal (x,z) plane. This is the usual case for ocean currents.[4] The components of $\vec{c}$ in the spatial coordinate system are given by

$$\vec{c} = \begin{Bmatrix} c_x \\ c_y \\ c_z \end{Bmatrix} = \begin{Bmatrix} c \cos \alpha \\ 0 \\ c \sin \alpha \end{Bmatrix} \qquad (15)$$

where c(y) is the magnitude of $\vec{c}$ and is a function of the depth y, and α is the angle which the relative velocity makes with the x-axis. The above decomposition of the relative velocity into magnitude and direction makes it convenient to enter ocean current profiles into the present program since they are usually given in this manner.[4] Convenient choices for the x-direction may be the direction of tow for towed cable systems, the direction of the surface current for a cable system moored in the ocean, or some assigned compass direction.

The fluid drag and side forces are most conveniently obtained by expressing the relative velocity in the cable (X,Y,Z) coordinate system. On using the transformation matrix [A] given in Appendix A, these components are found to be

$$c_X = c\,(\cos \phi_V \, \cos \alpha) \qquad (16a)$$

$$c_Y = c\,(-\cos \theta \, \sin \phi_V \, \cos \alpha + \sin \theta \, \sin \alpha) \qquad (16b)$$

$$c_Z = c\,(\sin \theta \, \sin \phi_V \, \cos \alpha + \cos \theta \, \sin \alpha) \qquad (16c)$$

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[4] U.S. Naval Oceanographic Office, "Oceanographic Atlas of the North Atlantic Ocean, Section I, Tides and Currents," USNOO Publication 700 (1965).

Fluid Drag Forces

The fluid drag forces are those forces due to $\vec{c}$ which occur in the plane formed by $\vec{c}$ and the cable segment. These forces are usually divided into the normal drag force F_{n0} and the tangential drag force G_0. These forces are functions of ϕ_r, the angle between the relative velocity and the cable segment. Surveys by Springston[5] and by Casarella and Parsons[6] indicate that numerous different functions have been proposed for F_{n0} and G_0. Springston gives a general mathematical form to describe these functions as a trigonometric series:

$$F_{n0} = R_0 \left[A_{n0} + \sum_{m=1}^{\infty} A_{nm} \cos m\phi_r + B_{nm} \sin m\phi_r \right] \tag{17}$$

$$|G_0| = R_0 \left[A_{t0} + \sum_{m=1}^{\infty}{}' A_{tm} \cos m\phi_r + B_{tm} \sin m\phi_r \right] \tag{18}$$

where $R_0 = \rho C_D d_0 c^2/2$ is the cable drag when cable is normal to $\vec{c}$

ρ = fluid density

C_D = drag coefficient of the cable

d_0 = thickness of the cable at the reference state

$A_{n0}, A_{nm}, B_{nm}, A_{t0}, A_{tm}, B_{tm}$ = numerical coefficients

ϕ_r = angle between the relative fluid velocity vector and the cable segment

$$\sin \phi_r = c_n/c \tag{19a}$$

$$\cos \phi_r = |c_Y|/c \tag{19b}$$

$$c_n = \sqrt{c^2 - c_Y{}^2} = \sqrt{c_X{}^2 + c_Z{}^2}$$

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[5] Springston, G.B., Jr., "Generalized Hydrodynamic Loading Functions for Bare and Faired Cables in Two-Dimensional Steady-State Cable Configurations," NSRDC Report 2424 (Jun 1967).

[6] Casarella, M.J. and M. Parsons, "A Survey of Investigations on the Configuration and Motion of Cable Systems under Hydrodynamic Loading," Marine Tech. Soc. J., Vol. 4, No. 4, pp. 27–44 (Jul–Aug 1970).

The ratios F_{n0}/R_0 and $|G_0|/R_0$ are usually referred to as the normal and tangential loading functions, respectively. By proper selection of the numerical coefficients, Equations (17) and (18) may be used to represent given loading functions. For all the loading functions considered by Springston,[5] it is necessary to consider terms only up to $m = 2$ in Equations (17) and (18). Accordingly, this is the largest value of m considered in the present program. However, more terms in Equations (17) and (18) can be accounted for by simply changing a few cards in Subroutine DAUX, or entirely different expressions can be written for F_{n0} and G_0.

I_0 and E_0, the components of F_{n0} along the X- and Z-directions, respectively, are given by

$$I_0 = (F_{n0})_X = F_{n0} \frac{c_X}{c_n} \tag{20}$$

$$E_0 = (F_{n0})_Z = F_{n0} \frac{c_Z}{c_n} \tag{21}$$

The tangential force G_0 is obtained from $|G_0|$ by noting that G_0 must act in the same direction as the component of relative velocity tangential to the cable, i.e.,

$$G_0 = |G_0| \frac{c_Y}{|c_Y|} \tag{22}$$

Fluid Side Forces

The fluid side forces are those forces due to $\vec{c}$ which act normal to the plane formed by $\vec{c}$ and the cable segment. In the present study, two types of side forces are considered: those acting on stranded cables and those acting on faired cables with angle of attack or camber.

The side forces acting on stranded cables are discussed by Gay[7] and by Choo and Casarella.[8] Based on an examination of several experimental results, Gay proposes the following formula for the side force acting on stranded cables L_{S0}:

$$\vec{L}_{S0} = \frac{1}{2} \rho d_0 c^2 \left[K_s \frac{\cos^{1/2} \phi_r \sin \phi_r}{\sqrt{Re}} \right] \frac{c_Y}{|c_Y|} \frac{\vec{c}_n \times \vec{j}_c}{c_n} \tag{23}$$

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[7] Gay, S.M., Jr., "New Engineering Techniques for Application to Deep-Water Mooring," ASME Paper 66-Pet-31, Petroleum Mechanical Engineering Conference, New Orleans, La. (Sep 1966).

[8] Choo, Y.I. and M.J. Casarella, "Configuration of a Towline Attached to a Vehicle Moving in a Circular Path," J. Hydronautics, Vol. 6, No. 1, pp. 51–57 (Jan 1972).

where K_s = an experimental constant

Re = Reynolds number = cd/ν

ν = kinematic viscosity of the fluid

$$\vec{c}_n = c_X \vec{i}_c + c_Z \vec{k}_c \tag{24}$$

Here $\vec{i}_c$, $\vec{j}_c$, $\vec{k}_c$ are unit vectors in the X,Y,Z directions, respectively. Choo and Casarella suggest that K_s = 10 is a conservative value to use.

The side force acting on faired cables $\vec{L}_{F0}$ is given by

$$\vec{L}_{F0} = \frac{1}{2} \rho C_L h_0 c_n^2 \frac{\vec{c}_n \times \vec{j}_c}{c_n} \tag{25}$$

where h_0 is the chord of the cable at the reference state and C_L is the side force coefficient.

Two approaches for calculating C_L, which basically depends on the angle of attack γ, are given in Appendix A. Both involve solving a linear algebraic equation for γ. These equations represent considerable simplifications of the angle of attack problem which generally requires the solution of a complex second-order differential equation of the boundary-value type. The applicability of the two simplified approaches is briefly discussed in Appendix A.

The total lift force $\vec{L}_0$ is given by the vector sum of $\vec{L}_{S0}$ and $\vec{L}_{F0}$

$$\vec{L}_0 = \vec{L}_{S0} + \vec{L}_{F0} = L_{X0} \vec{i}_c + L_{Z0} \vec{k}_c \tag{26}$$

This vector decomposition into the components L_{X0} and L_{Z0} follows from applying Equation (24) to the vector product $\vec{c}_n \times \vec{j}_c$

$$\vec{c}_n \times \vec{j}_c = (c_X \vec{i}_c + c_Z \vec{k}_c) \times \vec{j}_c = (c_X \vec{k}_c - c_Z \vec{i}_c) \tag{27}$$

When Equation (27) is substituted into Equations (23) and (25), the following expressions are obtained for the components L_{X0} and L_{Z0}

$$L_{X0} = -\frac{\rho}{2} c_Z \left[C_L h_0 c_n + \frac{K_s c d_0 \sqrt{\cos \phi_r}}{\sqrt{Re}} \frac{c_Y}{|c_Y|} \right] \tag{28}$$

$$L_{Z0} = \frac{\rho}{2} c_X \left[C_L h_0 c_n + \frac{K_s c d_0 \sqrt{\cos \phi_r}}{\sqrt{Re}} \frac{c_Y}{|c_Y|} \right] \tag{29}$$

ATTACHED BODIES

Intermediate Bodies

The integration of Equations (8)–(14) must be stopped when an intermediate body, such as a subsurface float or a sensor package, is reached. Wang[1] derives three equations of force equilibrium that relate the tensions and angles above and below the body and the fluid and gravity forces acting on it. The fluid forces are restricted to the hydrostatic buoyancy force and the drag force in the direction of the relative flow. Since the system considered in Wang[1] is a moored cable system and the integration proceeds downward from the upper buoy, the cable variables T, θ, and ϕ_V above the intermediate body are taken to be known. The three equations of equilibrium are then solved to yield expressions for T, θ, and ϕ_V below the body.

When the cable takes on an arbitrary configuration, it is not necessarily true that the cable variables above the body are known and that the cable variables below the body are the unknowns to be solved for. For example, in a towing cable problem where the integration proceeds from the towed body upward, the reverse is true. What this means is that the concepts of above and below used in Wang[1] must now be generalized. In the present study, the terms above and below are respectively generalized to minus and plus, where the direction from the minus point to the plus point is taken to be in the +Y direction shown in Figure 1. The sign of the cable scope, i.e., whether the actual direction of integration is in the +Y or −Y direction, is determined in the following section.

The concept of plus and minus is used as follows to generalize the expressions for T, θ, and ϕ_V given in Wang:[1]

$$T_\pm = \sqrt{(\sin \phi_{V\mp} \cos \theta_\mp T_\mp \pm F_{Bx})^2 + (-\cos \phi_{V\mp} \cos \theta_\mp T_\mp \pm (F_{By})^2 + (\sin \theta_\mp T_\mp \pm F_{Bz})^2} \tag{30}$$

$$\phi_{V\pm} = \tan^{-1}\left[\frac{\sin\phi_{V\mp}\cos\theta_{\mp}T_{\mp} \pm F_{Bx}}{\cos\phi_{V\mp}\cos\theta_{\mp}T_{\mp} \mp F_{By}}\right] \tag{31}$$

$$\theta_{\pm} = \tan^{-1}\left[\frac{(\sin\theta_{\mp}T_{\mp} \mp F_{Bz})\cos\phi_{V\pm}}{\cos\phi_{V\mp}\cos\theta_{\mp}T_{\mp} \mp F_{By}}\right] \tag{32}$$

where the upper (lower) sign is to be used on the right-hand side of the above equations if the upper (lower) sign is used on the left-hand side. Here too, F_{Bx}, F_{Bz} are the fluid drag forces acting on the body in the x,z directions, respectively, and F_{By} is the weight of the body in fluid.

The upper sign is to be used if the cable scope is positive, and the lower sign is to be used if the cable scope is negative. As pointed out in the following section, the sign of the cable scope is computed internally by the program and thus is not a quantity of concern to the user.

In the present study, the drag area of the body is taken to be the same for any direction of flow relative to the body. For the horizontal flow assumed here, the body must either be a sphere or a vertical cylinder. This assumption may be satisfactory for many cable systems for one of two reasons:

1. Many intermediate bodies found in cable systems have shapes similar to one of the above two shapes. For example, since the sphere is the most efficient buoyancy member, many subsurface floats resemble spheres.

2. Intermediate bodies which do not serve as buoyancy members are often fairly small and hence may not have a large effect on the overall cable configuration. Thus, errors in modeling the drag of these bodies may not be important.

In general, the drag forces acting on an arbitrary body vary in a complex manner with the direction of flow relative to the body. An accurate modeling of the drag force for an arbitrary body would require an accurate description of this variation of drag with relative direction. In addition, moment equations of equilibrium must also be solved in order to obtain the correct orientation of the body axes. Where such accuracy is needed for the body, changes must, of course, be implemented into the program. The result of these changes is to increase the number of input variables needed for the body as well as to substantially increase the complexity of the program logic for the body.

Initial Body

The initial body may be considered as an intermediate body with only one cable attachment point. The cable variables T, ϕ_V, and θ are needed in order to start the integration of differential Equations (8)–(14). The program assumes that the cable attachment point occurs on the plus side of the initial body and uses the upper sign in Equations (30)–(32) to calculate the initial values of T, ϕ_V, and θ, based on the forces acting on the initial body and assuming that T_- is equal to zero. This is equivalent to assuming that the direction of integration is in the +Y direction, i.e., cable scope is initially assumed to be positive. It should be noted that since one of the tensions is equal to zero, the only difference that would occur if the cable attachment point were assumed to be on the minus side is that ϕ_V and θ would be shifted by 180 degrees. Equation (30) shows that T would have the same value in either case. In the general case of an intermediate body where both tensions are nonzero, it is, of course, exceedingly important that the correct signs be used in Equations (30)–(32).

Once the initial values of T, ϕ_V, and θ have been calculated, the program checks whether it was indeed correct to assume that the attachment point was on the plus side. The check is based on the fact that the cable tension at the attachment point should be directed exactly opposite to the resultant of the fluid and gravity forces acting on the initial body. Since the only error which may be present in the initial values of θ and ϕ_V is a shift of 180 degrees, it is sufficient to check only one component of the forces. If the vertical force F_{By} is nonzero, the program determines the sign of cable scope by checking the vertical component as follows

$$\mathrm{SNSS} = \mathrm{sgn}\left[\frac{dy}{ds}\Big/(-F_{By})\right] \tag{33}$$

where sgn is the sign function and gives the sign of its argument, and dy/ds is given by Equation (13) when both sides are divided by (1+e).

Equation (33) then defines the sign of the cable scope. If SNSS is positive, then the initial values of ϕ_V and θ are correct since they give a direction which is opposite to the resultant fluid and gravity forces acting on the initial body. Thus, cable scope is positive. Similarly, if SNSS is negative, the direction of the cable must be reversed, i.e., cable scope is negative. If F_{By} is identically zero, the program performs a similar check on the x or z directions, depending on whether F_{Bx} or F_{Bz} has the larger magnitude.

The preceding shows that the program internally computes the sign of the cable scope and the initial cable angles from the forces acting on the initial body. The user simply needs to ensure that these forces are entered into the program in the correct algebraic sense. On the other hand, the Cuthill Program[3] requires the user to input the sign of the cable scope and the initial cable angle into the program by referring to a cable circle.[3,5] The use of this cable circle requires the user to know, to a certain extent, the approximate configuration of his cable. Thus, it is felt that the present program is significantly simpler to use than the Cuthill Program.

DESCRIPTION OF COMPUTER PROGRAM

Program CAB3E consists of a main program and seven subroutines.

MAIN PROGRAM

The main program accepts input data for the initial body, cable system, various conditions at which the integration of the differential equations is to be stopped, the relative velocity profile, and the physical properties of two different fluids in which the cable system may lie. A detailed description of the input scheme is given later in the report.

The program is written to accept up to 100 different cable segments and intermediate bodies. This number should be sufficient for the large majority of cable applications. It can be increased by changing a few DIMENSION and COMMON statements.

After accepting the input data from punched cards, the main program calls on Subroutine ITERA (described in greater detail later in the present section) which may change one or more of the conditions of the initial body. The program then sets the accuracy to which the differential equations are to be integrated. This accuracy is presently set at 0.001 percent.

After printing out the input data obtained from input cards and possibly from Subroutine ITERA, the main program performs various conversions of the input data, expressing force in pounds, length in feet, and angles in radians.

The main program ends by calling on Subroutine STEA3D.

