Naval Coastal Systems Center

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USER'S MANUAL FOR DYNTOCABS

A FINITE SEGMENT COMPUTER CODE

TO SIMULATE THE DYNAMICS

OF TOWED CABLE SYSTEMS

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13. ABSTRACT (Maximum 200 words)

This report presnets a User's Manual for the computer program DYNTOCABS (DYNamics of TOwed CABle Systems). The program is designed to predict steady-state configurations, and linear and nonlinear dynamic motions of submerged and partially submerged towed systems. These systems may consist of a single towing cable or a branched system of cables, but no closed loops may be formed. Each branch may be terminated with a towed sphere or a towed vehicle.

This manual provides instsruction for using DYNTOCABS to study such cable systems. It also provides sample input and output data.

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CONTENTS

CONTENTS (continued)

CONTENTS (continued)

ILLUSTRATIONS

INTRODUCTION

This is a User's Manual for the computer program DYNTOCABS (*DYN*amic analysis of *TO*wed *CAB*le *S*ystems). The program is designed for analysis of the three-dimensional steady-state configurations and linear and nonlinear dynamics of submerged and partially submerged towed systems. The system may consist of a single towing cable or a branched system of cables. Each cable branch is usually terminated with a towed sphere or towed vehicle, but this is not a requirement. Figure 1 shows an illustration of a typical towed system. The system can, of course, be much simpler than that shown in Figure 1. For example, it could consist of a single cable segment such as a buoy- or balloon-mooring as depicted in Figure 2.

This manual provides instruction for using DYNTOCABS to study these cable systems. It also provides sample input and output data. The language of DYNTOCABS is FORTRAN; all input data are accepted in free-format.

CAPABILITIES OF DYNTOCABS

DYNTOCABS is designed to perform three basic types of analysis: 1) a steady-state analysis, 2) a linear dynamic time-domain analysis, and 3) a nonlinear dynamic time-domain analysis. Options are also available that allow execution to begin with a steady-state analysis and continue with either of the dynamic analyses. For a steady-state analysis, the program requires the following: (1) the physical data of the towing cables (weight, buoyancy, diameter, length, etc.) and towed vehicles (weight, length, volume, inertia properties, mass-center location, etc.); (2) the connectivity of the system's branches; (3) the fluid properties; and (4) the motion of the towed end of the cable (steady forward motion or circular turn). DYNTOCABS then calculates the steady-state configuration of the towed system. In addition to items (1)-(3) above, a dynamic analysis requires the motion of the towed end of the cable (steady or unsteady) and the initial configuration of the system. It then computes the kinematics (position, velocity, and acceleration) of the towed system and the cable forces at a set of discrete times over some prescribed time interval.

DYNTOCABS provides the user with the following options:

1. Steady-state and linear and nonlinear time domain analyses may be chosen.

2. Towed vehicles may be included with or without closed-loop control laws or open-loop inputs.

3. Long nonlinear dynamic analysis runs may be restarted from the finishing time of an earlier execution.

4. Either US Customary or metric units may be used.

5. Fluid forces may be applied to the cable system. These forces include:

      a. Normal drag forces
      b. Tangential drag forces
      c. Side (or lift) forces
      d. Buoyancy forces

These forces may be partially or totally neglected by the user.

1

6. Cable drag forces may be calculated using velocity dependent normal and tangential drag coefficients or by using empirically-determined loading functions.

7. Gravitational forces may be included or neglected.

8. Point loads may be located along the cable.

9. The towed system may be immersed in two fluid media - normally air and water.

10. The fluid media may be given a uniform "stream" velocity.

11. The tow point of the towed system may have arbitrary motion relative to the ship. The ship itself may have arbitrary horizontal plane motion.

In addition to the above options, the user may select numerical integration parameters and certain output options.

THEORETICAL BASIS OF DYNTOCABS

The cables in the towed system are modelled by a series of cylindrical links connected in a chain with frictionless spherical joints to simulate a flexible cable. Figure 3 depicts such a model. The masses and fluid and gravitational loads are assumed to be uniformly distributed over each link. These masses and loads are then halved and lumped at the connecting joints. Hence, the links are two-force members, carrying forces only along their length. The spherical towed bodies are assumed to be concentrated masses coincident with the lumped mass of the connecting cable link. The more general towed vehicles are three-dimensional bodies with mass and inertia. They are connected to their adjacent cable links by frictionless spherical joints at some reference point of the vehicle that need not be located at its mass center.

The model of Figure 3 is a lumped-mass, finite-segment model of the cable. References 1 through 3 provide the specific technical details required to formulate the equations of motion of these types of systems. This methodology has shown to yield results quite similar to those provided by the methodology presented in reference 4, but with a substantial increase in execution speed.

The fluid forces on the system are computed using procedures similar to those outlined in references 3 through 12. These include normal and tangential drag forces and side forces for cable links, general hydrodynamic forces for towed vehicles (drag and added mass, based on a set of hydrodynamic coefficients), and buoyancy forces. As previously stated, the cable loads are represented by forces at the connecting joints of the system; the vehicle loads are represented by forces passing through the mass centers of the vehicles together with couples.

Finally, the governing equations are solved using either a fixed-step predictor-corrector or a fourth-order fixed-step Runge-Kutta numerical integration algorithm. DYNTOCABS is written, however, so that other numerical integrators may be implemented.

2

DEFINITIONS OF TERMS

The terminology used in DYNTOCABS is defined in this section. These definitions are useful in understanding the input requirements. Bold print is used to further identify terms of interest.

1. TOWED SYSTEM MODEL

Figure 4 shows a finite-segment **towed system model**. It consists of cable links, towed vehicles, and towed spheres connected in a tree-like fashion such that no closed loops are formed.

2. CABLE LINK

A **cable link** is an individual member of a **towed system model** (aside from towed vehicles and spheres). A cable link is rigid and is connected to adjacent links and the towed vehicles by frictionless spherical joints.

3. REFERENCE LINK AND REFERENCE POINTS

The uppermost link of the towed system model is called the **system reference link** as shown in Figure 5. The lower end of the system reference link is called the **system reference point** Q. In a typical dynamic configuration of the system, Q is given a prescribed motion relative to the **mean ship frame** (see (7) below).

