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CALCULATION OF STATIC AND DYNAMIC CONFIGURATIONS OF A SINGLE POINT MOORING CABLE

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OF A SINGLE POINT MOORING CABLE

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Cable Equations

The program calculates the configuration of the cable system in the presence of a steady state current alone, in the absence of time dependent excitations.

The differential equations for the steady-state configuration are well known and take the following form for the co-ordinate system as in figure 1, e.g. Berteaux:

\[-T \frac{d\phi}{ds_0} + I + \sin \phi \ w = 0 \quad A\]

\[\frac{dT}{ds_0} + G + \cos \phi \ w = 0 \quad B\]

\[\frac{ds}{ds_0} = 1 + \varepsilon \quad C\]

\[\frac{dx}{ds_0} = -(1 + \varepsilon) \sin \phi \quad D\]

\[\frac{dy}{ds_0} = (1 + \varepsilon) \cos \phi \quad E\]
where \( T \) = cable tension
\( \phi \) = angle of the cable segment from the vertical
\( s_0 \) = reference cable length \((T = T_0)\), measured from initial point
\( T_0 \) = reference tension
\( I, G \) = normal and tangential drag forces, per unit length, acting on the cable, respectively.
\( w \) = weight of the cable per unit length in the fluid.
\( s \) = stretched cable length measured from initial point
\( \varepsilon \) = cable strain, \( \varepsilon = 0, T = T_0 \)
\( x \) = horizontal displacement, +ve to the right
\( y \) = vertical displacement, +ve to downward

For smooth, approximately round cable, the normal and tangential drag may be taken as respectively proportional to the squares of the velocities normal and tangential to the cable.

Thus
\[
I = \frac{1}{2} \rho C_D d C_n |C_n|^2
\]
\[
G = \frac{1}{2} \rho C_T d C_t |C_t|^2
\]

where \( \rho \) is the fluid density
\( C_D, C_T \) normal and tangential drag coefficients
\( d \) cable diameter
\( C_n \) component of the current normal to the cable, \( C \cos \phi \)
\( C_t \) component of the current tangential to the cable, \( C \sin \phi \)
\( C \) magnitude of the current, acting in the x-direction only.

The tension strain function is assumed to be of the form
\[
T = T_0 + C_1 \varepsilon^2
\]

where \( C_1 \) constant of elasticity, \( C_1 = AE \) for linear elastic cable
\( A \) cross sectional area \( \pi d^2/4 \) for round cable
\( E \) modulus of elasticity
$C_2$, an exponent, $C_2 = 1$ for linear elastic model.

Thus equation 3 enables a non-linear tension strain relation to be modeled by only two input variables $C_1$ and $C_2$. It is often convenient to express $\epsilon$ as a function of $(T-T_0)$ in order to eliminate it from the cable equations (A-E)

Thus

$$\epsilon = \left(\frac{T-T_0}{C_1}\right)^{1/C_2}$$

**Intermediate Bodies**

In the integration of the conditions at the top of the cable, it is assumed that these are known; the integration of the cable equations proceeds down the cable. To allow for discontinuities in the cable, the integration procedure must be interrupted, and the unknown cable variables $T_u, \phi_u$ below the body must be related to the known variables $T_k, \phi_k$ above the body. For two dimensional cases the equations become

$$T_u = \sqrt{\left((\sin\phi_k)T_k + D_x\right)^2 + \left(-T_k \cos\phi_k + W_B\right)^2}$$

$$\phi_u = \tan^{-1}\left\{\frac{\sin\phi_k T_k + D_x}{\cos\phi_k T_k + W_B}\right\}$$

where $D_x$ = the drag on the body
$W_B$ = the weight of the body in the fluid

$$D_x = \frac{1}{2} p C_D A_x |c|$$

$C_D A_x$ is the drag area of the body for the flow in the $x$-direction.