SUBROUTINE STEA3D

This subroutine performs a variety of functions. It first performs the calculations for the cable variables and sign of the cable scope at the initial body. The (x,y,z) components of initial cable tension are printed out. The subroutine then calls on Subroutine KUTMER to integrate the seven differential Equations (8)–(14) for specified intervals of the reference cable scope s_0. After the return from KUTMER, this subroutine checks to determine whether any of the dependent variables have passed the input stop conditions placed on them. If none of the stop conditions has been passed, the subroutine prints out s_0 and the following nine cable dependent variables at s_0:

s	stretched cable scope in feet
x	x-distance measured from the initial body in feet
y	y-distance measured from the origin of the spatial (x,y,z) coordinate system in feet
z	z-distance measured from the initial body in feet
RHOR	total horizontal distance $\sqrt{x^2 + z^2}$ measured from the initial body in feet
ϕ_y	angle with the vertical = $\cos^{-1}$ (dy/|ds|) in degrees;

$$0^\circ \leqslant \phi_y \leqslant 180^\circ \tag{34}$$

ϕ_V	angle defined in Figure 1 in degrees
θ	angle defined in Figure 1 in degrees
T	tension in pounds

If $|CLCH(K)| \geqslant 100$, in which case the program goes to Subroutine TWIST to calculate the angle of attack γ, the program also prints out γ in degrees.

Variables s, x, y, z, ϕ_V, θ, and T are the seven dependent variables which appear in the seven differential Equations (8)–(14). Variable γ appears in the algebraic Equation (A10). The two additional variables ϕ_y and RHOR have also been printed out since they are considered to be physically significant. When the cable lies in all three dimensions, the physical significance of the angles ϕ_V and θ is not readily apparent. On the other hand, the angle ϕ_y directly gives the inclination of the cable with the vertical. In particular, when ϕ_y = 0 degrees, the cable is pointed downward; when ϕ_y = 90 degrees, the cable is horizontal; and when ϕ_y = 180 degrees, the cable is pointed upward. The variable RHOR is significant in, for example, the case of a cable system moored in a nonplanar current profile. In this case, RHOR at the anchor point gives the resultant horizontal excursion of the upper buoy from the anchor. This distance is often referred to in moored cable literature as the watch circle of the buoy.

When an intermediate body is encountered, this subroutine performs the calculations given in Equations (30)–(32) to obtain the new conditions required to continue the integration.

The above process continues until cable scope is exhausted or until one of the cable-dependent variables passes its input stop condition. In the latter case, the subroutine goes into an iteration for the reference cable scope s_0 until the particular cable-dependent variable is within 0.004 of its stop condition. The iteration basically consists of restricting s_0 to lie between successively closer barriers and checking the value of the particular dependent variable returned by Subroutine KUTMER for each value of s_0.

When cable scope is exhausted or the stop condition has been met to within 0.004, the subroutine calculates and prints out the (x,y,z) components of the cable tension at this end point. The subroutine then renames the cable variables at the end point so that they may be transferred to Subroutine ITERA.

Subroutine STEA3D ends by returning to the main program for a new case.

SUBROUTINE KUTMER

This subroutine is used to numerically integrate the differential Equations (8)–(14). It calls on Subroutine DAUX for the definition of these equations. Subroutine KUTMER has already been described in detail,[3] and hence will be mentioned only briefly here. This subroutine uses the Kutta-Merson method for solving systems of ordinary differential equations. The subroutine automatically reduces the integration step size until specified error criteria are met. If the dependent variable has an absolute value less than a certain number, 0.00001 in the present program, the subroutine continually reduces the step size until there is an absolute difference of less than 0.00001 between the dependent variable obtained by using the smallest step size and its corresponding value for the next larger step size. If the dependent variable has an absolute value greater than 0.00001, the subroutine continually reduces the step size until the dependent variable obtained by using the smallest step size agrees to within 0.01 percent (0.00001) of the corresponding value for the next larger step size. Since the dependent variables in Equations (8)–(14) seldom have an absolute value less than 0.00001, it is clear that the latter error criterion is almost always used.

SUBROUTINE DAUX

This subroutine defines the differential Equations (8)–(14), including the expressions for the fluid drag and side forces. In the two places indicated by comment cards, more general expressions for the fluid drag and side forces may be used by simply adding or changing a few cards after the comment cards. This subroutine calls on Subroutine CUR for the components of the relative fluid velocity and on Subroutine ELAS for the value of the strain.

SUBROUTINE CUR

This subroutine furnishes the horizontal x and z components of the fluid velocity relative to the cable system. For a given value of the vertical distance y, the subroutine linearly interpolates between the input magnitudes and directions which are read in as a function of y. For cases where the given value of y is greater (less) than the largest (smallest) value of y which is read in, the subroutine takes the magnitude and direction to correspond to their respective values at the largest (smallest) algebraic value of y which is read in.

SUBROUTINE ELAS

This subroutine furnishes the value of the strain. For a given value of the tension T, the subroutine linearly interpolates between the input strains which are read in as a function of the tension difference $(T-T_0)$ for each cable segment. For cases where the given value of T is such that the corresponding value of $(T-T_0)$ is greater (less) than the largest (smallest) value of $(T-T_0)$ which is read in, the subroutine calculates the strain by linearly extending the line segment connecting the two largest (smallest) input values of $(T-T_0)$.

SUBROUTINE ITERA

As listed in Appendix B, this subroutine is basically a dummy subroutine. It is to be programmed by the user for boundary-value problems where one or more of the initial conditions must be iterated until prescribed conditions at the end of the cable are met. Examples of steady-state boundary-value problems are free-floating cable systems,[9] cable systems moored with a given cable scope in a given ocean depth,[2] and a cable system with two or more anchor points.[10] The end conditions for a particular set of initial conditions are transmitted from Subroutine STEA3D to Subroutine ITERA through COMMON/BLKSI/. Initial conditions are transmitted from Subroutine ITERA to the main program through COMMON/BLK1/. As pointed out by the COMMENT card, changes in the cable system drift velocity components VSX and VSZ in the case of free-floating cable systems are transmitted from Subroutine ITERA to Subroutine CUR through COMMON/BLK2/. In other cable applications, VSX and VSZ should usually be set equal to zero. This subroutine may also be used when one or more initial conditions are to be varied in a systematic manner, and saves the need to punch input cards for each new set of initial conditions. The section on program usage includes an example of the use of Subroutine ITERA.

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[9] Wang, H.T. and T.L. Moran, "Analysis of the Two-Dimensional Steady-State Behavior of Extensible Free-Floating Cable Systems," NSRDC Report 3721 (Oct 1971).

[10] Skop, R.A. and G.J. O'Hara, "The Static Equilibrium Configuration of Cable Arrays by Use of the Method of Imaginary Reactions," Naval Research Laboratory Report 6819 (Feb 1969).

SUBROUTINE TWIST

Subroutine DAUX calls on this subroutine to calculate the value of $C_L\ h_0$ when the input variable CLCH(K), which is defined later, is read in with a magnitude greater than or equal to 100. The subroutine calculates the angle of attack by using Equation (A10) and then uses Equation (A12) to calculate $C_L\ h_0$. This value of $C_L\ h_0$ is then returned to Subroutine DAUX.

When this subroutine is used, the user must directly input a number of variables into this subroutine. Detailed instructions for entering these variables are given in the COMMENT cards included at the beginning of the subroutine; see Appendix B. These instructions are not repeated here. A sample set of representative faired cable variables is also listed. It is helpful, but not necessary, to refer to Figure 3 (see Appendix A) when reading these instructions. As pointed out by one of the COMMENT cards, the user may prescribe any distribution of the camber lift coefficient along the cable.

PROGRAM STORAGE AND TIME REQUIREMENTS

On the CDC 6700 currently in use at the Center, the program requires a memory of about 52,000 octal words and a period of about 25 seconds to compile. Program execution time for a given set of initial conditions varies with such factors as the total length of cable and the rate of variation of the dependent variables along the cable. The variation in execution time is usually between 2 and 7 seconds. For the case of boundary-value problems where the initial conditions must be continually iterated until the prescribed end conditions are met, the execution time would be approximately equal to the number of iterations times 2 to 7 seconds.

USE OF THE PROGRAM

READ STATEMENTS

As shown by the listing of the program given in Appendix B, the READ statements by means of which data are input to the program are all grouped together near the beginning of the main program. These READ statements may be arranged in various ways. One convenient arrangement is as follows:

```
READ(5,8) NCASES                                           Card  1
DO 400 ICASE = 1, NCASES
READ(5,11) TITLE                                           Card  2
READ(5,8) NCUR, NCAB                                       Card  3
READ(5,3) CDAS, TSX, TSZ, TSY, SUBM                        Card  4
READ(5,3) PYSTOP, YSTOP, XSTOP, ZSTOP, TSTOP               Card  5
READ(5,5) RHO1, RHO2, FNU1, FNU2, YIF                      Card  6
READ(5,2) AON, A1CN, A2CN, A1SN, A2SN                      Card  7
READ(5,2) AOT, A1CT, A2CT, A1ST, A2ST                      Card  8
READ(5,3) (FLC(K), K=1, NCAB)                              Card  9
READ(5,8) (NPR(K), K=1, NCAB)                              Card 10
READ(5,2) (DC1(K), K=1, NCAB)                              Card 11
READ(5,2) (CDC(K), K=1, NCAB)                              Card 12
READ(5,2) (CKS(K), K=1, NCAB)                              Card 13
READ(5,2) (CLCH(K), K=1, NCAB)                             Card 14
READ(5,2) (WC1(K), K=1, NCAB)                              Card 15
READ(5,2) (WC2 (K), K=1, NCAB)                             Card 16
READ(5,3) (CDAB(K), K=1, NCAB)                             Card 17
READ(5,3) (WBD1(K), K=1, NCAB)                             Card 18
READ(5,3) (WBD2(K), K=1, NCAB)                             Card 19
READ(5,3) (TREF(K), K=1, NCAB)                             Card 20
READ(5,2) (P(K), K=1, NCAB)                                Card 21
READ(5,8) (NST(K), K=1, NCAB)                              Card 22
DO 101 NE=1, NCAB
NN=NST(NE)
READ(5,5) (EE(NE,K), K=1, NN)                              Card 23
READ(5,3) (TEND(NE,K), K=1, NN)                            Card 24
101 CONTINUE
READ(5,3) (YY(I), I=1, NCUR)                               Card 25
READ(5,2) (CCK(I), I=1, NCUR)                              Card 26
READ(5,2) (AAD(I), I=1, NCUR)                              Card 27
.
.
.
400 CONTINUE
```

The READ statements are given numbers simply for identification purposes in the discussion which follows.

The corresponding FORMAT statements are:

```
2 FORMAT (6F12.6)
3 FORMAT (6F12.4)
5 FORMAT (6F12.8)
```

```
 8 FORMAT (24I3)
11 FORMAT (18A4)
```

DEFINITION OF INPUT VARIABLES

The input variables which appear in the above READ statements are now defined in the order in which they appear there:

NCASES	Number of cases to be computed, NCASES $\geqslant 1$
TITLE	Title of case; may be any 72 alphabetic or numerical characters
NCUR	Number of points defining the profile of the fluid velocity relative to the cable system, $2 \leqslant$ NCUR $\leqslant 29$
NCAB	Number of cable segments = number of intermediate bodies, $1 \leqslant$ NCAB $\leqslant 100$
CDAS	Drag area of initial body in feet^2
TSX,TSZ	Applied force on initial body in the (x,z) direction, in addition to the drag force resulting from CDAS, in pounds
TSY	Vertical force acting on initial body, in pounds
SUBM	Value of y at initial body in feet
PYSTOP	Value of ϕ_y, angle with the vertical defined in Equation (34), in degrees, at which the integration of the equations is stopped when ϕ_y exactly reaches this value; $0° \leqslant \phi_y \leqslant 180°$
YSTOP, XSTOP ZSTOP	Value of (y,x,z) in feet at which the integration of the equations is stopped when (y,x,z) exactly reaches this value
TSTOP	Value of tension in pounds at which the integration of the equations is stopped when the tension exactly reaches this value
RHO1, RHO2	Density of fluid (above, below) fluid interface in slugs/feet^3
FNU1, FNU2	Kinematic viscosity of fluid (above, below) fluid interface in feet^2/seconds
YIF	Value of y at fluid interface in feet
AON,A1CN, A2CN,A1SN, A2SN	Normal drag loading function, defined in Equation (17), $= A_{0n} + A_{1cn} \cos \phi_r + A_{2cn} \cos 2\phi_r + A_{1sn} \sin \phi_r + A_{2sn} \sin 2\phi_r$
AOT,A1CT, A2CT,A1ST, A2ST	Tangential drag loading function, defined in Equation (18), $= A_{0t} + A_{1ct} \cos \phi_r + A_{2ct} \cos 2\phi_r + A_{1st} \sin \phi_r + A_{2st} \sin 2\phi_r$
FLC(K)	Length of K th cable segment at the reference tension in feet
NPR(K)	Number of equal print intervals for K th cable segment
DCI(K)	Thickness of K th cable segment at the reference tension in inches
CDC(K)	Drag coefficient of K th cable segment

CKS(K)	Experimental constant K_s in the expression for the side force acting on stranded cables; given in Equation (23)
CLCH(K)	Side force coefficient C_L times chord h_0 of K th cable segment at the reference tension; if CLCH(K) is read in with an absolute value $\geq$ 100, the program goes to Subroutine TWIST to calculate C_L h_0
WC1(K),WC2(K)	Weight of K th cable segment in fluid (above, below) fluid interface at the reference cable tension in pounds/feet
CDAB(K)	Drag area of K th intermediate body in feet^2
WBD1(K), WBD2(K)	Weight in fluid of K th intermediate body in fluid (above, below) fluid interface in pounds
TREF(K)	Reference tension of K th cable segment in pounds
P(K)	Poisson's ratio of K th cable segment
NST(K)	Number of points defining the strain-tension function for K th cable segment; $2 \leq$ NST(K) ≤ 10
EE(NE,K)	Strain measured from strain at the reference tension for K th cable segment; EE(NE,K) = 0 at TEND(NE,K) = 0
TEND(NE,K)	Tension measured from the reference tension for K th cable segment in pounds; TEND(NE,K) = T − TREF(K)
YY(I)	Value of y in feet
CCK(I)	Magnitude of the relative fluid velocity in knots at y = YY(I)
AAD(I)	Angle in degrees which the relative fluid velocity makes with the x axis at y = YY(I)

COMMENTS ON ENTERING INPUT DATA

1. All of the forces and distances which are read in are algebraic quantities and have signs in accordance with the spatial (x,y,z) coordinate system shown in Figure 1. In particular, forces and distances in the upward direction are negative and those in the downward direction are positive.

2. The quantities YY(I) and TEND(NE,K) should be read in algebraically ascending order, i.e., YY(1) < YY(2) < YY(3) < · · · ·, and TEND(1,K) < TEND(2,K) < · · · .

3. The origin of the strain-tension function for a given K th cable segment is the strain at the reference tension, i.e., as pointed out above, EE(NE,K) = 0 at TEND(NE,K) = 0. In accordance with the definition for strain given in Equation (11), the strain is to be based on the length of the cable segment at the reference tension.

4. The numbering of the cable segments and intermediate bodies is as follows. The first cable segment follows the initial body, the first intermediate body follows the first cable

segment, the second cable segment follows the first intermediate body, and so forth. The initial body is not considered to be an intermediate body. Instead, its characteristics are given by the input variables CDAS, TSX, TSY, and TSZ given in Card 4.

From the numbering system described above, it is clear that the last body follows the last cable, i.e., the cable system ends with a body. In those applications where there is no body at the end of the cable system, the parameters for the last body should be read in equal to zero. This is the case, for example, in most towing cable problems where the cable is attached directly to the towing platform. On the other hand, free-floating cable systems usually have a body at both ends. For these systems, the last body would have nonzero parameters. In the case of cable systems moored to the ocean bottom, the reading in of zero parameters for the last body will cause the program to yield the components of tension exerted by the lower end of the cable on the anchor. This information would give the required holding power of the anchor. If, however, the parameters of the last body are read in corresponding to those of the anchor, the resulting forces printed by the program at the lower end of the cable system are those exerted by the ocean bottom on the anchor.