Also, each of the links and the towed vehicles of the towed system model has its own reference point. For the system reference link, it is Q the system reference point. For any other link L, it is QK the joint location at the lower end of the link. For any towed vehicle V, it is QV the joint location at the cable attach point. See Figure 5.

4. TOWED VEHICLES

DYNTOCABS has the provisions for handling many typical towed bodies at the ends of the branches of the cable system. DYNTOCABS refers to these as **towed vehicles**. These vehicles are connected to their adjacent cable links by a frictionless spherical joint at the reference point of the body. Neither this reference point, the center of buoyancy, nor the hydrodynamic center of the vehicle need be located at its mass center. These vehicles may only be located at the ends of the cable branches.

5. TOWED SPHERES

A **towed sphere** may be located at any of the connecting joints of the towed system model. Each sphere is considered to be a point source of mass and fluid force; the fluid force is determined from the diameter of the sphere.

6.   BODY CONNECTION ARRAY

Cable links, towed vehicles, and towed spheres are all referred to as **bodies** of the towed system model. Corresponding to each body in the system is a unique lower link. This link is defined as the link next in line on the shortest path from that body (along the system's links) to the system reference point. (As this statement suggests, towed spheres are never considered to be lower bodies, even when they are located at intermediate joints within the system.) Corresponding to each link in the model there may also be upper bodies. These upper bodies are defined by moving outward along the model's bodies from the system's reference point to the ends of its branches. The upper bodies of each link are those next in line on these "outward" paths. A link has multiple upper bodies when it precedes a branch point or sphere on these paths and has no upper bodies when it is located at the end of a branch.

The configuration of the towed system model and the arrangement of its branches can be described by a **body connection array**. To develop this array, let the bodies of the system be numbered as follows: First, let the **system reference link** be called link 1. Next, number the remaining links, towed spheres, and towed vehicles in ascending progression away from link 1 through the branches of the system; let the **mean ship frame** be body 0. Figure 6 illustrates this numbering procedure for the cable system of Figures 4 and 5.

Using this numbering scheme, each body is associated with a lower link having a lower body number; this link is called the **lower numbered link**. The array listing the lower numbered links is called the body connection array. For the system shown in Figure 6, this array is:

Link/Sphere/ Towed Vehicle:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Body Connection Array:	0	1	2	3	4	5	2	7	8	9	10	11	9	13

Note that the connectivity of the system can be constructed once the body connection array is known. That is, there is an equivalence between the towed system model connectivity and the body connection array.

7.   MEAN SHIP FRAME, INERTIAL FRAME, AND COORDINATE SYSTEMS

In DYNTOCABS, the **system reference point** Q at the lower end of the system reference link may be given arbitrary prescribed motion relative to the **mean ship frame**, which itself may be given a prescribed motion relative to an **inertial reference frame**. This is depicted in Figure 7. The mean ship frame is assumed to be rigidly attached to a towing vessel, such as a ship or a helicopter.

Coordinate systems are associated with both the mean ship frame and the inertial frame. In the mean ship frame, the X_s direction is forward, the Y_s direction is starboard, and the Z_s direction is downward. The mean ship frame is assumed to move in a horizontal plane relative to the inertial frame; its position (relative to the inertial frame) is given by the X and Y coordinates of its origin and its orientation is given by a single turning angle ψ measured as positive when the ship is in a starboard turn. The system reference point Q may have arbitrary motion relative to the mean ship frame.

Finally, DYNTOCABS has the option of locating the fluid interface (or water level) at any distance h below (or above, if h is negative) the mean ship frame.

8. ACCELERATION PROFILES

In a nonlinear time-domain analysis, the specification of the motion of the system reference point Q relative to the mean ship frame and the motion of the mean ship frame relative to the inertial frame (Figure 7) may be accomplished either by using an **acceleration profile**, described here, or by using a **precoded function**, described below.

An acceleration profile is simply a set of data points representing the coordinates of selected points of an acceleration-time curve. Such coordinates may be obtained from the graph of the acceleration function.

DYNTOCABS has the capability of accepting as many as 25 data points from such an acceleration curve. A piecewise linear approximation is then made of the acceleration function. For example, consider the acceleration function approximation shown in Figure 8. The acceleration, velocity, and displacement during the i^{Th} time interval are then:

$$a = a_i + \left(\frac{a_{i+1} - a_i}{t_{i+1} - t_i} \right)(t - t_i)$$

$$v = v_i + a_i(t - t_i) + \frac{1}{2}\left(\frac{a_{i+1} - a_i}{t_{i+1} - t_i} \right)(t - t_i)^2$$

$$d = d_i + v_i(t - t_i) + \frac{1}{2}a_i(t - t_i)^2 + \frac{1}{6}\left(\frac{a_{i+1} - a_i}{t_{i+1} - t_i} \right)(t - t_i)^3$$

where a_i, v_i, d_i, and t_i are the acceleration, velocity, displacement, and time at the beginning of the i^{Th} interval. Thus, the entire kinematic profile (displacement, velocity, and acceleration) is known when the a_i are given, and when v_1 and d_1, the initial velocity and displacement (at time t_1), are given.

9. PRECODED FUNCTIONS

Depending on the analysis being performed, DYNTOCABS requires the user to specify motions of the system as a function of time. If they take on a relatively simple form, it may be convenient to describe the motion using a **precoded function**. DYNTOCABS provides the user with two different precoded functions for this purpose. The first may be used to describe the displacement of the system reference point Q relative to the mean ship frame (See (7) above); it has the following form:

$$f = f_0 + Ae^{bt} \cos(pt + \phi) \tanh(mt)$$

where f_0, A, b, p, ϕ, and m are user supplied constants. Note, for example, that this function can be used to provide a constant value and decaying, sinusoidal values. The second form of the precoded function is used to describe the motion of the mean ship frame (See (7) above) and commanded variable inputs in the closed-loop control law (See (20) below); it has the form:

$$f = f_0 + Ae^{bt} \cos(pt + \phi)$$

5

This function is similar to that function described above, except that it does **not** employ the hyperbolic tangent function.

10.   FLUID VELOCITIES

DYNTOCABS also has the provision of allowing each of the fluids to have a uniform (constant in time and space) stream velocity. The default condition is zero velocity for both fluids; the default fluids are air and water.