**Boundary Conditions**

The integration of the differential equations is most convenient when the tension $T$ and the angle $\phi$ are known at one
end of the cable. These will be known for certain cases of single-point moored cables and towing cables. For the moored cases, the program starts with the known condition at the top of the cable and integrates the five differential equations until the lower end of the cable is reached. This is the simplest case for the program, since the numbering of the cable segments starts at the top. For towing cables, where the conditions are known at the lower towed end, the program integrates the equation twice. They are first integrated from the towed body to the upper point, thus fixing the conditions at this point. Then in order to conform to the numbering system which is used for the dynamic calculation, the equations are integrated once again from the upper point down to the lower towed body.

In many applications, the values of \( T \) and \( \theta \) are not known \( \text{a priori} \) any point along the cable. It is necessary to treat these cases as boundary value problems and use iteration techniques to obtain the solution.

The program contains two iteration schemes of particular interest to sonobuoy systems.

A. A cable of given length moored in a given ocean depth.
B. A free floating cable system.

For a long wave, according to linear theory, the wave particles prescribe the following motion

\[
\begin{align*}
x_w &= a e^{-ky} \cos (kx - \omega t + \theta) \\
y_w &= -a e^{-ky} \sin (kx - \omega t + \theta)
\end{align*}
\]

where \( x_w, y_w \) are the water particle displacement, 
\( a \) is the wave amplitude, 
\( k \) is the wave number \( = 2\pi/\lambda \), 
\( \lambda \) is the wavelength, 
\( \omega \) is the radian frequency \( = 2\pi f = \sqrt{2\pi g/\lambda} \) for long waves.
\[ f \] is the wave frequency
\[ t \] is time
\[ g \] is gravity constant
\[ \theta \] is the wave phase angle

For an irregular sea consisting of \( N \) distinct components, the resultant water particle displacement are obtained as

\[ x_W = \sum_{i=1}^{N} a_i e^{-k_i y} \cos (k_i x - \omega_i t + \theta_i) \]  \hspace{1cm} 9a

\[ y_W = -\sum_{i=1}^{N} a_i e^{-k_i y} \sin (k_i y - \omega_i t + \theta_i) \]  \hspace{1cm} 9b

The program allows the user to specify the irregular seaway in one of two ways.

1. By specifying \( N, k_i, \theta_i, a_i \) for 9a and 9b

2. By using a known energy spectrum \( S(\omega) \)

The latter defines the wave amplitudes as

\[ a_i = \sqrt{S(\omega_i) \Delta \omega} \]  \hspace{1cm} 10

where \( \omega_i = \omega_{i-1} + \Delta \omega \)
\[ \Delta \omega = (\omega_u - \omega_L)/N \]
\( \omega_u \) is the upper limit of \( \omega \)'s
\( \omega_L \) is the lower limit of \( \omega \)'s

The program uses \( S(\omega) = \frac{A}{\omega^5} e^{-B/\omega^4} \)  \hspace{1cm} 11

where \( A = 0.0081 \text{ } \text{g}^2 \), \( B = 33.56 \text{ } h_3^2 \), where \( h_3 \) is the significant wave height in feet. The values of \( \theta_i \) are evenly spaced from \( \theta_1 \) to \( 360 + \theta_1 \) degrees.
Prescribed Surface Motions

The program allows the user to prescribe the motion at the surface or to describe it by means of differential equations of motion for a surface buoy.

If the surface buoy or ship is sufficiently large that its motions are not appreciably affected by the presence of the cable, these motions may be calculated separately and used as input for the present program.

The program considers the prescribed motion of the upper end of the cable as composed of a series of sinusoidal components in the horizontal and vertical direction

\[ x_s = \sum_{i=1}^{m} a_{xi} \cos (-\omega_i t + \phi_i) \]  
\[ y_s = \sum_{i=1}^{m} -a_{yi} \sin (-\omega_i t + \phi_i) \]

where \( x_s, y_s \) are the horizontal and vertical components of the surface motion

\( a_{xi}, a_{yi} \) are the amplitudes of the \( i^{th} \) component of \( x_s, y_s \)

\( \omega_i, \phi_i \) are the frequency and phase angle of the \( i^{th} \) component.

It is equally as easy to prescribe any analytic function of time in the program.