5. When the program passes one of the stop conditions for the dependent variables ϕ_y, y, x, z, and T given in Card 5, the program stops its usual integration of the differential equations for specified intervals of the reference scope. Instead, the program iterates for the cable scope which will give the particular stop condition to within 0.004. For those dependent variables for which stop conditions are not desired, it is important to read in values for these stop conditions to ensure that the program never encounters these values along the entire cable scope. One way to accomplish this is to read in a value with a large magnitude. If the sign of the variable is known, then another way is to read in a value for the stop condition with the opposite sign. In the case of tension, which always takes on a positive value, the reading in of any negative value for TSTOP will ensure that the program never encounters the stop condition for tension. In the case of ϕ_y, which is restricted to lie between 0 and 180 degrees, the reading in of any value outside of this range for PYSTOP will ensure that the stop condition for ϕ_y is inoperative.

6. The program will stop if it finds that the initial value of y, SUBM, is identically equal to the value of y at the interface, YIF. In these cases, the program is unable to tell whether to compute the drag on the initial body by using the density of the fluid above or below the interface. For example, if SUBM and YIF both nominally occur at y=0 and it is desired to compute the drag resulting from CDAS based on the density of the fluid below the interface, then one should enter, say, SUBM = +0.001 and YIF = −0.001.

7. For those cases where the cable system does lie in two fluid media, it is important to read in the proper values for the fluid properties above and below the interface. It is also important to read in the correct value for YIF, the y value of the interface. An example of a

cable system lying in two fluid media is the sample helicopter towing problem presented below. For those cases where the cable system lies entirely in one fluid medium, it is probably most convenient to read in the properties of the fluid above and below the interface equal to each other. Or one may choose to read arbitrary values for the properties of the fluid in which the cable does not lie.

8. For a number of runs where only a few of the input variables are varied, the READ statements containing those variables which remain constant may be shifted out of the DO 400 loop. This will result in a considerable saving of time and effort in entering input data. For example, if it is desired to systematically investigate the effect of fairing angle of attack on a faired cable system with all other variables held fixed, then all of the READ statements may be shifted out of the DO loop except that containing CLCH(K). As another example, if it is desired to systematically study the effect of current magnitude and direction on a moored cable system with all other variables fixed, then all of the READ statements may be shifted out of the DO loop except those containing AAD(I) and CCK(I).

9. For cases where Subroutine ITERA is operative and continually furnishes one or more conditions of the initial body given on Card 4 to the main program, it is possible that all of the READ statements will be outside of the DO 400 loop. As pointed out previously, Subroutine ITERA may be viewed as furnishing input conditions in place of Card 4. This fact is illustrated by one of the sample problems given below.

SAMPLE PROBLEMS

The present section presents three sample problems to give an indication of the versatility of the program. For each problem, a listing of the input data cards is given. For Problem 3, which requires the use of Subroutine ITERA, this subroutine is listed as well. A complete listing of the program output is given for one of the cases of Problem 1, but only some final results are shown for the other two problems.

Sample Problem 1 – Stranded Towing Cable Subject to Various Stop Conditions

Problem: A surface ship is advancing in the +x direction at a speed of 10 knots. It has a maximum of 4000 feet of stranded round cable available to perform its towing mission. The characteristics of the cable, lower body, and fluid are as follows:

Cable:

reference tension T_0	0 lb
length S_0	4000 ft
diameter d_0	0.52 in.
weight in water W_0	0.31 lb/ft
drag coefficient C_D	1.4
Poisson's ratio p	0.3
side force constant for stranded cable K_s	10.0
tension-strain function	e: 0.0, 0.002; $T-T_0$: 0 lb, 10,000 lb

$$\frac{F_{n0}}{R_0} = 0.98 \sin^2 \phi_r + 0.02 \sin \phi_r = 0.49 - 0.49 \cos 2\phi_r + 0.02 \sin \phi_r$$

$$\frac{|G_0|}{R_0} = 0.02 \cos \phi_r$$

Lower body:

drag area $C_D A_B$	0.3 ft^2
weight in water F_{By}	3000 lb
initial value of y SUBM	0 ft

Fluid:

density ρ	1.94 slugs/ft^3
kinematic viscosity ν	10^{-5} ft^2/sec
value of y at fluid interface YIF	−5000 ft

The above cable loading functions are those proposed by Eames, as reported by Springston.[5]

The cable configuration is desired up to the following conditions:

1. Cable scope s_0 is exhausted
2. Angle with the vertical ϕ_y = 120 deg
3. Vertical distance y = −500 ft
4. Trail distance x = 3000 ft
5. Side displacement z = +50 ft
6. Side displacement z = −50 ft
7. Tension T = 3500 lb

Cable dependent variables are to be printed for every 100 ft of the reference scope.

Solution: The only difference between the seven cases is in the stop condition. Thus, all the READ cards may be shifted out of the DO 400 loop except for Card 5 which accepts the various stop conditions. In the present runs, Card 2, the title card, has also been retained in the DO 400 loop so that each case is identified with a different title.

The data cards for this problem are listed in Table 1. In this table, as well as in the subsequent listing of data cards for the other two problems, the symbol b is used to denote a blank. Also, vertical lines are drawn next to Columns 1, 13, 25, 37, 49, and 61 since most of the data start in these columns.

The complete output of the program for Case 1 is listed in Table 2. It can be seen that the output consists of two principal parts: a listing of the input variables and a listing of the calculated cable variables at prescribed values of the reference cable scope. Table 2 shows that two lines of output are generated at the end of the cable, s_0 = -4000. The upper line represents the conditions of the cable just ahead of the final body while the lower line represents the conditions of the cable just after the final body. In the present problem, the final body does not physically exist and therefore has been assigned zero drag area and weight. Thus, all the cable variables should have identical values in both lines. The changes of +180 and -180 degrees shown respectively for ϕ_V and θ in going from the upper line to the lower line are simply due to the ATAN2 function which is used to compute the arctangents shown in Equations (31) and (32). The ATAN2 function limits the values of the angles to lie between -180 and +180 degrees. It can be readily shown that the substitution of (ϕ_V $-$ 180) and (180 $-$ θ) for ϕ_V and θ, respectively, does not alter the differential Equations (8)–(14).

Table 3 shows the output of the program at the cable scope corresponding to the required stop condition for each of the cases listed above. The output entered for Cases 1 and 6 is the upper of the two lines corresponding to s_0 = 4000 feet. The output for the other cases for values of cable scope less than those shown in Table 3 are identical with the corresponding output for Case 1 shown in Table 2. Table 3 shows that the required stop conditions have been met to an accuracy of at least two decimal places. Case 6 shows that the stop condition of z = -50 ft is never met since z is always positive. Thus the integration is carried out along the entire cable scope, as in Case 1.

Sample Problem 2 – Helicopter Towing a Faired Cable at Various Speeds

Problem: A helicopter has a maximum of 3000 feet of faired cable to perform its towing mission. The towed body is to remain 125 feet below the ocean surface while the helicopter is to operate 100 feet above the ocean surface. It is desired to determine the amount of cable scope needed to satisfy the above requirements for towing speeds of 0, 5, 10, 20, 30, 40, 60,

TABLE 1 — INPUT DATA FOR SAMPLE PROBLEM 1

	Column Number					
	1	13	25	37	49	61
Card 1	bb7					
Card 3	bb2bb1					
Card 4	0.3	0.	0.	3000.	0.	
Card 6	1.94	1.94	0.00001	0.00001	−5000.	
Card 7	0.49	0.	−0.49	0.02	0.	
Card 8	0.	0.02	0.	0.	0.	
Card 9	4000.					
Card 10	b40					
Card 11	0.52					
Card 12	1.4					
Card 13	10.					
Card 14	0.					
Card 15	0.31					
Card 16	0.31					
Card 17	0					
Card 18	0.					
Card 19	0.					
Card 20	0.					
Card 21	0.3					
Card 22	bb2					
Card 23	0.	0.002				
Card 24	0.	10000.				
Card 25	0.	25000.				
Card 26	10.	10.				
Card 27	180.	180.				
Card 2	bbb TOWING CABLE – NO STOP CONDITIONS					
Card 5	60000.	60000.	60000.	60000.	−100.	
Card 2	bbb TOWING CABLE – b PYSTOP = 120 DEG					
Card 5	120.	60000.	60000.	60000.	−100.	
Card 2	bbb TOWING CABLE – YSTOP = −500 FT					
Card 5	60000.	−500.	60000.	60000.	−100.	
Card 2	bbb TOWING CABLE – XSTOP = 3000 FT					
Card 5	60000.	60000.	3000.	60000.	−100.	
Card 2	bbb TOWING CABLE – ZSTOP = +50 FT					
Card 5	60000.	60000.	60000.	50.	−100.	
Card 2	bbb TOWING CABLE – ZSTOP = −50 FT					
Card 5	60000.	60000.	60000.	−50.	−100.	
Card 2	bbb TOWING CABLE – TSTOP = 3500 LB					
Card 5	60000.	60000.	60000.	60000.	3500.	

TABLE 2 – COMPLETE PROGRAM OUTPUT FOR CASE 1 OF SAMPLE PROBLEM 1

```
         TOWING CABLE- NO STOP CONDITIONS

*****LISTING OF CABLE AND OCEAN ENVIRONMENT CHARACTERISTICS*****

INITIAL BODY.....
     INITIAL VERTICAL POSITION (FT)                                    0.00000
     DRAG AREA (FT SQ)                                                  .30000
     FORCE IN VERTICAL DIRECTION (LBS)                               3000.00000
     APPLIED FORCE IN X DIRECTION (LBS)                                0.00000
     APPLIED FORCE IN Z DIRECTION (LBS)                                0.00000

     FLUID DENSITY ABOVE INTERFACE(SLUGS/CUBIC FT)                     1.94000000
     FLUID KINEMATIC VISCOSITY ABOVE INTERFACE(FT SQ/SEC)               .00001000
     Y AT FLUID INTERFACE                                          -5000.0000
     FLUID DENSITY BELOW INTERFACE(SLUGS/CUBIC FT)                     1.94000000
     FLUID KINEMATIC VISCOSITY BELOW INTERFACE(FT SQ/SEC)               .00001000

OCEAN PROFILE.....
     DEPTH (FT)          CURRENT (KNOTS)     ANGLE FROM X AXIS (DEG)
        0.0000              10.0000                180.0000
     25000.0000             10.0000                180.0000

     CABLE HYDRODYNAMIC LOADING FUNCTION COEFFICIENTS
NORMAL=     .490000+     0.000000 COS( PHIR)+     -.490000 COS(2PHIR)+      .020000 SIN( PHIR)+    0.000000 SIN(2PHIR)
  TANG=    0.000000+      .020000 COS( PHIR)+    -0.000000 COS(2PHIR)+    -0.000000 SIN( PHIR)+   -0.000000 SIN(2PHIR)
                                                                                                            BODY PROPERTIES
     CABLE PROPERTIES                                                                                  CDA(FTSQ)    WT1(LBS)    WT2(LBS)
NUM LENGTH(FT) T REF(LBS)  DIAM(IN) W1(LB/FT) W2(LB/FT) DRAG COEF  POI RATIO CLXCRD(FT)  K[illegible]JAS       0.0000      0.0000      0.0000
  1   4000.000     0.000    .520000   .310000   .310000  1.400000   .300000    0.00000  10.30000

     CABLE  1  STRAIN-TENSION DIFFERENCE RELATION
     0.00000000   .00200000
     0.0000  10000.0000

STOP CONDITIONS.....                                                   60000.00000
     ANGLE FROM VERTICAL (DEG)                                         60000.00000
     VERTICAL DISTANCE  (FT)                                           60000.00000
     X DISTANCE (FT)                                                   60000.00000
     Z DISTANCE (FT)                                                    -100.00000
     TENSION (LBS)
```

TABLE 2 (Continued)

RUN NUMBER 1

THE COMPONENT OF TENSION IN THE X DIRECTION IS -82.8963 LBS.
THE COMPONENT OF TENSION IN THE Z DIRECTION IS .0000 LBS.
THE VERTICAL COMPONENT OF TENSION IS 3000.0000 LBS.

S REF(FT)	S STR(FT)	X(FT)	Y(FT)	Z(FT)	R HOR(FT)	PHIY(DEG)	PHIV(DEG)	THETA(DEG)	T(LBS)	GAMMA(DEG)
0.00	0.00	0.00	.00	0.00	0.00	178.42	-178.42	180.00	3001.15	
-100.00	-100.06	28.29	-94.89	.29	28.29	149.87	-149.87	180.37	3040.03	
-200.00	-200.12	92.36	-171.20	1.26	92.37	131.75	-131.76	180.72	3085.14	
-300.00	-300.18	173.12	-230.03	2.72	173.14	121.30	-121.31	180.93	3130.44	
-400.00	-400.25	261.50	-276.90	4.46	261.54	114.94	-114.95	181.05	3174.56	
-500.00	-500.31	353.75	-315.46	6.38	353.81	110.79	-110.80	181.13	3217.46	
-600.00	-600.39	448.18	-348.49	8.40	448.26	107.92	-107.92	181.19	3259.34	
-700.00	-700.44	543.93	-377.45	10.51	544.03	105.84	-105.84	181.22	3300.41	
-800.00	00.51	640.55	-403.39	12.67	640.68	104.27	-104.28	181.25	3340.83	
-900.00	-900.57	737.77	-426.99	14.87	737.92	103.07	-103.07	181.27	3380.73	
-1000.00	-1000.64	835.41	-448.78	17.09	835.58	102.12	-102.12	181.28	3420.21	
-1100.00	-1100.71	933.36	-469.11	19.34	933.56	101.36	-101.36	181.29	3459.34	
-1200.00	-1200.78	1031.55	-488.27	21.61	1031.78	100.74	-100.74	181.30	3498.19	
-1300.00	-1300.85	1129.93	-506.46	23.88	1130.18	100.23	-100.23	181.31	3536.80	
-1400.00	-1400.92	1228.45	-523.85	26.17	1228.73	99.80	-99.80	181.31	3575.21	
-1500.00	-1500.99	1327.09	-540.57	28.46	1327.40	99.44	-99.45	181.31	3613.46	
-1600.00	-1601.07	1425.83	-556.72	30.76	1426.16	99.14	-99.15	181.32	3651.56	
-1700.00	-1701.14	1524.64	-572.39	33.06	1524.99	98.89	-98.89	181.32	3689.53	
-1800.00	-1801.21	1623.51	-587.66	35.36	1623.90	98.67	-98.67	181.32	3727.40	
-1900.00	-1901.29	1722.44	-602.58	37.67	1722.85	98.49	-98.48	181.32	3765.19	
-2000.00	-2001.37	1821.42	-617.19	39.98	1821.86	98.32	-98.32	181.32	3802.89	
-2100.00	-2101.44	1920.43	-631.54	42.28	1920.90	98.18	-98.18	181.32	3840.52	
-2200.00	-2201.52	2019.49	-645.66	44.59	2019.98	98.05	-98.06	181.32	3878.10	
-2300.00	-2301.60	2118.56	-659.59	46.90	2119.08	97.95	-97.95	181.32	3915.62	
-2400.00	-2401.68	2217.66	-673.35	49.20	2218.21	97.85	-97.86	181.32	3953.10	
-2500.00	-2501.76	2316.79	-686.95	51.51	2317.36	97.77	-97.77	181.32	3990.54	
-2600.00	-2601.84	2415.93	-700.42	53.81	2416.53	97.70	-97.70	181.32	4027.94	
-2700.00	-2701.92	2515.09	-713.77	56.12	2515.71	97.64	-97.64	181.32	4065.32	
-2800.00	-2802.00	2614.26	-727.03	58.42	2614.91	97.53	-97.58	181.32	4102.66	
-2900.00	-2902.08	2713.45	-740.19	60.72	2714.13	97.53	-97.53	181.32	4139.99	
-3000.00	-3002.16	2812.65	-753.27	63.02	2813.35	97.49	-97.49	181.32	4177.29	
-3100.00	-3102.25	2911.85	-766.28	65.32	2912.59	97.45	-97.45	181.32	4214.57	
-3200.00	-3202.33	3011.07	-779.22	67.61	3011.83	97.42	-97.42	181.31	4251.84	
-3300.00	-3302.42	3110.30	-792.11	69.91	3111.08	97.38	-97.39	181.31	4289.09	
-3400.00	-3402.50	3209.53	-804.95	72.20	3210.34	97.36	-97.36	181.31	4326.32	
-3500.00	-3502.59	3308.77	-817.75	74.49	3309.61	97.33	-97.33	181.31	4363.55	
-3600.00	-3602.68	3408.01	-830.50	76.78	3408.88	97.31	-97.31	181.31	4400.77	
-3700.00	-3702.77	3507.26	-843.22	79.07	3508.16	97.29	-97.29	181.31	4437.97	
-3800.00	-3802.86	3606.52	-855.91	81.36	3607.44	97.27	-97.28	181.31	4475.17	
-3900.00	-3902.95	3705.78	-868.57	83.65	3706.72	97.26	-97.26	181.31	4512.36	
-4000.00	-4003.04	3805.04	-881.20	85.93	3806.01	97.24	-97.25	181.31	4549.55	
-4000.00	-4003.04	3805.04	-881.20	85.93	3806.01	97.24	82.75	-1.31	4549.55	

THE VERTICAL COMPONENT OF TENSION IS -573.7269 LBS.
THE COMPONENT OF TENSION IN THE X DIRECTION IS 4512.0306 LBS.
THE COMPONENT OF TENSION IN THE Z DIRECTION IS 103.8678 LBS.