11.   LINK ORIENTATION ANGLES

The orientation of cable link is described relative to the mean ship frame. Specifically, it is defined by two successive right-handed (or dextral) rotations about link fixed axes. First, let x, y, and z represent coordinate axes fixed in the link such that x aligns with the axis of the link. Also, let x, y, and z be initially aligned with the X, Y, and Z axes of the mean ship frame. The link can now be oriented relative to the mean ship frame by two successive right-handed (or dextral) rotations through angles β downward about the y (or Y) axis and γ outward about the z (or Z') axis. Positive β and γ rotations are shown in Figure 9.

12.   TOWED VEHICLE ORIENTATION ANGLES

The orientation of a towed vehicle is also described relative to the mean ship frame. Let x, y, and z represent coordinate axes located at the mass-center of the vehicle, such that x points forward (the **axial** direction), y starboard (the **lateral** direction), and z downward (the **normal** direction)[10]. Also, let these axes initially align with the X, Y, and Z axes of the mean ship frame. The orientation of the vehicle relative to the mean ship frame is now given by three successive rotations (in a right-handed or dextral sense) th   ugh angles γ, β, and α about the vehicle-fixed z, y, and x axes, respectively. These angular rot ions are shown in Figure 10.

13. INITIAL CABLE AND TOWED VEHICLE CONFIGURATION

The initial configuration of the cable system before the equations of motion are integrated depends upon the initial values of the orientation angles of the cable links and towed vehicles. For example, if the initial values of all the orientation angles are zero, the initial configuration of a single branched towed system model with a towed vehicle would be as shown in Figure 11.

14.   LINK WEIGHT, BUOYANCY, LENGTH. AND DIAMETER

The physical parameters needed by DYNTOCABS to describe the cable links are the weight per unit length (weight density), the buoyant force per unit length, the link length, and the link diameter. These parameters may be different for each cable link; that is, the cable need not be uniform in its physical properties.

15.   TOWED SPHERE PHYSICAL DATA

In addition to the link physical parameters, DYNTOCABS requires the physical parameters of the towed spheres. These are simply the sphere weights and diameters.

16. TOWED VEHICLE PHYSICAL DATA

The physical data needed by DYNTOCABS to describe the towed vehicles is somewhat more extensive, since these bodies can have more general shapes. Specifically, the vehicle's weight, axial length, volume, moments and products of inertia, and the mass center, buoyancy center, and hydrodynamic center position vectors are required. The mass moments and products of inertia are those about the aforementioned axial (x), lateral (y), and normal (z) axes fixed at the center of mass. The mass center position vector R_g is specified by components of the position vector of the mass center of the body relative to the cable point of attachment (the vehicle's reference point). The buoyancy center position vector R_b and the hydrodynamic center position vector R_h are specified by components of the position vectors of these points relative to the vehicle's mass center. Components are taken along the body-fixed coordinate axes with negative numbers indicating negative coordinate directions. See Figure 12.

Care should be taken to account for the mass of the enclosed water in vehicles with free-flooded compartments. In this case, choose the weight of the vehicle to be the sum of the weight of the vehicle in air and the weight of the enclosed water; the moments and products of inertia may need modification as well. Then choose the volume of the vehicle as calculated from its outer dimensions to insure that DYNTOCABS uses the correct weight in water.

17. FLUID FORCES ON CABLE LINKS

The total fluid-induced force per unit length along a typical cable link may be represented as follows:

$$f = f_{normal\ drag} + f_{tangential\ drag} + f_{side\ load} + f_{added\ mass} + f_{buoyancy}$$

DYNTOCABS calculates these forces on cable links using either formulae for flow over circular cylinders (default method) or using experimentally determined loading functions. In both cases, normal and tangential drag forces and buoyancy forces may be included. In addition, when loading functions are used, steady side (or lift) forces are also included. At the present time, however, DYNTOCABS does **not** include added mass forces on the cable links.

The default method for calculation of fluid drag forces resolves the fluid velocity relative to the centroid of the link into components normal and tangent to the link. The drag forces per unit length along the link are then represented as follows:

$$f_{normal\ drag} = \left(\frac{\rho}{2}\right) d\, C_n\, |v_n|\, v_n$$

$$f_{tangential\ drag} = \left(\frac{\rho}{2}\right) \pi d\, C_t\, |v_t|\, v_t$$

where ρ is the fluid mass density, d is the diameter of the cable link, C_n and C_t are normal and tangential drag coefficients dependent upon corresponding Reynold's numbers of the flow past the cable link. These coefficients are usually determined experimentally. DYNTOCABS calculates the normal drag coefficient using the following formulae[4-69]

$$C_n = \begin{cases} 0.0 & for \quad Re_n \le 0.1 \\[2ex] 0.45 + 5.93/(Re_n)^{0.33} & for \quad 0.1 < Re_n \le 400.0 \\[2ex] 1.27 & for \quad 400.0 < Re_n \le 10^5 \\[2ex] 0.3 & for \quad Re_n > 10^5 \end{cases}$$

where the Reynold's number Re_n is defined to be

$$Re_n = \rho d |v_n|/\mu$$

and μ is the fluid viscosity. The tangential drag coefficient is calculated using the method presented in Reid and Wilson.[12] Using this method, C_t can be ca   ated as a function of Reynold's number (based on the tangential velocity, $Re_t = \rho d |v_t|/\mu$) for a given roughness coefficient, λ as shown in Figure 13. The roughness coefficient is defined as the ratio of the equivalent sand roughness of the surface[13] and the cable radius; for a stranded cable, λ may be approximated by comparing the depths of the crevices between major strands of the cable to the radius of the cable.[12] As is evident from its definition, $0 \le \lambda \le 1$, the lower limit representing a perfectly smooth cable.