Dynamic Cable Equations

When the mooring cable is connected to a surface buoy the added mass coefficients of the surface buoy are in general functions of frequency. In the time domain, which is obviously where the solution should be, this requires the solution of integrodifferential equations, which usually contain convolution integrals. If the frequency dependent coefficients are expressed as simple polynomials of the frequency, then the integrodifferential equations may be replaced by a set of higher order differential equations. In either case the
solutions are costly. Thus usually the surface buoy motions have been solved in the frequency domain, then to give the response in the sea spectrum the principle of linear superposition is used. The one big failure of this method is that it fails to predict the large dynamic snap loads which occur when the load goes slack.

As the prediction of dynamic loads is of paramount importance, the frequency domain method was not used. To give some credence to the time domain approach, only spar buoys and small surface buoys are allowed, because their added mass and damping values are essentially those of infinite fluid.

There are two main methods of solution of this problem in the time domain, (1) by the method of characteristics; (2) by the finite element method. The main drawback of the method of characteristics is that it requires unusually long computation times.

The finite element method seeks to represent the actual cable system by a series of segments and nodes. The set of partial differential equations is then reduced to a set of ordinary differential equations of motion of the nodes.

The method has much flexibility allowing the user to choose the number and location of nodes. Only straight element nodes are used.

Formulation of Equations of Motion

The two unknowns are the inclination and stretch of the cable element, with all the forces defined in terms of the tangential and normal directions. The major problem is the presence of intermediate bodies along the cable, for which the inertia and drag are most conveniently expressed in the spatial x and y directions.

The cable is divided into a number of massless straight elastic segments. The inertia, weight, and drag forces acting
on each cable segment are equally divided between the two nodes at the ends of the segment.

The two second order differential equations of motion of the node $i$, in the x-y coordinate system are:

\[ J_x \ddot{x} + K_i y = F_x = T_x + D_{Nx} + D_{tx} + D_{Bx} \]
\[ K_i \ddot{x} + J_y \ddot{y} = F_y = T_y + D_{Ny} + D_{ty} + D_{By} + W_c + W_B \]

for all cable elements $i = 1, \ldots, M$

where

$J_x$, $J_y$, $K_i$ are the inertia coefficients defined below

$x$, $y$ subscripts denoting x, y direction

$F$ sum of all forces acting at the node

$T$ tension of the cable due to stretch and internal damping

$D_n$ normal drag force acting on the cable

$D_t$ tangential drag force acting on the cable

$W_c$ weight of cable in the fluid

$W_B$ weight of the intermediate body in the fluid

$M$ total number of nodes

Decoupling the above two equations to give

\[ \ddot{x} = \frac{(J_y F_x - K F_y)}{(J_x J_y - K^2)} \]
\[ \ddot{y} = \frac{(J_x F_y - K F_x)}{(J_x J_y - K^2)} \]
Definition of Cable Forces

Each cable element is taken to be a long thin cylinder for which fluid inertia is added only for acceleration normal to the segment.

\[
P = \left( \frac{u_a}{a} l_{oa} + \frac{u_b}{b} l_{ob} + \frac{\alpha \rho A_a l_{oa}}{2} \cos^2 \phi_a + \frac{\alpha \rho A_b l_{ob}}{2} \cos^2 \phi_b \right) x + \left( \frac{\alpha \rho A_a l_{oa}}{2} \sin \phi_a \cos \phi_a - \frac{\alpha \rho A_b l_{ob}}{2} \sin \phi_b \cos \phi_b \right) y \]

\[
+ \left( \frac{\alpha \rho A_a l_{oa}}{2} \sin \phi_a \cos \phi_a + \frac{\alpha \rho A_b l_{ob}}{2} \sin \phi_b \cos \phi_b \right) \dot{x}
\]

\[
+ \left( \frac{\mu_a l_{oa} + u_b l_{ob}}{2} + \frac{\alpha \rho A_a l_{oa}}{2} \sin^2 \phi_a + \frac{\alpha \rho A_b l_{ob}}{2} \sin^2 \phi_b \right) \dot{y}
\]

\[
+ \left( \frac{M_{BX}}{2} l_{oa} + \frac{M_{BY}}{2} l_{ob} + \frac{\alpha \rho A_a l_{oa} \sin \phi_a \cos \phi_a}{2} + \frac{\alpha \rho A_b l_{ob} \sin \phi_b \cos \phi_b}{2} \right) \ddot{y}
\]

\[
= \left[ J_x \ddot{x} + K_x \dot{x} \right] + \left[ J_y \ddot{y} + K_y \dot{y} \right]
\]

where the subscripts \(a\), \(b\) denote the cable segments above and below the node. \(M_{BX}, M_{BY}\) are the virtual mass of the intermediate body in the \(x, y\) directions.