TABLE 3 – PROGRAM OUTPUT AT THE REQUIRED STOP CONDITION FOR EACH CASE OF SAMPLE PROBLEM 1

Case	S REF (FT)	S STR (FT)	X (FT)	Y (FT)	Z (FT)	R HOR (FT)	PHIY (DEG)	PHIV (DEG)	THETA (DEG)	T (LB)
1	−4000.00	−4003.04	3805.04	−881.20	85.93	3806.01	97.24	− 97.25	181.31	4549.55
2	− 317.03	− 317.23	187.78	−238.72	3.00	187.80	120.00	−120.00	180.96	3138.05
3	−1263.94	−1264.77	1094.44	−500.00	23.06	1094.68	100.40	−100.40	181.30	3522.91
4	−3188.84	−3191.17	3000.00	−777.78	67.36	3000.76	97.42	− 97.42	181.31	4247.68
5	−2434.50	−2436.21	2251.86	−678.06	50.00	2252.42	97.82	− 97.83	181.32	3966.02
6	−4000.00	−4003.04	3805.04	−881.20	85.93	3806.01	97.24	− 97.25	181.31	4549.55
7	−1204.66	−1205.45	1036.14	−489.14	21.71	1036.37	100.71	−100.71	181.30	3500.00

80, and 100 knots. Cable dependent variables are to be printed for every 50 feet of cable scope. The direction of advance of the helicopter is in the $-x$ direction. The faired cable may be taken to be inextensible. It is also free-swiveling and without camber so that it is free of any side force. The characteristics of the cable, lower body, and fluid are as follows:

Cable:

reference tension T_0	0 lb		
length S_0	3000 ft		
thickness d_0	0.6 in.		
chord h_0	2.55 in.		
weight in air W_{10}	0.53 lb/ft		
weight in water W_{20}	0.28 lb/ft		
drag coefficient C_D	0.085		
Poisson's ratio p	0.3		
side force coefficient C_L times chord h_0	0.		
tension-strain function	e	0.	0.
	$T-T_0$	0 lb	70,000 lb

$$\frac{F_{n0}}{R_0} = \frac{d}{h} \sin^2 \phi_r + \left(1 - \frac{d}{h}\right) \sin \phi_r$$

$$= 0.118 - 0.118 \cos 2 \phi_r + 0.765 \sin \phi_r$$

$$\frac{|G_0|}{R_0} = \left(0.386 - 0.303 \frac{d}{h}\right) \cos \phi_r - \left(0.055 - 0.020 \frac{d}{h}\right) \cos^2 \phi_r$$

$$= -0.0251 + 0.3147 \cos \phi_r - 0.0251 \cos 2 \phi_r$$

Lower body:

drag area $C_D A_B$	0.18 ft^2
weight in water F_{By}	2400 lb
initial value of y SUBM	125 ft

Fluid:

density of air ρ_1	0.00238 slugs/ft^3
kinematic viscosity of air ν_1	1.8×10^{-4} ft^2/sec
value of y at ocean surface YIF	0 ft
density of water ρ_2	1.94 slugs/ft^3
kinematic viscosity of water ν_2	10^{-5} ft^2/sec

The above cable loading functions are those proposed by Whicker, as reported by Springston.[5]

Solution: The only difference between the nine cases to be run is in the towing speed. Thus, all the READ cards have been shifted out of the DO 400 loop except for Card 26 which accepts the magnitude of the fluid velocity relative to the cable.

The data cards for this problem are listed in Table 4. Table 5 lists for each speed the output of the program at the cable scope where the integration of the differential equations is stopped. For speeds less than or equal to 40 knots, the stopping point is the scope at which the cable reaches 100 feet above the ocean surface. For speeds greater than or equal to 60 knots, Table 5 shows that cable lengths greater than 3000 feet are required in order for the cable to reach the required height above the ocean surface.

Problem 3 – Determination of the Radius of a Moored Spherical Buoy

Problem: Determine the radius of the spherical upper float required to moor the cable system shown in Figure 2 15 feet below the ocean surface. Take the specific weight of sea-water to be 62.4 lb/ft^3. It is desired to know the configuration of the cable for every 100 feet of cable scope. Characteristics of the cable, second float, sensor, fluid, and current profile are as follows:

Cable:	Cable 1	Cable 2	Cable 3
reference tension T_0, lb	0	0	0
length S_0, ft	500	2200	300
diameter d_0, in.	0.22	0.11	0.11
weight in water W_0, lb/ft	0.13	0.027	0.027
drag coefficient C_D	1.2	1.2	1.2
Poisson's ratio p	0.3	0.3	0.3

tension-strain function for Cable 1	e	0.	0.0004
	$T-T_0$	0.	200 lb
tension-strain functions for Cables 2 and 3	e	0.	0.002
	$T-T_0$	0.	150 lb

TABLE 4 INPUT DATA FOR SAMPLE PROBLEM 2

	Column Number					
	1	13	25	37	49	61
Card 1	bb9					
Card 2	bbb HELICOPTER TOWING, SPEEDS FROM 0 TO 100 KNOTS					
Card 3						
Card 4	0.18	0.	0.	2400.	125.	
Card 5	−50.	−200.	70000.	70000.	−100.	
Card 6	0.00238	1.94	0.00018	0.00001	0.	
Card 7	0.118	0.	−0.118	0.765	0.	
Card 8	0.0251	0.3147	−0.0251	0.	0.	
Card 9	3000.					
Card 10	b60					
Card 11	0.60					
Card 12	0.085					
Card 13	0.					
Card 14	0.					
Card 15	0.53					
Card 16	0.28					
Card 17	0.					
Card 18	0.					
Card 19	0.					
Card 20	0.					
Card 21	0.3					
Card 22	bb2					
Card 23	0.	0.				
Card 24	0.	70000.				
Card 25	−500.	500.				
Card 27	0.	0.				
Card 26	0.	0.				
Card 26	5.	5.				
Card 26	10	10.				
Card 26	20.	20.				
Card 26	30.	30.				
Card 26	40.	40.				
Card 26	60.	60.				
Card 26	80.	80.				
Card 26	100.	100.				

TABLE 5 – PROGRAM OUTPUT AT $y = -100$ OR $s_0 = -3000$ FOR EACH CASE OF SAMPLE PROBLEM 2

Case	S REF (FT)	S STR (FT)	X (FT)	Y (FT)	Z (FT)	R HOR (FT)	PHIY (DEG)	PHIV (DEG)	THETA (DEG)	T (LB)
1	−225.00	−225.00	−0.00	−100.00	−.00	.00	180.00	180.00	180.00	2488.07
2	−225.03	−225.03	−3.59	−100.00	−.00	3.59	178.87	178.87	180.00	2488.15
3	−225.50	−225.50	−14.37	−100.00	−.00	14.37	175.47	175.47	180.00	2490.86
4	−233.13	−233.13	−58.43	−100.00	−.00	58.43	162.09	162.09	180.00	2532.98
5	−269.05	−269.05	−141.58	−100.00	−.00	141.58	141.50	141.50	180.00	2716.68
6	−395.67	−395.67	−314.59	−100.00	−.00	314.59	118.67	118.67	180.00	3270.59
7	−3000.00	−3000.00	−2978.66	−20.61	−.00	2978.66	91.78	91.78	180.00	25187.79
8	−3000.00	−3000.00	−2992.09	50.58	−.00	2992.09	90.29	90.29	180.00	63516.26
9	−3000.00	−3000.00	−2996.50	77.31	−.00	2996.50	90.18	90.18	180.00	98632.58

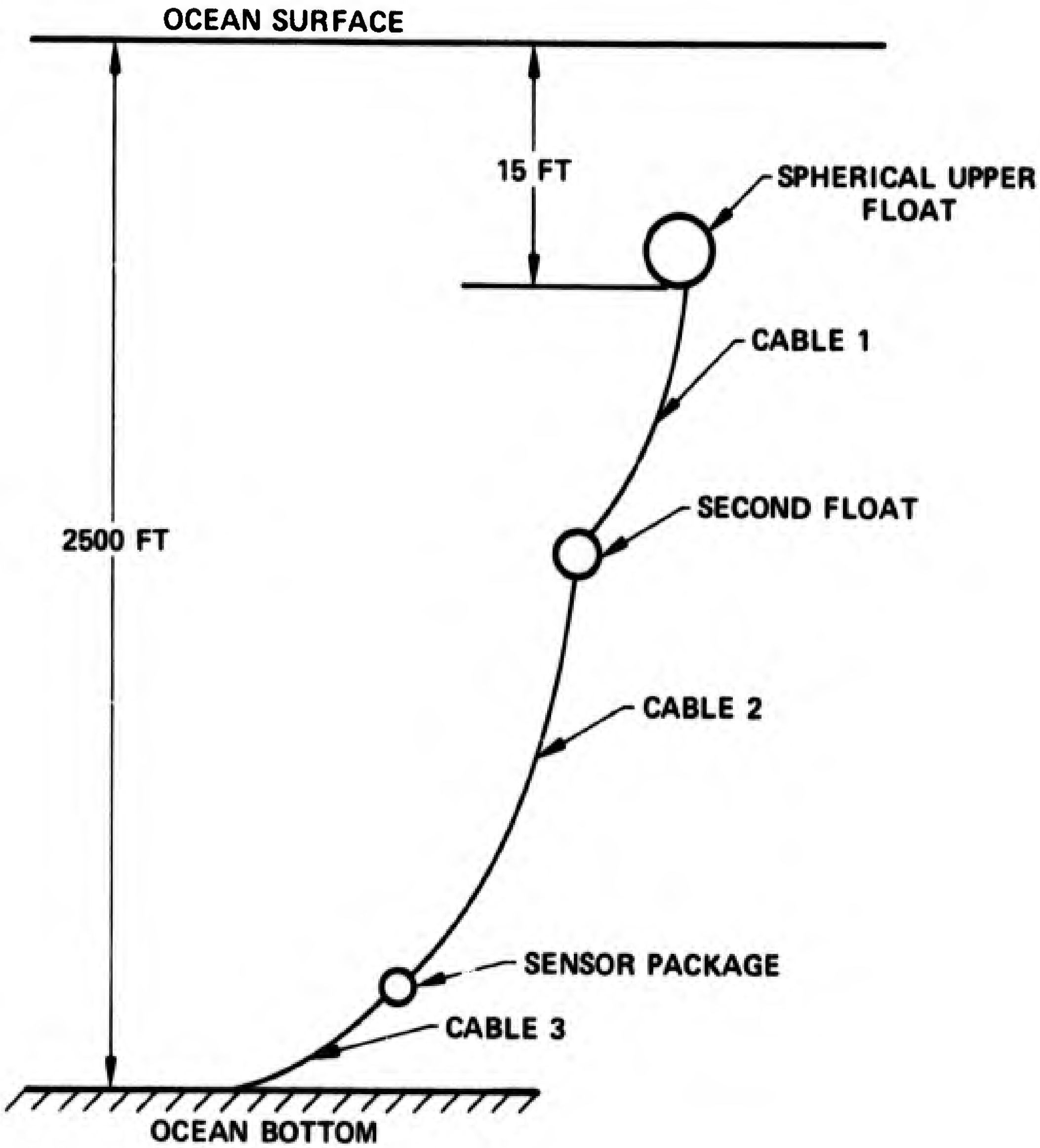

Figure 2 – Moored Cable System of Sample Problem 3

For all cables, $\dfrac{F_{n0}}{R_0} = \sin^2 \phi_r = 0.5 - 0.5 \cos 2\phi_r$ and $\dfrac{|G_0|}{R_0} = 0.02$.

Intermediate bodies:	Second float	Sensor package
drag area $C_D A_B$, ft^2	0.55	0.15
weight in water F_{By}, lb	−50	+20

Fluid:

density ρ	1.94 $slugs/ft^3$
kinematic viscosity	10^{-5} ft^2/sec
value of y at ocean surface YIF	0 ft

Current profile:

Depth y feet	Current magnitude c knots	Angle α degrees
0	3.4	0
100	2.5	20.0
500	1.7	75.0
1000	1.15	90.0
2500	0	90.0

The above loading functions are those proposed by Pode, as reported by Springston.[5]

Solution: An iteration is required to determine the radius of the upper buoy. Otherwise, all of the other system parameters are constant. Thus, for the present problem, all of the READ cards were shifted out of the DO 400 loop and an iteration scheme for the upper buoy radius was incorporated into Subroutine ITERA. The data cards for this problem are shown in Table 6 and Subroutine ITERA is shown in Table 7. The iteration scheme basically increases (decreases) the radius of the upper buoy if the depth reached by the given length of cable is less (greater) than the given ocean depth. Table 7 shows that the initial guess for the radius is 1 foot and that the radius is initially restricted to lie between 0.1 and 10 feet. These bounding values become increasingly closer as the iteration proceeds.

The buoy radius and the depth reached by the cable are indicated in Table 8 for each iteration. After 23 iterations, the required depth is reached to an accuracy of two decimal places.

TABLE 6 INPUT DATA FOR SAMPLE PROBLEM 3

	Column Number					
	1	13	25	37	49	61
Card 1	100					
Card 2	bbb DETERMINATION OF RADIUS OF SPHERICAL UPPER BUOY					
Card 3	bb6bb3					
Card 4	0.	0.	0.	0.	15.	
Card 5	−100.	5000.	5000.	5000.	−10.	
Card 6	1.94	1.94	0.00001	0.00001	0.	
Card 7	0.50	0.	−0.50			
Card 8	0.02					
Card 9	500.	2200.	300.			
Card 10	bb5b22bb3					
Card 11	0.22	0.11	0.11			
Card 12	1.2	1.2	1.2			
Card 13	0.	0.	0.			
Card 14	0.	0.	0.			
Card 15	0.13	0.027	0.027			
Card 16	0.13	0.027	0.027			
Card 17	0.55	0.15	0.			
Card 18	−50.	20.	0.			
Card 19	−50.	20.	0.			
Card 20	0.	0.	0.			
Card 21	0.3	0.3	0.3			
Card 22	bb2bb2bb2					
Card 23	0.	0.0004				
Card 24	0.	200.				
Card 23	0.	0.002				
Card 24	0.	150.				
Card 23	0.	0.002				
Card 24	0.	150.				
Card 25	0.	100.	500.	1000.	2500.	9000.
Card 26	3.5	2.5	1.7	1.15	0.	0.
Card 27	0.	20.	75.	90.	90.	90.