Alternatively, the cable loading is formulated using loading functions.[7,8] In this method the drag forces per unit length along a link are represented as

$$f_{normal \, drag} = \left(\frac{\rho}{2}\right) d \, C_n |v|^2 f_n \mathbf{n}$$

$$f_{tangential \, drag} = \left(\frac{\rho}{2}\right) d \, C_n |v|^2 f_t \mathbf{t}$$

Note that the normal drag coefficient and the total relative fluid velocity are used in both expressions. The terms f_n and f_t are called loading functions and are assumed to be of the form

$$f_n = A_{n0} + A_{n1} \cos(\phi) + B_{n1} \sin(\phi) + A_{n2} \cos(2\phi) + B_{n2} \sin(2\phi)$$
$$f_t = A_{t0} + A_{t1} \cos(\phi) + B_{t1} \sin(\phi) + A_{t2} \cos(2\phi) + B_{t2} \sin(2\phi)$$

where ϕ is the angle between the cable link and the fluid velocity relative to the mass center of the link. If this drag formulation is employed, the user must provide the values of $A_{ni}(i = 0, 1, 2)$, $B_{ni}(i = 1, 2)$, $A_{ti}(i = 0, 1, 2)$, and $B_{ti}(i = 1, 2)$ the coefficients of the loading functions and C_n the drag coefficient. Note that these coefficients are all assumed to be constant, so that their values must be consistent with the Reynold's number range of the specific example of interest.

When loading functions are used, the fluid induced load on a cable link also includes the side (or lift) force often present on stranded cables. As for the drag forces, this force is represented as

$$\mathbf{f}_{side\ load} = \left(\frac{\rho}{2}\right) d\, C_n \,|\,\mathbf{v}\,|^2 f_s \mathbf{s}$$

where, as before, f_s represents a loading function of the form

$$f_s = A_{s0} + A_{s1}\cos(\phi) + B_{s1}\sin(\phi) + A_{s2}\cos(2\phi) + B_{s2}\sin(2\phi)$$

As before, the values of the coefficients of the loading function must be consistent with the Reynold's number range of the specific example of interest.

The buoyant force per unit length due to hydrostatic pressure exerted on a cable link by fluid 2 (usually water) must be provided by the user. This force may be represented as

$$\mathbf{f}_{buoyancy} = \gamma_b \mathbf{k}$$

where γ_b is the buoyant force per unit length in fluid 2 and $\mathbf{k}$ is a unit vector pointing vertically upward. DYNTOCABS automatically modifies this force when a link is positioned in fluid 1.

DYNTOCABS calculates the fluid induced load per unit length on each cable link by adding (as vectors) the results from each of these formulae. Assuming these forces are constant over the length of a cable link, the total resultant force is found by multiplying this force per unit length by the link length. Finally, half of the resultant force is applied at each end of the link. For additional information, see reference 3.

18. FLUID FORCES ON TOWED SPHERES

DYNTOCABS has the option of including up to three kinds of fluid forces exerted on the spheres: 1) drag forces, 2) added mass forces, and 3) buoyancy forces. DYNTOCABS replaces this system of forces by a single force passing through the center of the sphere. The resultant force is taken to be of the form:[9][11]

$$\mathbf{F} = \left(\frac{\rho}{2}\right) d^2 C_D |\,\mathbf{v}\,|\,\mathbf{v} + (\rho/2)V_S C_m \mathbf{a} + (\rho)g V_S \mathbf{k}$$

where $\mathbf{v}$ and $\mathbf{a}$ represent the velocity and acceleration of the fluid relative to the center of the sphere, V_S represents the volume of the sphere, d represents the diameter of the sphere, and $\mathbf{k}$ represents a unit vector pointing vertically upward. C_D and C_m are coefficients dependent on the Reynold's number of the flow past the sphere. These coefficients are usually determined experimentally. DYNTOCABS uses the following values [9]

9

$$C_D = \begin{cases} 0.0 & for \quad Re \le 0.1 \\ 0.044 + 13.46/(Re)^{1/2} & for \quad 0.1 < Re \le 1000 \\ 0.47 & for \quad 1000 < Re \le 10^5 \\ 0.12 & for \quad Re > 10^5 \end{cases}$$

$$C_m = 1.0$$

with the Reynold's number Re defined as

$$Re = \rho d |v| / \mu$$

19. FLUID FORCES ON TOWED VEHICLES

DYNTOCABS has the option of including up to three kinds of fluid forces on the towed vehicles: 1) drag forces, 2) added mass forces, and 3) buoyancy forces. The drag and added mass forces are calculated from a set of 155 hydrodynamic coefficients. The forms of these forces are similar to those presented in reference 10.

Before defining the drag and added mass forces, first consider the typical towed vehicle shown in Figure 14. The directions associated with the vehicle-fixed x, y, and z coordinate axes are called the **axial, lateral,** and **normal** directions. u, v, and w represent the axial, lateral, and normal components of the velocity of the mass center of the vehicle, p, q, and r represent the axial, lateral, and normal components of the angular velocity of the vehicle, and δ_r and δ_s represent the angular deflections (in radians) of the rudder and sternplane control surfaces.

DYNTOCABS replaces the drag and added mass forces by a single force passing through the **hydrodynamic center** and a corresponding moment. The forms used in the present version of DYNTOCABS to calculate the vehicle-fixed components of the resultant force and moment are given in APPENDIX B. Note that DYNTOCABS has been written so that relatively few changes need be made to the code to incorporate a set of user-defined coefficients which may include the effects of up to four control surfaces. It is assumed that the vehicle undergoes a fully submerged tow.

The buoyancy force on a towed vehicle is calculated as the weight density of water times the volume of the body. This force is assumed to act vertically upward through the vehicle's center of buoyancy.

Finally, since DYNTOCABS assumes that the buoyancy, hydrodynamic, and mass centers of the vehicle do not necessarily coincide, it replaces the buoyancy and hydrodynamic forces and moments with an equivalent force-moment set acting at the mass center.

10

numbers and then bandlimited by digital filtering with a low pass filter. DYNTOCABS requires the standard deviation of the noise and its desired cut-off frequency (Hz.). The mean value of the noise is assumed to be zero.

23. WEIGHT FORCES

The weight forces on the cable links are represented as

$$\mathbf{W} = -\gamma l \mathbf{k}$$

where γ represents the weight density of the link per unit length, l represents the length of the link, and $\mathbf{k}$ represents a unit vector pointing vertically upward.

Similarly, the weight forces on towed spheres and vehicles may be represented by single forces passing through their mass centers with magnitude equal to their weights.