The tension forces for an extensible cable segment, depends upon the strain \(\varepsilon\), and the strain rate \(\dot{\varepsilon}\).

\[
\varepsilon = \frac{\Delta k}{k_0} = \frac{k - 1}{k_0} = \frac{(x_k - x_u)^2 + (y_k - y_u)^2}{k_0} - 1
\]

\[
\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{\left( \frac{x_k}{k_0} - \frac{x_u}{k_0} \right) \left( \frac{\dot{x}_k}{k_0} - \frac{\dot{x}_u}{k_0} \right) + \left( \frac{y_k}{k_0} - \frac{y_u}{k_0} \right) \left( \frac{\dot{y}_k}{k_0} - \frac{\dot{y}_u}{k_0} \right)}{k \frac{1}{k_0}}
\]
where \( l \) is the stretched length of the cable segment, and the subscripts \( l, t, u \) refer to the lower and upper ends of the cable segment.

The general relationship for tension that is used is

\[
T = T_0 + C_l \varepsilon + C_I \dot{\varepsilon}
\]

where \( C_I \) is the internal damping coefficient.

Since the cable segments above and below act on the node, then

\[
T_x = T_a \sin\phi_a - T_b \sin\phi_b
\]
\[
T_y = T_a \cos\phi_a + T_b \cos\phi_b
\]

The drag forces on the cables are proportional to the relative velocities normal, and tangential to the cable.

\[
V_{xn} = (C + \dot{x}_w - \dot{x}) \cos\phi + (\dot{y}_w - \dot{y}) \sin\phi
\]
\[
V_{xt} = -(C + \dot{x}_w - \dot{x}) \sin\phi + (\dot{y}_w - \dot{y}) \cos\phi
\]

If one half of the drag forces acting on the cable segments above and below the node are summed, then

\[
D_{nx} = \frac{1}{2} D_{na} \cos\phi_a + \frac{1}{2} D_{nb} \cos\phi_b
\]
\[
D_{ny} = \frac{1}{2} D_{na} \sin\phi_a + \frac{1}{2} D_{nb} \sin\phi_b
\]
\[
D_{tx} = -\frac{1}{2} D_{ta} \sin\phi_a - \frac{1}{2} D_{tb} \sin\phi_b
\]
\[
D_{ty} = \frac{1}{2} D_{ta} \cos\phi_a + \frac{1}{2} D_{tb} \cos\phi_b
\]
with

\[ D_n = \frac{1}{2} C_D d R_0 V_{rn} |V_{rn}| \]

\[ D_t = \frac{1}{2} C_T d R_0 V_{rt} |V_{rt}| \]

\[ V_{rn} = \dot{x}_r \cos\phi + \dot{y}_r \sin\phi \]

\[ V_{rt} = -\dot{x}_r \sin\phi + \dot{y}_r \cos\phi \]

where the subscript a, or b can be applied to the above four equations.

INPUT.

Card 1 N CASES   FORMAT (I3)
   This allows different number of current profiles
to be input N CASES \geq 1

Card 2 TITLE   FORMAT (20A4)
   Title of the job. This has to appear on one card.

Card 3 NSM, NSW, NCAB; NCUR, ITER, MTRC. FORMAT (6I3)
   NSM number of surface motion components \leq 20
   NSW number of surface wave components \leq 20
   NCAB number of cable segments 2 \leq NCAB \leq 50
   NCUR number of current profiles 2 \leq NCUR \leq 10
   MTRC \geq 1 metric units, \leq 0 Imperial units
   ITER iteration index.
   ITER = 0, no iteration (prescribed initial steady state card)
   1, free floating cable system
   2, moored cable with given length in given depths