TABLE 7 – SUBROUTINE ITERA FOR SAMPLE PROBLEM 3

```
      SUBROUTINE ITERA
      COMMON /BLK1/ CDAS,EPSLON,TSX,TSZ,TSY,SUBM,NCAB,EP2,ICS
      COMMON /BLK2/ YY(30),CC(30),AA(30),VCX,VCZ
      COMMON /BLKSI/ XXL,YYL,ZZL,RHL,PHYL,TTL,THORX,THORY,THORZ
C   THIS SUBROUTINE PERFORMS ITERATIONS OF CONDITIONS AT THE INITIAL
C   POINT
      VCX=0.
      VCZ=0.
C   VCX AND VCZ ARE THE VELOCITIES OF THE CABLE SYSTEM IN THE X AND Z
C   DIRECTIONS
C   FOR FREE-FLOATING CABLE SYSTEMS VCX AND/OR VCZ ARE ITERATED
    2 FORMAT(/5X,12HBUOY RADIUS=,F10.6,1X,2HFT)
      IF(ICS.EQ.1) GO TO 40
      IF(ICS.GT.75) STOP
      ERRORY=YYL-2500.
      ABSERY=ABS(ERRORY)
      IF(ABSERY.LT.0.004) STOP
      IF(ERRORY)15,15,20
   15 R=0.5*(RTEMP+RMAX)
      RMIN=RTEMP
      GO TO 25
   20 R=0.5*(RTEMP+RMIN)
      RMAX=RTEMP
   25 TSY=-62.4*1.333333*3.141592*R*R*R
      CDAS=0.5*3.141592*R*R
      RTEMP=R
      WRITE(6,2) R
   30 RETURN
   40 R=1.
      RMAX=10.
      RMIN=0.1
      GO TO 25
      RETURN
      END
```

TABLE 8 – DEPTH REACHED BY THE LOWER END OF THE CABLE FOR EACH ITERATION OF SAMPLE PROBLEM 3

Iteration Number	Buoy Radius ft	Depth ft
1	1.000000	2020.62
2	5.500000	4504.46
3	3.250000	3313.93
4	2.125000	3068.92
5	1.562500	2936.66
6	1.281250	2743.28
7	1.140625	2505.23
8	1.070313	2304.97
9	1.105469	2414.13
10	1.123047	2461.74
11	1.131836	2483.98
12	1.136230	2494.72
13	1.138428	2500.01
14	1.137329	2497.37
15	1.137878	2498.69
16	1.138153	2499.35
17	1.138290	2499.68
18	1.138359	2499.84
19	1.138393	2499.92
20	1.138411	2499.96
21	1.138419	2499.98
22	1.138423	2500.00
23	1.138426	2500.00

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The author thanks the various users of earlier versions of this program for questions and comments that served to indicate those areas which needed revision or expansion. Several technical discussions with Dr. Bruce D. Cox of the Center during the later stages of the present work were also helpful.

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APPENDIX A
DETERMINATION OF THE FAIRING ANGLE OF ATTACK

The equations for the twisting of a faired cable have been derived in a general way by Dillon.[11] The equations combine to basically form a second-order differential equation for the angle of attack γ which the fairing makes with the fluid velocity normal to the cable c_n. The incorporation of this equation into the present formulation would introduce a number of considerable difficulties and complexities.

First, the addition of this second-order differential equation, which may be rewritten as two first-order differential equations, would raise the number of first-order differential equations from seven to nine. Also, the differential equation for γ[11] is considerably more complex than any of the seven differential Equations (8) – (14) contained in the present report. Second, the solution of this differential equation leads to a boundary-value problem where the moment and angle of attack at one end of the cable depend on the moment and angle of attack at the other end. As pointed out previously, the solution of these boundary-value problems generally requires iterative procedures which may greatly increase computer time. In addition, if the torsional stiffness GJ is sufficiently small and/or the cable is sufficiently long, the differential equation can become of the singular perturbation type, with attendant numerical difficulties. As an indication of this difficulty, Dillon shows that for the case of the twisting of a taut vertical cable, there is an unstable component of γ whose rate of propagation is inversely proportional to GJ. Third, the complexity of the differential equation for γ leads to the requirement for a considerable amount of input data. These include the values of the torsional and bending stiffnesses and the locations of various structural and hydrodynamic centers of the fairing. This large amount of input data tends to make the program inconvenient to use and also requires the user to know a considerable amount about the mechanical details of his cable system.

In view of the above difficulties, it is desirable to find an alternate, simpler equation for the angle of attack. For example, Schram[12] simply prescribes the angle of attack along the cable but gives no basis for doing this.

If all of the terms involving torsional and structural stiffnesses are omitted, the differential equation for γ reduces to an algebraic equation for γ. This algebraic equation is derived below for the coordinate systems used in the present report. The omission of the torsional

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[11] Dillon, D.B., "The Configuration and Loading of a Torsionally Elastic Faired Cable," Hydrospace Challenger, Inc. Report 4557-001 (Oct 1973).

[12] Schram, J.W., "A Three-Dimensional Analysis of a Towed System," Ph.D. Thesis, Rutgers University (Jan 1968).

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stiffness terms is approximately correct for free-swiveling faired cables which are designed to have low torsional rigidities. Moreover, Hegemeier and Bryson[13] show that structural stiffnesses are usually small for fairings where a relatively small, high tensile strength member is surrounded by a relatively large, structurally weak plastic or rubber fairing. The use of this algebraic equation eliminates the first two difficulties mentioned above and reduces the third.

Figure 3 shows a view of the fairing normal to the Y-axis, which is directed along the cable. The X- and Z-axes which appear in this figure are also those shown in Figure 1. Figure 3 indicates that a rotation by the angle $(\psi + \gamma)$ is required to align the X-axis with the X_f-axis which is parallel to the nose-tail line and passes through the center of tension. The Z_f-axis is the axis in the plane of the fairing normal to the X_f-axis. The angle ψ is the angle between the direction of the current normal to the cable and the X-axis and is given by

$$\psi = \tan^{-1} \left(\frac{c_Z}{c_X}\right) \tag{A1}$$

where c_X and c_Z are respectively defined in Equations (16a) and (16c).

The moments are taken about the center of tension. Hence, the various moment distances shown in Figure 3 are measured relative to this center. The various forces shown in Figure 3 all act in the fairing section plane. The tension components $T \cos\theta \, (d\phi_V/ds)$ and $T\,(d\theta/ds)$ which arise due to cable curvature, obtained respectively from Equations (1) and (3), act through the center of tension and hence contribute no moments. The remaining forces contribute moments about the Y-axis and are defined as follows, per unit stretched length of the cable

L_p = side force due to angle of attack variation

L_c = side force due to camber

D_n = normal drag force

$(Wa)_{Z_f}$ = Z_f component of Wa, the weight of the cable in vacuum

$(B)_{Z_f}$ = Z_f component of B, the buoyancy force

The side force due to camber L_c is usually caused by manufacturing errors which result in asymmetrical fairing sections.

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[13] Hegemeier, G.A. and R.L. Bryson, "Numerical Programs to Predict Faired Tow Cable Flutter and Divergence," Systems Exploration Report (Sep 1969).

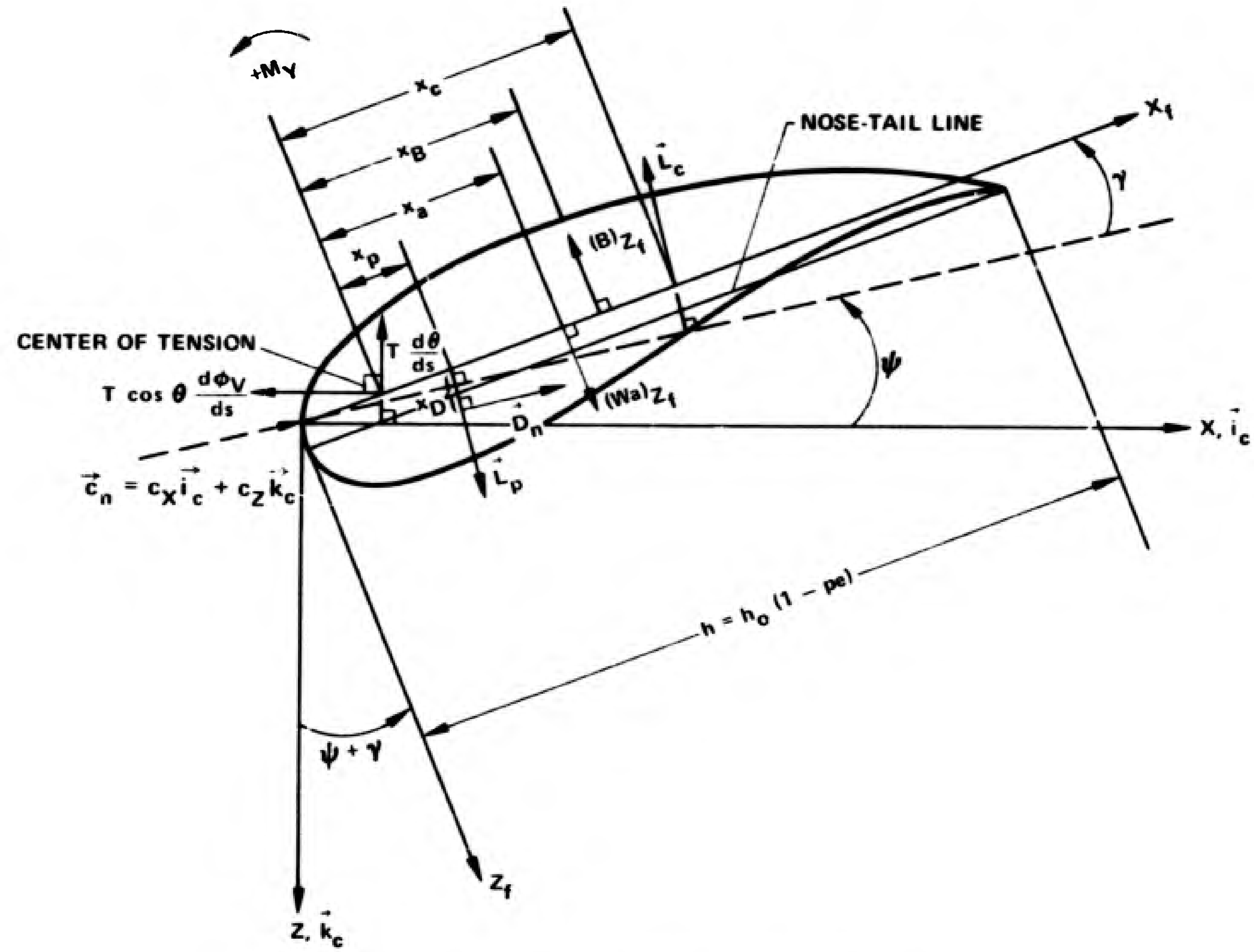

Figure 3 – View of Fairing Normal to the Cable Y-Axis

Since the hydrodynamic forces L_p, L_c, and D_n act in the X_f-Z_f fairing section plane, their moments are easily obtained from Figure 3. The gravity and hydrostatic forces Wa and B are directed along the spatial y-axis. In order to obtain their moments, their components along the Z_f-axis must be obtained. These components may be conveniently obtained by using the transformation matrix $[A_f]$ given by

$$[A_f] = [\psi + \gamma]\ [\theta]\ [\phi_V]$$

$$= \begin{bmatrix} \cos(\psi+\gamma) & 0 & -\sin(\psi+\gamma) \\ 0 & 1 & 0 \\ \sin(\psi+\gamma) & 0 & \cos(\psi+\gamma) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cos\phi_V & \sin\phi_V & 0 \\ -\sin\phi_V & \cos\phi_V & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{(A2)}$$

The matrix

$$[A] = [\theta]\ [\phi_V] = \begin{bmatrix} \cos\phi_V & \sin\phi_V & 0 \\ -\cos\theta\sin\phi_V & \cos\theta\cos\phi_V & \sin\theta \\ \sin\theta\sin\phi_V & -\sin\theta\cos\phi_V & \cos\theta \end{bmatrix} \quad \text{(A3)}$$

is used to derive the cable differential Equations (1) to (3). On carrying out the matrix products given in Equation (A3), the matrix $[A_f]$ is found to be

$$[A_f] = \begin{bmatrix} \cos(\psi+\gamma)\cos\phi_V - \sin(\psi+\gamma)\sin\theta\sin\phi_V & \cos(\psi+\gamma)\sin\phi_V + \sin(\psi+\gamma)\sin\theta\cos\phi_V & -\sin(\psi+\gamma)\cos\theta \\ -\cos\theta\sin\phi_V & \cos\theta\cos\phi_V & \sin\phi \\ \sin(\psi+\gamma)\cos\phi_V + \cos(\psi+\gamma)\sin\theta\sin\phi_V & \sin(\psi+\gamma)\sin\phi_V - \cos(\psi+\gamma)\sin\theta\cos\phi_V & \cos(\psi+\gamma)\cos\theta \end{bmatrix} \quad \text{(A4)}$$

The components of Wa and B along the Z_f-axis are then found by premultiplying the following column matrix

$$(\vec{Wa}, \vec{B}) = \begin{Bmatrix} 0 \\ Wa, -B \\ 0 \end{Bmatrix} \quad \text{(A5)}$$

by the matrix $[A_f]$ given above, resulting in

$$(Wa, B)_{Z_f} = (Wa, -B)\,[\sin(\psi + \gamma) \sin \phi_V - \sin \theta \cos(\psi + \gamma) \cos \phi_V] \qquad \text{(A6)}$$

With the aid of Equation (A6), all the moments about the center of tension in the Y direction may now be conveniently obtained, resulting in the following moment equation of equilibrium

$$\begin{aligned} \Sigma M_Y = & - L_p(\gamma) \cos \gamma\, x_p + L_c \cos \gamma\, x_c + D_n(\gamma) \cos \gamma\, x_D - D_n(\gamma) \sin \gamma\, x_p \\ & - [\sin(\psi + \gamma) \sin \phi_V - \sin \theta \cos(\psi + \gamma) \cos \phi_V]\,(x_a\, Wa - x_B\, B) = 0 \end{aligned} \qquad \text{(A7)}$$

where the moment distances x_p, x_c, x_D, x_a, and x_B are shown in Figure 3.

The above equation is a moment balance of only the hydrodynamic, buoyancy, and gravity forces acting on the cable fairing section. As mentioned previously, all the moment terms due to torsional and bending stiffnesses have been neglected. It still is a formidable transcendental equation for γ. The solution can be simplified considerably if γ is taken to be small. This is not a restricting assumption since it can easily be shown that even in the case where the side force is of the order of the drag force, which results in severe side displacements of the cable, the angle γ is still only a few tenths of a degree. By using this assumption, the following simplifications result

$$\begin{aligned} & \sin \gamma \approx \gamma \\ & \cos \gamma \approx 1 \\ & D_n(\gamma) \approx D_n\,(\gamma = 0) \\ & L_p(\gamma) = 1/2\, \rho\, c_n^2\, C_\gamma\, \gamma\, h \end{aligned} \qquad \text{(A8)}$$

where C_γ is the side force coefficient slope and is approximately equal to 2π per unit radian change in γ for thin airfoils, and h is the chord length of the stretched cable.

In solving for γ, it is also convenient to explicitly write out the expression for L_c

$$L_c = 1/2\, \rho\, c_n^2\, C_c\, f\, h \qquad \text{(A9)}$$

where $C_c\, f$ = lift coefficient for the camber line

f = ratio of the maximum camber to chord

C_c = a factor which varies with the shape of the camber line; e.g., $C_c = 4\pi$ for a circular arc camber line.