24. UNITS

DYNTOCABS allows the user to select either U.S. Customary or SI (metric) units for the input and output data. If U.S. Customary units are selected, the units are slugs, feet, and seconds for mass, length, and time; however, inches are used for the link and sphere diameters. If SI (metric) system of units is selected, the units are kilograms, meters, and seconds with centimeters used for link and sphere diameters.

25. LABELS

DYNTOCABS allows the user to arbitrarily label or name the links and towed vehicles and their reference points and the spheres.

26. EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS

In general, the **nonlinear equations of motion** of the towed system model may be expressed in the form:

$$\dot{y}_i = f_i(y_j, u_k) \qquad (i = 1, \ldots, 2n; j = 1, \ldots, 2n; k = 1, \ldots, m)$$

where the $y_j (j = 1, \ldots, n)$ represent the orientation angles of the cable links and towed vehicles relative to the mean ship frame, the $y_j (j = n + 1, \ldots, 2n)$ represent the first derivatives of these angles, the $u_k (k = 1, \ldots, m)$ represent **external inputs** (such as motions of the system tow point motion and vehicle control surfaces), and the $f_i (i = 1, \ldots, 2n)$, in general, represent nonlinear functions of the y_j and u_k. These equations govern the general dynamic motion of the towed system.

During steady forward or steady turning motion and, in the absence of external disturbances, the system can exhibit **steady-state equilibrium configurations**. In these situations, the orientation angles relative to the mean ship frame remain constant. These angles satisfy the following n nonlinear algebraic equations:

$$f_{n+i}((y_j)_e, (y_{n+j})_e = 0, (u_k)_e) = 0 \qquad (i,j = 1,...,n)$$

where the $(y_j)_e$, $(y_{n+j})_e$, and $(u_k)_e$ represent the constant values of the orientation angles, their first time derivatives (equal to zero), and the external inputs corresponding to the equilibrium configuration.

Although these equations could be used to solve for the steady-state angles, DYNTOCABS uses a successive free-body diagram approach to do so. It determines the equilibrium angles of each of the bodies of the system individually as it progresses from the ends of the system's branches toward the system reference point. This process is repeated, using the results of each iteration to seed the next, until the changes in the overall configuration of the system does not significantly change. Specifically, DYNTOCABS calculates the square root of the sum of the squares of the differences in the calculated steady-state angles from iteration to iteration and insures that value is less than a user-specified tolerance. The user also supplies the maximum number of these system iterations. It should be noted that sufficient system iterations should be allowed to attain the tolerances specified; DYNTOCABS requires a minimum of 6 such iterations. Up to 20-30 may be needed for partially submerged systems or systems undergoing a steady turn.

To describe the motion of the system that results from small disturbances in the y_j or to the u_k away from their steady-state values, these equations are **linearized** about the steady-state equilibrium configuration. To this end, introduce the **deviations** z_i and v_k so that

$$y_i = (y_i)_e + z_i \qquad (i = 1,...,2n)$$
$$u_k = (u_k)_e + v_k \qquad (k = 1,...,m)$$

Substituting these values into the nonlinear equations of motion, expanding in a Taylor Series about the equilibrium, and omitting second and higher order terms in the deviations z_i and v_k results in the **linear equations of motion**

$$\dot{z}_i = A_{ij} z_j + B_{ik} v_k$$

where

$$A_{ij} = (\partial f_i / \partial y_j)_e$$
$$B_{ik} = (\partial f_i / \partial u_k)_e$$

The subscript e on the partial derivatives indicates that they are evaluated at the equilibrium configuration. Many of the A_{ij} and B_{ik} are easily evaluated; those that are not are approximated using second-order central differences. DYNTOCABS requires a set of **increments** that will be individually applied to the y_i and u_k so that these partial derivatives can be calculated. Note that since the steady-state motion is stationary, the A_{ij} and B_{ik} are constant throughout the motion.

13

27. DEVIATIONS OF EXTERNAL INPUTS AND LINEAR SYSTEM DYNAMICS

In a linear dynamic analysis, v_i represents the **deviations** of the external inputs to the towed system from their steady-state values. Specifically, they represent the deviations of the components along the ship-fixed directions of the position, velocity, and acceleration vectors of the system reference (tow) point relative to the mean-ship frame (9 deviations, 3 for each vector) and the towed vehicle control surface angles (4 deviations for each towed vehicle). The vehicle control surface angles are always considered to be external inputs to the towed system, but DYNTOCABS gives the user the option of excluding the tow point motion.

The actual deviations are not part of the user input, but rather must be calculated in user-supplied subroutines. The deviations of the position, velocity, and acceleration of the system tow point are calculated in SUBROUTINE TPMOTN, and the deviations of the control surface angles of the towed vehicles are calculated in SUBROUTINE CVSPCL. The subroutine statement for these routines must appear as follows:

SUBROUTINE TPMOTN (TIME, X0DV, DX0DV, DDX0DV)

SUBROUTINE CVSPCL(TIME,DELADV,DELBDV,DELRDV,DELSDV,NTOWB)

where the individual variables in the parameter lists are defined as follows (The values of the variables shown in bold print are supplied by DYNTOCABS.):

Variable	Meaning
TIME	Value of time in seconds
NTOWB	Number of towed vehicles
X0DV(I)	The forward, starboard, and downward deviations (I=1,2,3) (ft or meters) of the steady-state position of the system tow point.
DX0DV(I)	The first derivatives (ft/sec or meters/sec) of the deviations X0DV(I) (I=1,2,3).
DDX0DV(I)	The second derivatives (ft/sec^2 or meters/sec^2) of the deviations X0DV(I) (I=1,2,3).
DELADV(ITV)	The deviation in radians of the angle of control surface A of towed vehicle "ITV" from its steady-state value.
DELBDV(ITV)	The deviation in radians of the angle of control surface B of towed vehicle "ITV" from its steady-state value
DELRDV(ITV)	The deviation in radians of the rudder angle of towed vehicle "ITV" from its steady-state value

DELSDV(ITV)   The deviation in radians of the sternplane angle of
                        towed vehicle "ITV" from its steady-state value

Note that the order of the deviations of the control surface angles in arrays DELADV, DELBDV, DELRDV, and DELSDV must be the same as the order that the towed bodies appeared in the input data list. Note also that the deviations of the displacements and displacement derivatives of the system tow point are not independent; together they must consistently represent the motion of the tow point away from its steady-state position.