Card 4 FSM(K), K = 1, NSM   FORMAT (8F10.4)
   Frequencies of surface motion in Hz.
   N.B. is 2000 > FSM(1) \geq 1000, the program takes the prescribed
   surface motion components equal to the surface wave components
   by setting FSM(K) = FRSW(K), AXSM(K) = AYSM(K) = ASW(K), FIDSM(K)
   = FIDSW(K), for K = 1, to NSM, and automatically NSM = NSW.
if \( 3000 \geq FSM \geq 2000 \), the program accepts input data for a spar buoy and considers \( AXSM(K) \) to be the cross-sectional area of the buoy at depth \( AYSM(K) \) below the surface. \( AYSM(1) = 0 \), and \( AYSM(NSM) = \) total draught under the combined action of the buoy weight in air and the vertical component of the steady state tension. NSM should be odd.

if \( FSM \geq 3000 \), the program accepts input data for a spheroidal buoy and considers \( AXSM(1) \) to be the radius of the buoy cross-section at the free surface, \( AXSM(1) \) to be the draught. The rest of the input values \( AXSM(K) \), \( AYSM(K) \), \( FIDS(M) \), \( K = 2, \ldots \) can take any value, e.g. 0

Card 5  \( AXSM(K), K = 1, NSM \)  FORMAT (8F10.4)
These are the amplitude of the horizontal surface motion.

Card 6  \( AYSM(K), K = 1, NSM \)  FORMAT (8F10.4)
These are the amplitudes of the vertical surface motion.

Card 7  \( FIDS(M), K = 1 \)  NSM  FORMAT (8F10.4)
These are the phase angles of the surface motion components.

Card 8  \( ASW(K), K = 1 \)  NSW  FORMAT (8F10.4)
These are the amplitude of the surface wave components

if \( ASW(1) > 1000 \), the program computes the amplitude of the NSW surface wave components by using the Pierson Moskowitz sea spectrum. The program considers the significant wave height to be \( (ASW(1) - 1000) \), and \( FRSW(1) \), and \( FRWS(2) \) to be the upper and lower frequencies of the sea spectrum in Hz. The program internally generates the phases of the wave components by considering them to be uniformly separated by 360/NSW degrees. The phase of the lowest frequency is \( FIDSW(1) \).
Card 9  FRSW(K), K = 1, NSW  FORMAT (8F10.4)
The frequency components in Hz of the surface waves.

Card 10  FIDSW(K), K = 1, NSW  FORMAT (8F10.4)
The phase of the surface wave components.

Card 11  RHO, SUBM, TWX, TIY, CDASX, AMC, APAC, TMIN  FORMAT (8F10.4)
RHO fluid density in slug / ft$^3$ (Kg / m$^3$)
SUBM submergence of top point of cable below free surface
TWX horizontal force acting at top of cable
TIY vertical component of tension at top of cable
CDASX drag area of surface buoy perpendicular to the x-axis
AMC added mass coefficient of cable, 1.0 for round cable
APAC cross-section area of cable = APAC *πd$^2$/4, APAC = 1 for round
TMIN minimum algebraic tension which can be supported

N.B. For the case of the surface buoy, the program calculates the drag acting on the surface buoy due to the ocean current by taking the value of the current at SUBM units below the surface.

The total horizontal at the top point of the cable
TIX = TWX + \frac{1}{2} C * CDASX * CCFC(SUBM)* ABS(CCF(SUBM))

In the cases where there is no surface buoy (i.e. prescribed motion), TWX and / or CDASX may be set equal to zero. For surface buoys, TWX represents the wind loading.

Card 12  TINVI, DTI, TOTT, DT2, DIR, TBH, TBMYX  FORMAT (8F10.4)
TINVI initial time interval in seconds for dynamic calculations
DTI time step in seconds for which print out is required 0 < t < TINVI
TOTT total time interval for which dynamic calcs are required
DT2 time step in seconds for printout TINVI < t < TOTT
DIR, DIR < 0 if the initial conditions are special at the bottom (e.g. towed cable), otherwise DIR > 0.
TBH applied force on lower weight body NCAB-1, in x direction
TBMYX maximum absolute value of tension in cable just below buoy
for buoy-cable system set TBMYX = to say 99999.
Card 13  FLC(K), K = 1, NCAB  FORMAT (8F10.2)
length of Kth cable segment