Substituting Equations (A8) and (A9) into Equation (A7) results in the following explicit expression for γ

$$\gamma(s) = \frac{-1/2\,\rho\,c_n^{\,2}\,C_c\,f\,h\,x_c - D_n\,x_D + (x_a\,Wa - x_B\,B)(\sin\psi\,\sin\phi_V - \sin\theta\,\cos\psi\,\cos\phi_V)}{-1/2\,\rho\,c_n^{\,2}\,C_\gamma\,h\,x_p - D_n\,x_p - (x_a\,Wa - x_B\,B)(\cos\psi\,\sin\phi_V + \sin\theta\,\sin\psi\,\cos\phi_V)} \tag{A10}$$

The above equation is solved in Subroutine TWIST. The equation shows that γ is a function of the cable scope s since it is a function of the variables D_n, ψ, ϕ_V, and θ which vary along the cable. These variables are computed in other parts of the program. Once the angle γ is known, the side force $\vec{L}_F$ is given by

$$\vec{L}_F = 1/2\,\rho\,C_L\,h\,c_n^{\,2}\,\frac{\vec{c}_n \times \vec{j}_c}{c_n} \tag{A11}$$

where

$$C_L = C_\gamma\,\gamma - C_c\,f \tag{A12}$$

Equation (A11) is similar to Equation (25) except that the latter gives the side force in terms of the reference chord h_0. Recall that the differential equations of equilibrium, (8)–(10), are based on the cable parameters for the reference tension T_0.

Equations (A11) and (A12), which compute the side force based on the two-dimensional characteristics of the fairing section, make use of the independence principle which states that the development of the chordwise flow is independent of the spanwise flow. The brief survey by Choo and Casarella[14] indicates that in the case of turbulent flow, the independence principle does not hold at sufficiently low values of ϕ_r when the spanwise flow dominates the chordwise flow. Their results tentatively suggest that the independence principle may break down for values of ϕ_r less than approximately 30 degrees.

Equation (A10) can be simplified further if the equation is examined in greater detail. It can be shown that the moment terms due to drag, gravity, and hydrostatic buoyancy forces in the denominator of Equation (A10) are usually substantially smaller than the first moment term which is due to the side force arising from an angle of attack of one radian. In the

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[14] Choo, Y.J. and M.J. Casarella, "Resistance of Towed Cables," J. Hydronautics, Vol. 5, No. 4, pp. 126–131 (Oct 1971).

numerator, the distance x_D normal to the chord line of the drag force is due to the fact that fluid velocities over the low pressure side are faster than those over the high pressure side. This gives rise to unequal friction drags over the two sides. For small cambers and angle of attack, these differences in velocities are not large, with the result that x_D is usually small. Moreover, it can be shown that for small values of side displacement of the cable, the gravity and hydrostatic terms in the numerator are small. For instance, for fluid velocity along the x-direction, the angles ψ and θ are identically zero if the side displacement z is zero. The side displacement of the cable from the vertical plane containing the fluid velocity is often referred to in towing cable literature as the kite distance.

Accordingly, for small values of the side displacement, the equation for γ involves only the side forces due to camber and angle of attack. This results in the following simpler equation for γ

$$\gamma = \frac{C_c \, f \, x_c}{C_\gamma \, x_p} \tag{A13}$$

The value of γ is now completely determined by the input values for the coefficient and location of the side forces due to camber and angle of attack. It is no longer dependent on cable shape and can be prescribed as an input into the program. In particular, the input variable CLCH(K), described in the section dealing with input variables, corresponds to

$$\text{CLCH(K)} = C_L \, h_0 = (C_\gamma \, \gamma - C_c \, f) \, h_0 = \frac{C_c \, f}{x_p} \, (x_c - x_p) \, h_0 \tag{A14}$$

The accuracy of Equation (A13) depends on the side displacement of the cable which, in turn, depends on factors such as the camber lift coefficient C_c f, cable length relative to towed body weight, cable weight to drag ratio, and the relative magnitude and location of the gravity and hydrostatic forces Wa and B. Figure 3 shows that the moment due to the gravity force Wa tends to decrease γ whereas the moment due to the buoyancy force B tends to increase γ. Thus if the stabilizing gravity moment term x_a Wa is greater than the destabilizing buoyancy moment term x_B B, the use of the more accurate Equation (A10) will give rise to lower values of γ and hence lower side displacements than the corresponding values obtained by using the simpler Equation (A13). The reverse will be the case if x_B B is greater than x_a Wa. The differences between the two approaches will increase with increasing side displacements of the cable.

APPENDIX B
LISTING OF COMPUTER PROGRAM

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```
      PROGRAM CAB3E(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
      COMMON /BLK1/ CDAS,EPSLON,TSX,TSZ,TSY,SUBM,NCAB,EP2,ICS
      COMMON /BLK2/ YY(30),CC(30),AA(30),VCX,VCZ
      COMMON /BLK5/ YSTOP,XSTOP,ZSTOP,TSTOP,PYSTOP
      COMMON /BLK7/ NPR(100),DC(100),WC1(100),FLC(100),CDC(100),
     1TREF(100),P(100),WBD1(100),DCI(100),WBD2(100),
     2CDAB(100),CLCH(100),CKS(100),WC2(100)
      COMMON /BLK6/ TEND(100,10),EE(100,10),NST(100)
      COMMON /BLK9/ AON,A1CN,A2CN,A1SN,A2SN,AOT,A1CT,A2CT,A1ST,A2ST
      COMMON /BLK8/ RHO1,RHO2,FNU1,FNU2,YIF,ICASE
      DIMENSION CCK(30),AAD(30),TITLE(18)
C     THIS IS THE MAIN PROGRAM.
    2 FORMAT(6F12.6)
    3 FORMAT(6F12.4)
    5 FORMAT(6F12.8)
    8 FORMAT(24I3)
    9 FORMAT(4X,10F12.8)
   10 FORMAT(10F12.4)
   11 FORMAT(18A4)
C     READ INPUT DATA
      READ(5,8) NCASES
      DO 400 ICASE=1,NCASES
      READ(5,11) TITLE
      READ(5,8) NCUR,NCAB
      READ(5,3) CDAS,TSX,TSZ,TSY,SUBM
      READ(5,3) PYSTOP,YSTOP,XSTOP,ZSTOP,TSTOP
      READ(5,5) RHO1,RHO2,FNU1,FNU2,YIF
      READ(5,2) AON,A1CN,A2CN,A1SN,A2SN
      READ(5,2) AOT,A1CT,A2CT,A1ST,A2ST
      READ(5,3) (FLC(K),K=1,NCAB)
      READ(5,8) (NPR(K),K=1,NCAB)
      READ(5,2) (DCI(K),K=1,NCAB)
      READ(5,2) (CDC(K),K=1,NCAB)
      READ(5,2) (CKS(K),K=1,NCAB)
      READ(5,2) (CLCH(K),K=1,NCAB)
      READ(5,2) (WC1(K),K=1,NCAB)
      READ(5,2) (WC2(K),K=1,NCAB)
      READ(5,3) (CDAB(K),K=1,NCAB)
      READ(5,3) (WBD1(K),K=1,NCAB)
      READ(5,3) (WBD2(K), K=1,NCAB)
      READ(5,3) (TREF(K),K=1,NCAB)
      READ(5,2) (P(K),K=1,NCAB)
      READ(5,8) (NST(K),K=1,NCAB)
      DO 101 NE=1,NCAB
      NN=NST(NE)
      READ(5,5) (EE(NE,K),K=1,NN)
      READ(5,3) (TEND(NE,K),K=1,NN)
  101 CONTINUE
      READ(5,3) (YY(I),I=1,NCUR)
      READ(5,2) (CCK(I),I=1,NCUR)
      READ(5,2) (AAD(I),I=1,NCUR)
      ICS=ICASE
      WRITE(6,298)
      EPSLON=0.00001
      EP2=0.00001
```

```
PROGRAM     CA93E     TRACE                    CDC 6600 FTN V3.0-P340 OPT=0  04/10/74  08.24.51.      PAGE     2

              CALL ITERA
          298 FORMAT(1H1)
          299 FORMAT(10X,18A4)
          300 FORMAT( 1X,64H*****LISTING OF CABLE AND OCEAN ENVIRONMENT CHARACTE
             1RISTICS*****)
          301 FORMAT(1X,17HINITIAL BODY.....)
          360 FORMAT(6X,30HINITIAL VERTICAL POSITION (FT),25X,F12.5)
          306 FORMAT(6X,17HDRAG AREA (FT SQ),38X,F12.5)
          312 FORMAT(1X,4X,F12.4,14X,F8.4,16X,F9.4)
          310 FORMAT(1X,18HOCEAN PROFILE.....)
          311 FORMAT(5X,1X,10HDEPTH (FT),10X,15HCURRENT (KNOTS),5X,
             123HANGLE FROM X AXIS (DEG))
          329 FORMAT(6X,33HFORCE IN VERTICAL DIRECTION (LBS),22X,F12.5)
          330 FORMAT(1X)
          382 FORMAT(6X,48HCABLE HYDRODYNAMIC LOADING FUNCTION COEFFICIENTS)
          383 FORMAT(1X,7HNORMAL=,
             1F12.6,1H+,F12.6,1X,11HCOS( PHIR)+,F12.6,1X,11HCOS(2PHIR)+,
             2F12.6,1X,11HSIN( PHIR)+,F12.6,1X,10HSIN(2PHIR))
          384 FORMAT(3X,5HTANG=,
             1F12.6,1H+,F12.6,1X,11HCOS( PHIR)+,F12.6,1X,11HCOS(2PHIR)+,
             2F12.6,1X,11HSIN( PHIR)+,F12.6,1X,10HSIN(2PHIR))
          350 FORMAT(6X,16HCABLE PROPERTIES,84X,15HBODY PROPERTIES)
          351 FORMAT(1X,3HNUM,1X,10HLENGTH(FT),1X,10HT REF(LBS),
             12X,8HDIAM(IN),1X,9HW1(LB/FT),1X,9HW2(LB/FT),1X,9HDRAG COEF,2X,
             29HPOI RATIO,1X,10HCLXCRD(FT),3X,5HKSUBS,5X,
             39HCDA(FTSQ),4X,8HWT1(LBS),2X,8HWT2(LBS))
          352 FORMAT(1X,I3,2F11.3,5F10.6,F11.5,F10.5,2X,3F11.4)
          361 FORMAT(6X,5HCABLE,I3,2X,34HSTRAIN-TENSION DIFFERENCE RELATION)
          340 FORMAT(1H1,10HRUN NUMBER,1X,I3)
          341 FORMAT(2X)
          344 FORMAT(1X,20HSTOP CONDITIONS.....)
          346 FORMAT(6X,22HVERTICAL DISTANCE (FT),33X,F12.5)
          411 FORMAT(6X,25HANGLE FROM VERTICAL (DEG),30X,F12.5)
          397 FORMAT(6X,15HX DISTANCE (FT),40X,F12.5)
          398 FORMAT(6X,15HZ DISTANCE (FT),40X,F12.5)
          399 FORMAT(6X,13HTENSION (LBS),42X,F12.5)
          354 FORMAT(6X,34HAPPLIED FORCE IN X DIRECTION (LBS),21X,F12.5)
          355 FORMAT(6X,34HAPPLIED FORCE IN Z DIRECTION (LBS),21X,F12.5)
          392 FORMAT(6X,45HFLUID DENSITY ABOVE INTERFACE(SLUGS/CUBIC FT),
             112X,F12.8)
          393 FORMAT(6X,
             152HFLUID KINEMATIC VISCOSITY ABOVE INTERFACE(FT SQ/SEC),6X,F12.8)
          394 FORMAT(6X,20HY AT FLUID INTERFACE,34X,F12.4)
          395 FORMAT(6X,45HFLUID DENSITY BELOW INTERFACE(SLUGS/CUBIC FT),
             113X,F12.8)
          396 FORMAT(6X,52HFLUID KINEMATIC VISCOSITY BELOW INTERFACE(FT SQ/SEC),
             17X,F12.8)
          402 FORMAT(/6X,22HYIF AND SUBM ARE EQUAL)
        C     WRITE INPUT DATA
              WRITE(6,299) TITLE
              WRITE(6,330)
           31 WRITE(6,300)
              WRITE (6,330)
              WRITE (6,301)
              WRITE(6,360) SUBM
```

```
      WRITE(6,306) CDAS
      WRITE(6,329) TSY
      WRITE(6,354) TSX
      WRITE(6,355) TSZ
      WRITE (6,330)
      WRITE(6,392) RHO1
      WRITE(6,393) FNU1
      WRITE(6,394) YIF
      WRITE(6,395) RHO2
      WRITE(6,396) FNU2
      WRITE(6,330)
      WRITE (6,310)
      WRITE (6,311)
      WRITE(6,312) (YY(I),CCK(I),AAD(I),I=1,NCUR)
      WRITE(6,330)
      WRITE(6,382)
      WRITE(6,383) A0N,A1CN,A2CN,A1SN,A2SN
      WRITE(6,384) A0T,A1CT,A2CT,A1ST,A2ST
      WRITE (6,330)
      WRITE(6,350)
      WRITE(6,351)
      DO 370 K=1,NCAB
      WRITE(6,352) K,FLC(K),TREF(K),DCI(K),WC1(K),WC2(K),CDC(K),P(K),
     1CLCH(K),CKS(K),CDAB(K),WBD1(K),WBD2(K)
  370 CONTINUE
      WRITE(6,330)
      DO 375 JJ=1,NCAB
      NN=NST(JJ)
      WRITE(6,361) JJ
      WRITE(6,9) (EE(JJ,K),K=1,NN)
      WRITE(6,10) (TEND(JJ,K),K=1,NN)
  375 CONTINUE
      WRITE(6,330)
      WRITE(6,344)
      WRITE(6,411) PYSTOP
      WRITE(6,346) YSTOP
      WRITE(6,397) XSTOP
      WRITE(6,398) ZSTOP
      WRITE(6,399) TSTOP
      WRITE(6,340) ICASE
      WRITE(6,341)
      DO 50 J=1,NCAB
      DC(J)=DCI(J)/12.
   50 CONTINUE
C     CONVERT FROM KNOTS TO FEET PER SECOND AND DEGREES TO RADIANS
      DO 32 I=1,NCUR
      CC(I)=1.6878*CCK(I)
      AA(I)=AAD(I)/57.29578
   32 CONTINUE
      YY(NCUR+1)=YY(NCUR)+90000.
      CC(NCUR+1)=CC(NCUR)
      AA(NCUR+1)=AA(NCUR)
      SUMYI=SUBM-YIF
      IF(ABS(SUMYI)-0.000001) 405,405,404
  405 WRITE(6,402)
```

```
      GO TO 400
  404 IF(ABS(SUBM).LE.0.000001) SUBM=0.000001*(-YIF/ABS(YIF))
C     CALL THE SUBROUTINE STEA3D TO CALCULATE THE 3D CONFIGURATION
      CALL STEA3D
  400 CONTINUE
      STOP
      END
```