INPUT DATA

This part of the manual describes the specific input requirements of DYNTOCABS. The data itself is described in terms of line images, generated by any general-purpose text editor. As noted earlier, DYNTOCABS is written in FORTRAN; hence, the input data is to be submitted in FORTRAN format. Unless otherwise specified, all input is free-format; that is, each data line must contain the necessary data items separated by a comma or one or more spaces. The order of the input data is in the same order as described below. The units of the input data are either English or metric, according to the option selected.

HEADING OR TITLE

The first line of input to DYNTOCABS contains a title which may be used to identify the particular data entered. It may contain up to 75 characters, and it will appear at the top of each computer output data page.

OPTIONS

DYNTOCABS has a number of user options to define the desired analysis. These options are selected by specifying integer values as follows:

1)   Analysis: DYNTOCABS allows the user to perform any of five different types of analysis. Enter an integer value between 1 and 5 indicating which type of analysis as follows:

Integer Value	Analysis
1	Linear dynamic analysis
2	Nonlinear dynamic analysis
3	Steady-State analysis (SSA)
4	SSA followed by linear dynamic analysis
5	SSA followed by nonlinear dynamic analysis

2)   Closed-Loop control: If the towed system is to include towed vehicles, the user may specify a closed-loop control law for those vehicles. Enter 1 to include closed-loop control for some or all of the towed vehicles. Enter 0 to neglect closed-loop control. Note that DYNTOCABS allows closed-loop control for nonlinear dynamic analyses (options 2 and 5) only.

3)   Restart: During each execution, DYNTOCABS records data in a restart file every 50 integration steps. A minimum of data is recorded to reduce the time required for this process; the data includes, for example, the values of the link and vehicle angles necessary for restarting DYNTOCABS at the last recorded time. If the restart option is activated, DYNTOCABS reads the restart file generated by the most recent execution of DYNTOCABS and uses this information to "restart" the present execution at the point when that execution stopped.

An input data file used to restart DYNTOCABS should specify analysis option 2, and the input data format should be consistent with that option. If the initial execution specified analysis option 5, minor modifications are required to that data set. Since DYNTOCABS reads most of the data from the present input data file, it is important that this file be consistent with the input data file from the initial execution.

Enter 1 to read data from a restart file; enter 0 to neglect this option.

4)   Units: Enter 1 if U.S. Customary units are desired; enter 2 if metric units are desired.

5)   Normal Drag Forces: Enter 1 to include normal drag forces on cable links and total drag forces on spheres and towed vehicles; enter 0 to neglect these forces.

6)   Tangential Drag Forces: Enter 1 to include tangential drag forces on cable links and total drag forces on spheres and towed vehicles; enter 0 to neglect these forces.

7)   Cable Drag and Side Force (Lift) Formulation: Enter 0 to use the default velocity-dependent coefficients of normal and tangential drag; enter 1 if loading functions are to be used to calculate the drag and side forces on the cable links.

If the default velocity-dependent coefficients are to be used and if tangential drag force are to be included on the cable links, enter the roughness coefficient on the next line. This coefficient should be between 0.0 and 1.0, with 0.0 representing a perfectly smooth cable. See **DEFINITIONS OF TERMS**, Section 17 (FLUID FORCES ON CABLE LINKS).

If loading functions are to be used, the following lines of input-data must also be entered. On the next line, enter the number of different loading function sets (up to three are allowed). For each loading set the following three lines must be entered:

Line 1: A_{t0}, A_{t1}, B_{t1}, A_{t2}, and B_{t2}
Line 2: A_{n0}, A_{n1}, B_{n1}, A_{n2}, and B_{n2}
Line 3: A_{s0}, A_{s1}, B_{s1}, A_{s2}, and B_{s2}

These lines are repeated for each loading function set.

8)   Added Mass Forces: Enter 1 to include added mass forces for spheres and vehicles; enter 0 to neglect these forces.

9)   Buoyancy Forces: Enter 1 to include these forces; enter 0 to neglect these forces.

10)   Gravity Forces: Enter 1 to include these forces; enter 0 to neglect these forces.

11)   Point Loads: DYNTOCABS allows the user to enter point loads at the connecting joints between cable links and between cable links and towed vehicles. These loads are assumed to be constant in time and space. Enter 1 to include these forces; enter 0 to neglect these forces. The values of these are part of the link input.

12)   Viscosities and Fluid Mass Densities: Enter 0 to use the default values shown in the table below. If values different from these default values are desired, enter 1. Then enter the following four lines of data:

Line 1:   Viscosity of the first fluid (usually air) (lb-sec/ft^2 or N-sec/m^2)
Line 2:   Mass density of the first fluid (slug/ft^3 or kg/m^3)
Line 3:   Viscosity of the second fluid (usually water) (lb-sec/ft^2 or N-sec/m^2)
Line 4:   Mass density of the second fluid (slug/ft^3 or kg/m^3)

DEFAULT VALUES FOR FLUID VISCOSITIES AND MASS DENSITIES

	U.S. Customary	Metric
Viscosity (air)	3.7188×10^{-7} (lb-sec)/ft^2	1.7802×10^{-5} (N-sec)/m^2
Mass Density (air)	2.378×10^{-3} slug/ft^3	1.2252 kg/m^3
Viscosity (salt water)	2.48×10^{-5} (lb-sec)/ft^2	1.6831×10^{-3} (N-sec)/m^2
Mass Density (salt water)	1.9905 slug/ft^3	1.0231×10^{3} kg/m^3

13)   Fluid Velocities: DYNTOCABS has the option of allowing the fluids to have constant stream velocities in any direction. To use this option, enter 1. Then enter two lines of data providing the X, Y, and Z inertial components of the velocities of the two fluids (fluid 1 on the first line, and fluid 2 on the second line.).

To decline this option, enter 0. This means the fluids will have zero velocity.

14)   Fluid Interface Level: DYNTOCABS has the option of allowing the fluid interface level (that is, the water level) to be located at some non-zero vertical distance below the mean ship frame. To use this option, enter 1. Then, on the next line of input, enter the vertical distance (positive downward) from the mean ship frame to the interface.

To decline this option, enter 0. This means the fluid interface and the mean ship frame will be on the same level.