Card 14  DXI(K), K = 1, NCAB  FORMAT (8F10.4)
Diameter of Kth cable segment in inches (cms)

Card 15  CDN(K), K = 1, NCAB  FORMAT (8F10.4)
Normal drag coefficient of Kth cable segment

Card 16  CDT(K), K = 1, NCAB  FORMAT (8F10.4)
Tangential drag coefficient of Kth cable segment

Card 17  WC(K), K = 1, NCAB  FORMAT (8F10.4)
Weight in fluid of the Kth cable segment at the reference cable tension

Card 18  CM(K), K = 1, NCAB  FORMAT (8F10.6)
Mass of Kth cable segment at the reference cable tension

Card 19  TREF(K), K = 1 NCAB  FORMAT (8F10.2)
Reference cable tensions of the Kth cable segment

Card 20  C1(K), K = 1, NCAB  FORMAT (8F10.0)
The reference coefficient as in
Tension = TREF(K) + C1(K)\epsilon^C2(K) + CINT(K)\epsilon^C2
for linear elasticity C1 = AE, C2 = 1.

Card 21  C2(K), K = 1, NCAB  FORMAT (8F10.4)
Exponents of non-linear elasticity for Kth segment

Card 22  CINT(K), K = 1, NCAB  FORMAT (8F10.4)
Internal damping values for rate of elasticity.

Card 23  WBD(K), K = 1, NCAB  FORMAT (8F10.4)
Weight in fluid of the Kth body

Card 24  CDABX(K), K = 1, NCAB  FORMAT (8F10.4)
Drag area of Kth body for flow in x-direction.
Card 25  CDABY(K), K = 1, NCAB  FORMAT (8F10.4)
          Drag area of \( k^{th} \) body for flow in \( y \)-direction.

Card 26  XMVB(K), K = 1, NCAB  FORMAT (8F10.4)
          Virtual mass mass (mass + added mass) of \( k^{th} \) body in \( x \)-direction.

Card 27  YMVB(K), K = 1, NCAB  FORMAT (8F10.4)
          Virtual mass of \( k^{th} \) body in \( y \)-direction.

Card 28  YY(K), K = 1, NCUR  FORMAT (8F10.2)
          Value of \( y \) in feet of a current profile.

Card 29  PHID(K), K = 1, NCAB  FORMAT (8F10.4)
          Initial value of \( \phi \) of \( k^{th} \) cable element in degrees.

Card 30  TENI(K), K = 1, NCAB  FORMAT (8F10.2)
          Initial tension of \( k^{th} \) segment.

Card 31  XPI(K), K = 1, NCAB  FORMAT (8F10.2)
          Initial value of \( \dot{x} \) of \( k^{th} \) node.

Card 32  YPI(K), K = 1, NCAB  FORMAT (8F10.4)
          Initial value of \( \dot{y} \) of \( k^{th} \) node.

Card 33  CCK(I), K = 1, NCUR  FORMAT (8F10.4)
          These are the velocities of the current in knots (m/s) at the points on card 28.

          The card 33 is repeated for as many current profiles as card 1 says.

          If the surface float is a buoy then two extra cards are needed.

Card 34  CDASY, WAS, RWY, RTX, RTY, YCG, BIN
CDASY  Drag area in the \( y \)-direction
WAS  Weight in air
RWY  Vertical distance of wind loading centre of pressure from buoy centre of gravity YCG
RTX, RTY \((x, y)\) distance of cable attachment point from YCG.

YCG The distance of centre of gravity below the free surface under the action of its own weight in air WAS, and the vertical component of the steady state tension - TIY.

BIN Moment of inertia in air about YCG

XSI, ZETI, SYDI, Initial values of \((x, \zeta, \psi)\) where \(\zeta\) is the vertical displacement of the centre of gravity from the equilibrium value YCG.

XPSI, ZTFI, SYPDI Initial values of \((\dot{x}, \zeta, \dot{\psi})\)

Sample problems and their solutions follow.

All units in the program are in ft (metres) and slugs (kgm) except where stated explicitly.
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PROBLEM 10: C1=24000; C2 =1
References