```
      SUBROUTINE STEA3D
      DIMENSION S(400),X(400),Y(400),Z(400),PHIYD(400),T(400),RHR(400)
      DIMENSION Y0(7),PHIV(400)
      DIMENSION THETA(400),PHIVD(400),THETAD(400),SE(400)
      COMMON /BLK1/ CDAS,EPSLON,TSX,TSZ,TSY,SUBM,NCAB,EP2,ICS
      COMMON /BLK7/ NPR(100),DC(100),WC1(100),FLC(100),CDC(100),
     1TREF(100),P(100),WBD1(100),DCI(100),WBD2(100),
     2CDAB(100),CLCM(100),CKS(100),WC2(100)
      COMMON /BLK4/ DRAG1,FFTANG,TREFC,PC,RDK1,RCM1,RDC,CT,
     1DRAG2,RDK2,RCM2,WPUL1,WPUL2
      COMMON /BLK5/ YSTOP,XSTOP,ZSTOP,TSTOP,PYSTOP
      COMMON /BLK3/ FIRST,FEL,JE
      COMMON /BLK8/ RHO1,RHO2,FNU1,FNU2,YIF,ICASE
      COMMON /BLKSI/ XXL,YYL,ZZL,RML,PHYL,TTL,THORX,THORY,THORZ
      COMMON /BLKST/ GAMAD
C     THIS IS THE MAIN SUBROUTINE
      PI=3.14159
      RADIAN=57.29578
  202 FORMAT(1X)
  203 FORMAT(1X,2X,9HS REF(FT),2X,9HS STR(FT),4X,5HX(FT),6X,5HY(FT),
     16X,5HZ(FT),3X,9HR HOR(FT),4X,9HPHIY(DEG),3X,9HPHIV(DEG),3X,
     210HTHETA(DEG),2X,6HT(LBS),2X,10HGAMMA(DEG))
  204 FORMAT(1X,1X,F9.2,2X,F9.2,2X,F9.2,2X,F9.2,2X,F9.2,2X,
     1F9.2,2X,F9.2,2X,F9.2,4X,F9.2,2X,F10.2,2X,F9.4)
  207 FORMAT(1X,36HTHE VERTICAL COMPONENT OF TENSION IS,
     11X,F11.4,1X,4HLBS.)
  208 FORMAT(1X,46HTHE COMPONENT OF TENSION IN THE X DIRECTION IS,
     11X,F11.4,1X,4HLBS.)
  209 FORMAT(1X,46HTHE COMPONENT OF TENSION IN THE Z DIRECTION IS,
     11X,F11.4,1X,4HLBS.)
      WRITE(6,202)
    2 CONTINUE
C     CALCULATE VARIABLES AT THE INITIAL BODY
      BCY=TSY
      IF(ABS(BCY).LE.0.0000001) BCY=0.0000001
    8 FIRST=-100.0
      DEP=SUBM
      CALL CUR(DEP,CSUBX,CSUBZ)
      COX=CSUBX
      COZ=CSUBZ
      CO=SQRT(COX*COX+COZ*COZ)
      FIRST=100.0
      RHO=RHO1
      IF(SUBM.GT.YIF) RHO=RHO2
      DRAGBX=0.5*RHO*CDAS*COX*CO
      DRAGBZ=.5*RHO*CDAS*COZ*CO
      DRAGBX=DRAGBX+TSX
      DRAGBZ=DRAGBZ+TSZ
      T(1)=SQRT(DRAGBX*DRAGBX+DRAGBZ*DRAGBZ+BCY*BCY)
      PHIV(1)=ATAN2(DRAGBX,-BCY)
      FIV=PHIV(1)
      THETAN=DRAGBZ*COS(FIV)
      THETA(1)=ATAN2(-THETAN,-BCY)
      PHIVD(1)=PHIV(1)*RADIAN
      THETAD(1)=THETA(1)*RADIAN
```

```
      X(1)=0.0
      Y(1)=SUBM
      S(1)=0.0
      Z(1)=0.0
      SE(1)=0.
      RHR(1)=0.
      IF(ABS(YSTOP).LT.0.000001) YSTOP=0.000001*SUBM/ABS(SUBM)
      IF(ABS(PYSTOP).LT.0.000001) PYSTOP=0.000001
      IF(ABS(TSTOP).LT.0.000001) TSTOP=0.000001
      TSP=TSTOP/T(1)
      YSP=YSTOP/Y(1)
      NLAST=0
C     DETERMINE SIGN OF CABLE SCOPE
      BMAG=ABS(BCY)-0.00001
      XZMG=ABS(DRAGBX)-ABS(DRAGBZ)
      IF(BMAG.LE.0.) GO TO 270
      SNS=(COS(FIV)*COS(THETA(1)))/(-BCY)
      GO TO 280
  270 IF(XZMG)272,272,274
  274 SNS=(-COS(THETA(1))*SIN(FIV))/(-DRAGBX)
      GO TO 280
  272 SNS=SIN(THETA(1))/(-DRAGBZ)
  280 SNSS=SNS/ABS(SNS)
      DYDSA=COS(THETA(1))*COS(PHIV(1))*SNSS
      PHIYD(1)=ACOS(DYDSA)*RADIAN
      PHYSP=PYSTOP/PHIYD(1)
      STPQ=C.
      WRITE(6,208) DRAGBX
      WRITE(6,209) DRAGBZ
      WRITE(6,207) BCY
      WRITE(6,202)
      WRITE(6,202)
      WRITE(6,203)
      WRITE(6,204) S(1),SE(1),X(1),Y(1),Z(1),RHR(1),PHIYD(1),PHIVD(1),
     1THETAD(1),T(1)
C     START CALCULATIONS ALONG THE CABLE
      DO 240 JE=1,NCAB
      FEL=-10.
      START=0.0
      DRAG1=0.5*RHO1*CDC(JE)*DC(JE)
      RDK1=0.5*RHO1*DC(JE)*CKS(JE)
      RCH1=0.5*RHO1*CLCH(JE)
      DRAG2=0.5*RHO2*CDC(JE)*DC(JE)
      RDK2=0.5*RHO2*DC(JE)*CKS(JE)
      RCH2=0.5*RHO2*CLCH(JE)
      RDC=ABS(CKS(JE))+ABS(CLCH(JE))
      CT=DC(JE)
      WPUL1=WC1(JE)
      WPUL2=WC2(JE)
      TREFC=TREF(JE)
      PC=P(JE)
      FNP=NPR(JE)
      SPA=(FLC(JE)/FNP)*SNSS
      N1=NLAST+2
      NLAST=N1+NPR(JE)-1
```

```
      DO 250 M=N1,NLAST
      MINDEX=M
      Y0(1)=T(M-1)
      Y0(2)=PHIV(M-1)
      Y0(3)=THETA(M-1)
      Y0(4)=X(M-1)
      Y0(5)=Y(M-1)
      Y0(6)=Z(M-1)
      Y0(7)=SE(M-1)
      SS=S(M-1)
      CALL KUTMER(7,SS,Y0,EPSLON,SPA,START,HCX,EP2)
      T(M)=Y0(1)
      PHIV(M)=Y0(2)
      THETA(M)=Y0(3)
      PHIVD(M)=PHIV(M)*RADIAN
      THETAD(M)=THETA(M)*RADIAN
      X(M)=Y0(4)
      Y(M)=Y0(5)
      Z(M)=Y0(6)
      RHR(M)=SQRT(X(M)*X(M)+Z(M)*Z(M))
      DYDSA=COS(THETA(M))*COS(PHIV(M))*SNSS
      PHIYD(M)=ACOS(DYDSA)*RADIAN
      SE(M)=Y0(7)
      S(M)=SS
C   CHECK FOR STOP CONDITIONS
      IF((YSP.GT.0.).AND.(YSP.LT.1.).AND.((Y(M)/YSTOP).LT.1.)) STPQ=1.
      IF(((YSP.GT.1.).OR.(YSP.LT.0.)).AND.((Y(M)/YSTOP).GT.1.)) STPQ=2.
      IF((TSP.GT.0.).AND.(TSP.LT.1.).AND.((T(M)/TSTOP).LT.1.)) STPQ=3.
      IF((TSP.GT.1.).AND.((T(M)/TSTOP).GT.1.)) STPQ=4.
      IF((X(M)/XSTOP).GT.1.) STPQ=5.
      IF((Z(M)/ZSTOP).GT.1.) STPQ=6.
      IF((PHYSP.GT.0.).AND.(PHYSP.LT.1.).AND.
     1((PHIYD(M)/PYSTOP).LT.1.)) STPQ=7.
      IF((PHYSP.GT.1.).AND.((PHIYD(M)/PYSTOP).GT.1.)) STPQ=8.
      IF(STPQ.GE.1.) GO TO 810
      FEL=10.
      IF(ABS(CLCH(JE)).GE.100.) GO TO 248
      WRITE(6,204) S(M),SE(M),X(M),Y(M),Z(M),RHR(M),PHIYD(M),PHIVD(M),
     1THETAD(M),T(M)
      GO TO 250
  248 WRITE(6,204) S(M),SE(M),X(M),Y(M),Z(M),RHR(M),PHIYD(M),PHIVD(M),
     1THETAD(M),T(M),GAMAD
  250 CONTINUE
C  CALCULATE TENSION AND ANGLE AT BODY.
      CALL CUR(Y(NLAST),CSUBX,CSUBZ)
      CTOT=SQRT(CSUBX*CSUBX+CSUBZ*CSUBZ)
      RHO=RHO1
      IF(Y(NLAST).GT.YIF) RHO=RHO2
      FFAC=0.5*RHO
      FBX=FFAC*CSUBX*CTOT*CDAB(JE)
      FBY=WBD1(JE)
      IF(Y(NLAST).GT.YIF) FBY=WBD2(JE)
      FBZ=FFAC*CSUBZ*CTOT*CDAB(JE)
      SNDY=SNSS
      FBX=FBX*SNDY
```

```
      FBY=FBY*SNDY
      FBZ=FBZ*SNDY
      TB1-SIN(PHIV(NLAST))*COS(THETA(NLAST))*T(NLAST)+FBX
      TB2=-COS(PHIV(NLAST))*COS(THETA(NLAST))*T(NLAST)+FBY
      TB3=-SIN(THETA(NLAST))*T(NLAST)+FBZ
      T(NLAST+1)=SQRT(TB1*TB1+TB2*TB2+TB3*TB3)
      PHIV(NLAST+1)=ATAN2(TB1,-TB2)
      THETA(NLAST+1)=ATAN2(-TB3*COS(PHIV(NLAST+1)),-TB2)
      PHIVD(NLAST+1)=PHIV(NLAST+1)*RADIAN
      THETAD(NLAST+1)=THETA(NLAST+1)*RADIAN
      DYDSA=COS(THETA(NLAST+1))*COS(PHIV(NLAST+1))*SNSS
      PHIYD(NLAST+1)=ACOS(DYDSA)*RADIAN
      Y(NLAST+1)=Y(NLAST)
      X(NLAST+1)=X(NLAST)
      Z(NLAST+1)=Z(NLAST)
      S(NLAST+1)=S(NLAST)
      SE(NLAST+1)=SE(NLAST)
      RHP(NLAST+1)=RHP(NLAST)
      NW=NLAST+1
      WRITE(6,204) S(NW),SE(NW),X(NW),Y(NW),Z(NW),RHR(NW),PHIYD(NW),
     1PHIVD(NW),THETAD(NW),T(NW)
      IF((TSP.GT.0.).AND.(TSP.LT.1.).AND.((T(NW)/TSTOP).LT.1.)) GO TO 97
      IF((TSP.GT.1.).AND.((T(NW)/TSTOP).GT.1.)) GO TO 97
      IF((PHYSP.GT.0.).AND.(PHYSP.LT.1.).AND.
     1((PHIYD(NW)/PYSTOP).LT.1.)) GO TO 97
      IF((PHYSP.GT.1.).AND.((PHIYD(NW)/PYSTOP).GT.1.)) GO TO 97
  240 CONTINUE
   97 MPRINT=NLAST+1
   95 THORX=+T(MPRINT)*COS(THETA(MPRINT))*SIN(PHIV(MPRINT))
      THORZ=-T(MPRINT)*SIN(THETA(MPRINT))
      TVERT=-T(MPRINT)*COS(THETA(MPRINT))*COS(PHIV(MPRINT))
      GO TO 99
  810 MPRINT=MINDEX+100
      MM=MINDEX
      SPO2=SPA
      SPO2=0.5*SPO2
      SINT=SPO2
C     FIND THE CABLE SCOPE AT WHICH STOP CONDITION IS EXACTLY SATISFIED
  823 START=0.0
      DO 815 M=MM,MPRINT
      MINDEX=M
      SS=S(MM-1)
      Y0(1)=T(MM-1)
      Y0(2)=PHIV(MM-1)
      Y0(3)=THETA(MM-1)
      Y0(4)=X(MM-1)
      Y0(5)=Y(MM-1)
      Y0(6)=Z(MM-1)
      Y0(7)=SE(MM-1)
      START=0.0
      CALL KUTMER(7,SS,Y0,EPSLON,SPO2,START,HCX,EP2)
      T(M)=Y0(1)
      PHIV(M)=Y0(2)
      THETA(M)=Y0(3)
      PHIVD(M)=PHIV(M)*RADIAN
```

```
      THETAD(M)=THETA(M)*RADIAN
      X(M)=Y0(4)
      Y(M)=Y0(5)
      Z(M)=Y0(6)
      SE(M)=Y0(7)
      S(M)=SS
      DYDSA=COS(THETA(M))*COS(PHIV(M))*SNSS
      PHIYD(M)=ACOS(DYDSA)*RADIAN
      IF(STPQ.EQ.1.) ERR=-(Y(M)/YSTOP)+1.
      IF(STPQ.EQ.2.) ERR=(Y(M)/YSTOP)-1.
      IF(STPQ.EQ.3.) ERR=-(T(M)/TSTOP)+1.
      IF(STPQ.EQ.4.) ERR=(T(M)/TSTOP)-1.
      IF(STPQ.EQ.5.) ERR=(X(M)/XSTOP)-1.
      IF(STPQ.EQ.6.) ERR=(Z(M)/ZSTOP)-1.
      IF(STPQ.EQ.7.) ERR=-(PHIYD(M)/PYSTOP)+1.
      IF(STPQ.EQ.8.) ERR=(PHIYD(M)/PYSTOP)-1.
      IF(ABS(ERR).LT.0.000001) GO TO 820
      SINT=0.5*SINT
      SP02=SP02+SINT*(-ERR)/ABS(ERR)
  815 CONTINUE
  820 MPRINT=MM
      X(MM)=X(MINDEX)
      Y(MM)=Y(MINDEX)
      Z(MM)=Z(MINDEX)
      RHR(MM)=SQRT(X(MM)*X(MM)+Z(MM)*Z(MM))
      S(MM)=S(MINDEX)
      SE(MM)=SE(MINDEX)
      T(MM)=T(MINDEX)
      PHIVD(MM)=PHIVD(MINDEX)
      THETAD(MM)=THETAD(MINDEX)
      PHIV(MM)=PHIV(MINDEX)
      THETA(MM)=THETA(MINDEX)
      PHIYD(MM)=PHIYD(MINDEX)
      GO TO 95
  830 MPRINT=MINDEX
      STPQ=10.
      GO TO 95
   99 CONTINUE
      IF(STPQ.LE.0.1) GO TO 111
      MP=MPRINT
      WRITE(6,204) S(MP),SE(MP),X(MP),Y(MP),Z(MP),RHR(MP),PHIYD(MP),
     1PHIVD(MP),THETAD(MP),T(MP)
  111 WRITE(6,202)
C   WRITE TENSION COMPONENTS AT END OF CABLE
      WRITE(6,207) TVERT
      WRITE(6,208) THORX
      WRITE(6,209) THORZ
  130 CONTINUE
C   DEFINE END CONDITIONS FOR TRANSMITTAL TO SUBROUTINE ITERA
      XXL=X(MPRINT)
      YYL=Y(MPRINT)
      ZZL=Z(MPRINT)
      RHL=RHR(MPRINT)
      PHYL=PHIYD(MPRINT)
      TTL=T(MPRINT)
```

```
      RETURN
      END
```

SUBROUTINE CUR TRACE CDC 6600 FTN V3.0-P340 OPT=0 04/10/74 08.24.51. PAGE 1

```
      SUBROUTINE CUR(YR,CSUBX,CSUBZ)
      COMMON /BLK2/ YY(30),CC(30),AA(30),VCX,VCZ
      COMMON /BLK3/ FIRST,FEL,JE
      IF(FIRST.LT. 0.0) I=1
      Y=YR
      IF(Y.LT.YY(1)) GO TO 80
      IF(( Y.GE.YY(I)).AND.(Y.LE.YY(I+1))) GO TO 30
      IF((Y.GE.YY(I-1)).AND.(Y.LE.YY(I))) GO TO 40
      IF((Y.GE.YY(I+1)).AND.(Y.LE.YY(I+2))) GO TO 50
   60 I=1
   70 IF(Y.LE.YY(I+1)) GO TO 30
      I=I+1
      GO TO 70
   30 CTOT=CC(I)+((CC(I+1)-CC(I))/(YY(I+1)-YY(I)))*(Y-YY(I))
      ALPH=AA(I)+((AA(I+1)-AA(I))/(YY(I+1)-YY(I)))*(Y-YY(I))
   85 CSUBX=CTOT*COS(ALPH)-VCX
      CSUBZ=CTOT*SIN(ALPH)-VCZ
      RETURN
   40 I=I-1
      GO TO 30
   50 I=I+1
      GO TO 30
   80 CTOT=CC(1)
      ALPH=AA(1)
      GO TO 85
      END
```