NUMBER OF LINKS

Following the input of user options, enter the number of cable links on a single line.

INDIVIDUAL LINK DATA

The next input is a series of data describing the physical and geometric properties of each cable link, as follows:

1)   Body number. See **DEFINITIONS OF TERMS**, Section 6 (BODY CONNECTION ARRAY).

2)   Link label: Any name up to 10 characters in length (A10 format).

3)   Link reference point label: Any name up to 10 characters in length (A10 format).

4)   Body number of adjacent lower numbered link. See **DEFINITIONS OF TERMS**, Section 6 (BODY CONNECTION ARRAY).

5)   Link dry weight density per unit length (lb/ft or N/m).

6)   Link buoyant force (in fluid 2) per unit length (lb/ft or N/m).

7)   Link length (ft or m).

8)   Link diameter (in or cm).

9)   Point load: If point loads are to be included, enter the inertial X, Y, and Z components of the point load acting on the upper end (the end farthest from the system tow point) of the cable link.

10)   Analysis options 1 and 4: If the analysis option has been specified as either 1 (linear dynamic analysis) or 4 (steady-state analysis followed by a linear dynamic analysis), enter the following lines of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

      a)   Steady-state configuration of the link: This line contains two numbers representing the steady-state orientation angles of the cable link. For analysis type 1 the correct values must be given, whereas for analysis type 4 only estimates must be provided.

      b)   Initial deviations from the steady-state configuration: This line contains two numbers representing the deviations of the link orientation angles away from their steady-state values.

      c)   Initial deviations of the link motion from zero: This line contains two numbers representing the first derivatives of the deviations of the link orientation angles away from zero.

      d)   Increment of link configuration: This line contains two numbers representing increments in the link orientation angles used for calculating partial derivatives in the linearized equations of motion of the system.

18

e)   Increment of link motion: This line contains two numbers representing increments in the derivatives of the two link orientation angles used for calculating the partial derivatives in the linearized equations of motion of the system.

11)   Analysis option 2 with NO closed-loop control: If the analysis option of 2 (nonlinear dynamic analysis) with NO closed-loop control is specified, enter the following lines of data:

a)   Initial configuration of the link: This line contains two numbers representing the initial values of the orientation angles of the link. See **DEFINITIONS OF TERMS**, Section 11 (LINK ORIENTATION ANGLES).

b)   Initial motion of the link: This line contains two numbers representing the initial values of the first derivatives of the orientation angles of the link.

12)   Analysis option 2 **with** closed-loop control: If the analysis option of 2 (nonlinear dynamic analysis) with closed-loop control is specified, enter the following lines of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state configuration of the link: This line contains two numbers representing the steady-state orientation angles of the cable link.

b)   Initial deviations from the steady-state configuration: This line contains two numbers representing the deviations of the link orientation angles away from their steady-state values.

c)   Initial deviations of the link motion from zero: This line contains two numbers representing the deviations of the derivatives of the link orientation angles away from zero.

13)   Analysis option 3: If the analysis option of 3 (steady-state analysis) is specified, enter the following line of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state configuration of the link: This line contains two numbers representing initial estimates of the steady-state orientation angles of the cable link.

14)   Analysis option 5: If the analysis option of 5 (steady-state analysis followed by a nonlinear dynamic analysis) is specified, enter the following lines of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state configuration of the link: This line contains two numbers representing initial estimates of the steady-state orientation angles of the cable link.

b)   Initial deviations from the steady-state configuration: This line contains two numbers representing the deviations of the link orientation angles away from their steady-state values.

c)   Initial deviations of the link motion from zero: This line contains two numbers representing the deviations of the derivatives of the link orientation angles away from zero.

15)   Loading function number and coefficients: If loading functions are to be used, enter the set number, the normal drag coefficient, and the side (or lift) coefficient for the link. Note that positive side coefficients indicate a right-hand lay cable and negative coefficients indicate a left-hand lay cable.

NUMBER OF TOWED SPHERES

Following the input of the individual link data, enter the total number of towed spheres.

INDIVIDUAL TOWED SPHERE DATA

The next input is a series of data describing the physical properties of each towed sphere.

1)   Body number. See **DEFINITIONS OF TERMS**, Section 6 (BODY CONNECTION ARRAY).

2)   Towed sphere label (up to 10 characters in A10 format).

3)   Body number of adjacent lower numbered link. See **DEFINITIONS OF TERMS**, Section 6 (BODY CONNECTION ARRAY)

4)   Towed sphere dry weight (lb or N).

5)   Towed sphere diameter (in or cm).

NUMBER OF TOWED VEHICLES

Following the input of the individual sphere data, enter the total number of towed vehicles.

INDIVIDUAL TOWED VEHICLE DATA

The next input is a series of data sets describing the physical, geometric, and hydrodynamic properties of each towed vehicle, as follows:

1)   Body number. See **DEFINITIONS OF TERMS**, Section 6 (BODY CONNECTION ARRAY).

2)   Towed body label (up to 15 characters in A15 format).

3)   Towed body reference point label (up to 15 characters in A15 format).

4)   Body number of adjacent lower numbered link. See **DEFINITIONS OF TERMS**, Section 6 (BODY CONNECTION ARRAY).

5)   Towed body dry weight (lb or N).

6)   Towed body axial length (ft or m).

7)   Towed body volume (ft^3 or m^3)

8)   Towed body moments of inertia, Ixx, Iyy, Izz (slug-ft^2 or N-m^2).

9)   Towed body products of inertia, Ixy, Ixz, Iyz (slug-ft^2 or N-m^2).

10)   Mass center position vector: This line contains three numbers representing the vehicle-fixed x, y, and z components of the position vector of the mass center of the vehicle relative to the cable attachment point (ft or m). Negative numbers indicate negative coordinate directions. See **DEFINITIONS OF TERMS**, Section 16 (TOWED VEHICLE PHYSICAL DATA).

11)   Center of buoyancy position vector: This line contains three numbers representing the vehicle-fixed x, y, and z components of the position vector of the buoyancy center of the vehicle relative its mass center (ft or m). Negative numbers indicate negative coordinate directions. See **DEFINITIONS OF TERMS**, Section 16 (TOWED VEHICLE PHYSICAL DATA).