```
      SUBROUTINE DAUX(S,INTEG,DERIV)
      DIMENSION DERIV(7)
      COMMON /BLK4/ DRAG1,FFTANG,TREFC,PC,RDK1,RCH1,RDC,CT,
     1DRAG2,RDK2,RCH2,WPUL1,WPUL2
      COMMON /BLK9/ A0N,A1CN,A2CN,A1SN,A2SN,A0T,A1CT,A2CT,A1ST,A2ST
      COMMON /BLKB/ RHO1,RHO2,FNU1,FNU2,YIF,ICASE
      COMMON /BLKOT/ CNORM,QCABZ,QCABX,DN,PHIV,THETA,RCHA,RHO,PCE,OPE,SR
      REAL INTEG(7)
      CALL CUR(INTEG(5),CSUBX,CSUBZ)
      C=SQRT(CSUBX*CSUBX+CSUBZ*CSUBZ)
      QCABX=COS(INTEG(2))*CSUBX
      QCABY=-COS(INTEG(3))*SIN(INTEG(2))*CSUBX+SIN(INTEG(3))*CSUBZ
      QCABZ=SIN(INTEG(3))*SIN(INTEG(2))*CSUBX+COS(INTEG(3))*CSUBZ
      CNORM=SQRT(QCABX*QCABX+QCABZ*QCABZ)
      QCY=QCABY
      IF(ABS(QCY).LE.0.000001) QCY=0.000001
      QYR=QCY/ABS(QCY)
      TDIF=INTEG(1)-TREFC
      CALL ELAS(TDIF,STRN)
      DERIV(7)=1.+STRN
       PCE=1.-PC*STRN
      IF(INTEG(5)-YIF) 40,40,41
   40 DRAG=DRAG1
      WPUL=WPUL1
      FNU=FNU1
      RCH=RCH1
      RDK=RDK1*QYR
      RHO=RHO1
      GO TO 43
   41 DRAG=DRAG2
      WPUL=WPUL2
      RCH=RCH2
      RDK=RDK2*QYR
      FNU=FNU2
      RHO=RHO2
   43 REN=(CNORM*CT*PCE)/FNU
      RE=(C*CT*PCE)/FNU
   45 DRAGM=DRAG*PCE*DERIV(7)
      R=DRAGM*C*C
      IF(C) 20,20,25
   25 SINPH=CNORM/C
      COSPH=ABS(QCABY)/C
      SIN2PH=2.*SINPH*COSPH
      COS2PH=COSPH*COSPH-SINPH*SINPH
      FNORM=A0N+A1CN*COSPH+A2CN*COS2PH+A1SN*SINPH+A2SN*SIN2PH
      FTAN=A0T+A1CT*COSPH+A2CT*COS2PH+A1ST*SINPH+A2ST*SIN2PH
C   OTHER FORMS FOR FTAN AND FNORM CAN BE GIVEN HERE.
C   INCLUDING VARIATIONS WITH REYNOLDS NUMBERS RE OR REN
      G=R*SIGN(FTAN,QCABY)
      FI=R*FNORM*QCABX/CNORM
      FH=R*FNORM*QCABZ/CNORM
      IF(RDC) 30,30,15
   15 CONTINUE
      RCHA=RCH
C  FAIRING ANGLE OF ATTACK AS A FUNCTION OF S CAN BE GIVEN BY SETTING
```

```
C     RCHA EQUAL TO THE DESIRED FUNCTION OF S, RCHA=RCHXFN(S)
C     RCH=0.5XRHOXCLXCHORD
C     SAMPLE DISTRIBUTION OF RCHA FOR 500-FOOT CABLE
C     ICS1=ICASE-1$CS1=ICS1$S5=ABS(S)/500.$RCHA=RCH*COS(3.14159*CS1*S5)
      OPE=DERIV(7)
      DN=R*FNORM
      SR=S
      CLCHA=RCH*2./RHO
      PHIV=INTEG(2)
      THETA=INTEG(3)
C     IF ABS(CLCHA).GE.100., SUBROUTINE TWIST FURNISHES THE VALUE OF RCHA
      IF(ABS(CLCHA).GE.100.) CALL TWIST
      FNML=SQRT(COSPH)/SQRT(RE)
      FLFR=RCHA*CNORM
      FLKS=RDK*C*FNML
      FLT=(FLFR+FLKS)*PCE*DERIV(7)
      FI=FI-FLT*QCABZ
      FH=FH+FLT*QCABX
   30 DERIV(4)=-COS(INTEG(3))*SIN(INTEG(2))*DERIV(7)
      DERIV(5)=COS(INTEG(3))*COS(INTEG(2))*DERIV(7)
      DERIV(6)=SIN(INTEG(3))*DERIV(7)
      DERIV(1)=-G-COS(INTEG(3))*COS(INTEG(2))*WPUL
      DERIV(2)=(-FI-SIN(INTEG(2))*WPUL)/(-INTEG(1)*COS(INTEG(3)))
      DERIV(3)=(-FH+SIN(INTEG(3))*COS(INTEG(2))*WPUL)/INTEG(1)
      RETURN
   20 G=0.
      FI=0.
      FH=0.
      GO TO 30
      END
```

SUBROUTINE ELAS TRACE CDC 6600 FTN V3.0-P340 OPT=0 04/10/74 08.24.51. PAGE 1

```
      SUBROUTINE ELAS(TD,STRN)
      COMMON /BLK6/ TEND(100,10),EE(100,10),NST(100)
      COMMON /BLK3/ FIRST,FEL,JE
      IF(FEL.LE.0.) I=1
      J=JE
      N=NST(J)
      IF(TD.LT.TEND(J,1)) GO TO 75
      IF(TD.GT.TEND(J,N)) GO TO 80
      IF((TD.GE.TEND(J,I)).AND.(TD.LE.TEND(J,I+1))) GO TO 30
      IF((TD.GE.TEND(J,I-1)).AND.(TD.LE.TEND(J,I))) GO TO 40
      IF((TD.GE.TEND(J,I+1)).AND.(TD.LE.TEND(J,I+2))) GO TO 50
   60 I=1
   70 IF(TD.LE.TEND(J,I+1)) GO TO 30
      I=I+1
      GO TO 70
   30 STRN=EE(J,I)+((EE(J,I+1)-EE(J,I))/(TEND(J,I+1)-TEND(J,I)))*
     1(TD-TEND(J,I))
      RETURN
   40 I=I-1
      GO TO 30
   50 I=I+1
      GO TO 30
   75 STRN=EE(J,1)+((EE(J,2)-EE(J,1))/(TEND(J,2)-TEND(J,1)))*
     1(TD-TEND(J,1))
      RETURN
   80 STRN=EE(J,N)+((EE(J,N)-EE(J,N-1))/(TEND(J,N)-TEND(J,N-1)))*
     1(TD-TEND(J,N))
      RETURN
      END
```

```
      SUBROUTINE KUTMER(N,T,Y0,EPS,H,FIRST,HCX, A)
C      KUTMER ROUTINE REVISED FOR IVODE   JAN 30,1964             0020
      DIMENSION Y0(23),Y1(23),Y2(23),F0(23),F1(23),F2(23)        0010
      IF(FIRST)20,10,20                                          0030
   10 HC=H                                                       0040
      IPLOC=1                                                    0050
      FIRST=1.                                                   0060
   20 LOC=0                                                      0070
        HCX=HC                                                   0080
   30 CALL DAUX (T,Y0,F0)                                        0090
   35 DO 40 I=1,N                                                0100
   40 Y1(I)=Y0(I)+(HC/3.)*F0(I)                                  0110
      CALL DAUX (T+HC/3.,Y1,F1)                                  0120
      DO 50 I=1,N                                                0130
   50 Y1(I)=Y0(I)+(HC/6.)*F0(I)+(HC/6.)*F1(I)                    0140
      CALL DAUX (T+HC/3.,Y1,F1)                                  0150
      DO 60 I=1,N                                                0160
   60 Y1(I)=Y0(I)+HC/8.*F0(I)+.375*HC*F1(I)                      0170
      CALL DAUX (T+HC/2.,Y1,F2)                                  0180
      DO 70 I=1,N                                                0190
   70 Y1(I)=Y0(I)+HC/2.*F0(I)-1.5*HC*F1(I)+2.*HC*F2(I)           0200
      CALL DAUX (T+HC,Y1,F1)                                     0210
      DO 80 I=1,N                                                0220
   80 Y2(I)=Y0(I)+HC/6.*F0(I)+.66666667*HC*F2(I)+(HC/6.)*F1(I)   0230
      INC=0                                                      0240
      DO 110 I=1,N                                               0250
        ZZZ=ABS (Y1(I))-A                                        0260
        IF(ZZZ) 85,87,87
   85  ERROR = ABS(.2*(Y1(I)-Y2(I)) )                            0280
        IF(ERROR-A)100,100,90                                    0290
   87 ERROR=ABS (.2-.2*Y2(I)/Y1(I))                              0300
      IF(ERROR-EPS)100,100,90                                    0310
   90 CONTINUE                                                   0320
      KYSCIE=24                                                  0322
      CZATR=2.**KYSCIE
      XX= CZATR*ABS(HC)-ABS(H)                                   0326
      IF (XX) 91,95,95                                           0330
   91  WRITE(6,92)  T,ERROR,I                                    0340
   92 FORMAT(21H RELATIVE ERROR AT X= 1P1E12.3,3H ISF10.6/  6H  I=  ,I4)   0350
        FIRST = 2.                                               0360
        RETURN                                                   0370
   95 HC=HC/2.                                                   0380
      IPLOC=2 *IPLOC                                             0390
      LOC=2 *LOC                                                 0400
        HCX=HC                                                   0410
      GO TO 30                                                   0420
  100 IF(ERROR*64.-EPS)110,110,101                               0430
  101 INC=1                                                      0440
  110 CONTINUE                                                   0450
  111 T=T+HC                                                     0460
      DO 112 I=1,N                                               0470
  112 Y0(I)=Y2(I)                                                0480
      LOC=LOC+1                                                  0490
      IF(LOC-IPLOC)120,210,210                                   0500
  120 IF(INC)210,130,210                                         0510
                                                                 0520
```

```
130 IF(LOC-(LOC/2)*2)210,140,210
140 IF(IPLOC-1)210,210,200
200 HC=2.*HC
    LOC=LOC/2
    IPLOC=IPLOC/2
210 IF(IPLOC-LOC)30,220,30
220 RETURN
    END
```

```
      SUBROUTINE ITERA
      COMMON /BLK1/ CDAS,EPSLON,TSX,TSZ,TSY,SUBM,NCAB,EP2,ICS
      COMMON /BLK2/ YY(30),CC(30),AA(30),VCX,VCZ
      COMMON /BLKSI/ XXL,YYL,ZZL,RML,PHYL,TTL,THORX,THORY,THORZ
C  THIS SUBROUTINE PERFORMS ITERATIONS OF CONDITIONS AT THE INITIAL
C  POINT
      VCX=0.
      VCZ=0.
C  VCX AND VCZ ARE THE VELOCITIES OF THE CABLE SYSTEM IN THE X AND Z
C  DIRECTIONS
C  FOR FREE-FLOATING CABLE SYSTEMS VCX AND/OR VCZ ARE ITERATED
      RETURN
      END
```

```
      SUBROUTINE TWIST
      COMMON /BLKB/ RHO1,RHO2,FNU1,FNU2,YIF,ICASE
      COMMON /BLK3/ FIRST,FEL,JE
      COMMON /BLKOT/ CNORM,QCABZ,QCABX,DN,PHIV,THETA,RCHA,RHO,PCE,OPE,SR
      COMMON /BLKST/ GAMAD
C     PROGRAM ENTERS THIS SUBROUTINE IF INPUT ABSOLUTE VALUE OF CLCH IS
C     GREATER OR EQUAL TO 100.
C     USER MUST FURNISH VALUES FOR REFERENCE CHORD CHR IN FT,
C     LIFT COEFFICIENT SLOPE CGAM PER RADIAN, CAMBER LIFT COEFFICIENT CCF,
C     MOMENT DISTANCES XPH,XCH,XDH,XAH,XBH AS FRACTIONS OF CHORD,
C     REFERENCE MAGNITUDE OF THE WEIGHT IN VACUUM WAR IN LB/FT,
C     REFERENCE MAGNITUDE OF THE BUOYANCY BCYR IN LB/FT
C     XPH,XCH,XAH,XBH ARE CHORDWISE DISTANCES/CHORD MEASURED FROM THE
C     CENTER OF TENSION OF, RESPECTIVELY, ANGLE OF ATTACK LIFT,
C     CAMBER LIFT, WEIGHT IN VACUUM, AND BUOYANCY
C     XPH,XCH,XAH,XBH ARE POSITIVE AFT OF THE CENTER OF TENSION
C     XDH IS THE DISTANCE/CHORD OF THE DRAG FORCE MEASURED NORMAL TO THE
C     CHORD LINE THROUGH THE CENTER OF TENSION
C     XDH SHOULD BE SET EQUAL TO A POSITIVE NUMBER, THE PROGRAM ADJUSTS
C     THE SIGN OF XDH ACCORDING TO THE SIGN OF CCF (SEE STATEMENT 10)
C     SO THAT THE DRAG ACTS ON THE SUCTION SIDE OF THE FAIRING,
C     WHERE THE FLUID VELOCITIES AND HENCE THE FRICTIONAL DRAG ARE HIGHER
C     CAMBER LIFT COEFFICIENT CCF MAY BE PRESCRIBED AS A FUNCTION OF
C     CABLE SCOPE SR
C     IF THE CABLE SYSTEM CONSISTS OF CABLE SEGMENTS WITH SOME OR ALL OF
C     THE ABOVE FAIRING PARAMETERS VARYING WITH SEGMENT NUMBER JE, THIS
C     SHOULD BE ACCOUNTED FOR BY DIMENSIONING THE NECESSARY PARAMETERS,
C     OR BY USING IF STATEMENTS WHICH CHANGE THE PARAMETERS FOR DIFFERENT
C     VALUES OF JE
      CHR=0.20$CGAM=6.28$CCF=0.003$XPH=0.15$XCH=0.40$XDH=0.
      XAH=0.25$XBH=0.35$WAR=0.56$BCYR=0.28
      CH=CHR*PCE
      XP=XPH*CH$XC=XCH*CH$XD=XDH*CH$XA=XAH*CH$XB=XBH*CH
      WA=WAR/OPE$BCY=BCYR/OPE$DNORM=DN/OPE
      PSI=ATAN2(-QCABZ,QCABX)
      FC1=0.5*RHO*CNORM**2*CH
      FPM=-FC1*CGAM*XP
      CMBM=-FC1*CCF*XC
   10 DNMN=-DNORM*XD*(CCF/ABS(CCF))
      DNMD=-DNORM*XP
      WBF=XA*WA-XB*BCY
      FCN=SIN(PSI)*SIN(PHIV)-SIN(THETA)*COS(PSI)*COS(PHIV)
      FCD=COS(PSI)*SIN(PHIV)+SIN(THETA)*SIN(PSI)*COS(PHIV)
      GAMN=CMBM+DNMN+WBF*FCN
      GAMD=FPM+DNMD-WBF*FCD
      GAMA=GAMN/GAMD
      CL=(CGAM*GAMA-CCF)
      RCHA=0.5*RHO*CL*CHR
      GAMAD=GAMA*57.29578
      RETURN
      END
```

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