12)   Hydrodynamic center position vector: This line contains three numbers representing the vehicle-fixed x, y, and z components of the position vector of the hydrodynamic center of the vehicle relative its mass center (ft or m). Negative numbers indicate negative coordinate directions. See **DEFINITIONS OF TERMS**, Section 16 (TOWED VEHICLE PHYSICAL DATA).

13)   Analysis options 1 and 4: If analysis option 1 (linear dynamic analysis) or analysis option 4 (steady-state analysis followed by a linear dynamic analysis) is specified, enter the following lines of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

    a)   Steady-state configuration of the vehicle: This line contains three numbers representing the steady-state orientation angles of the towed vehicle. For analysis type 1 the correct values must be given, whereas for analysis type 4 only estimates must be provided.

    b)   Steady-state control surface angles: This line contains four numbers representing the steady-state values of the angles of the control surfaces A and B, the rudder, and the sternplane of the vehicle.

    c)   Initial deviations from the steady-state configuration: This line contains three numbers representing the deviations of the vehicle orientation angles away from their steady-state values.

    d)   Initial deviations of the link motion from zero: This line contains three numbers representing the deviations of the derivatives of the vehicle orientation angles away from zero.

    e)   Increment of vehicle configuration: This line contains three numbers representing increments in the vehicle orientation angles used for calculating partial derivatives in the linearized equations of motion of the system.

21

f)   Increment of vehicle motion: This line contains three numbers representing increments in the derivatives of the three vehicle orientation angles used for calculating the partial derivatives in the linearized equations of motion of the system.

g)   Increment of control surface angles: This line contains four numbers representing increments in the derivatives of the four vehicle control surface angles. These increments are used for calculating the partial derivatives in the linearized equations of motion of the system.

14)   Analysis option 2 **without** closed-loop control: If the analysis option of 2 (nonlinear dynamic analysis) **without** closed-loop control is specified, enter the following lines of data:

a)   Initial configuration of the vehicle: This line contains three numbers representing the initial values of the orientation angles of the vehicle. See **DEFINITIONS OF TERMS**, Section 11 (LINK ORIENTATION ANGLES).

b)   Initial motion of the vehicle: This line contains three numbers representing the initial values of the first derivatives of the orientation angles of the vehicle.

c)   Initial control surface angles: This line contains four numbers representing the initial values of the angles of the control surfaces A and B, the rudder, and the sternplane of the vehicle.

15)   Analysis option 2 **with** closed-loop control: If the analysis option of 2 (nonlinear dynamic analysis) **with** closed-loop control is specified, enter the following lines of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state configuration of the vehicle: This line contains three numbers representing the steady-state orientation angles of the vehicle.

b)   Steady-state control surface angles: This line contains four numbers representing the steady-state values of the angles of the control surfaces A and B, the rudder, and the sternplane of the vehicle.

c)   Initial deviations from the steady-state configuration: This line contains three numbers representing the deviations of the vehicle orientation angles away from their steady-state values.

d)   Initial deviations of the vehicle motion from zero: This line contains three numbers representing the deviations of the derivatives of the vehicle orientation angles away from zero.

16)   Analysis option 3: If the analysis option of 3 (steady-state analysis) is specified, enter the following line of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state configuration of the vehicle: This line contains three numbers representing initial estimates the steady-state orientation angles of the vehicle.

b)   Steady-state control surface angles: This line contains four numbers representing the steady-state values of the angles of the control surfaces A and B, the rudder, and the sternplane of the vehicle.

17)   Analysis option 5: If the analysis option of 5 (steady-state analysis followed by a nonlinear dynamic analysis) is specified, enter the following lines of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state configuration of the vehicle: This line contains three numbers representing initial estimates the steady-state orientation angles of the vehicle.

b)   Steady-state control surface angles: This line contains four numbers representing the steady-state values of the angles of the control surfaces A and B, the rudder, and the sternplane of the vehicle.

b)   Initial deviations from the steady-state configuration: This line contains three numbers representing the deviations of the vehicle orientation angles away from their steady-state values.

c)   Initial deviations of the vehicle motion from zero: This line contains three numbers representing the deviations of the derivatives of the link orientation angles away from zero.

18)   If the closed-loop control option was specified, then the user must next indicate whether the vehicle is actively controlled: Enter 1 if the towed vehicle contains active control surfaces piloted by a closed-loop control law; enter 0 if the vehicle has no active control surfaces. If active control surfaces are to be included, the following lines of data are required to define the active surfaces and specify the control laws. See **DEFINITIONS OF TERMS**, Section 20 (CLOSED LOOP CONTROL LAW).

a)   Number of active control surfaces on the vehicle (up to four).

b)   Active control surface identifiers: This line contains a single number for each active control surface on the vehicle. For each surface, enter its identifying integer as follows:

Integer	Control Surface
1	surface A
2	surface B
3	rudder
4	sternplane

The values of the angular deflections of these control surfaces are the entries of the vehicle control surface vector; the values appear in the order of their specifying integers defined above.

c)   Actuator switches: This line contains a single number for each active control surface. Enter 1 if an actuator model is to be used to "drive" the control surface; enter 0 if no actuator model is to be used. Note that specifying 0 provides ideal (instantaneous) control surface response, while specifying 1 can provide more realistic response of the mechanical actuation method. See **DEFINITIONS OF TERMS**, Section 21 (ACTUATOR MODEL).

d)   Actuator characteristics: For each active control surface that is to use an actuator model, enter the following three lines of data:

Line 1:   This line contains two numbers representing the natural frequency in Hertz and damping ratio of the actuator.

Line 2:   This line contains three numbers representing the minimum and maximum operating angles in degrees and the mechanical backlash in degrees of the actuator.

Line 3:   This line contains two numbers representing the minimum and maximum operating rates in degrees per second of the actuator.

e)   Number of state variables for the vehicle (up to eight).

f)   State variable identifiers: This line contains a single number for each state variable of the vehicle. For each variable, enter its identifying integer as follows:

Integer	State Variable
1	yaw angle
2	pitch angle
3	roll angle
4	yaw rate
5	pitch rate
6	roll rate
7	depth
8	depth rate

The state variables of the vehicle are the entries of the vehicle state vector; they appear in the order of their specifying integers in the table above.

g)   Noise switches: This line contains a single number for each state variable of the vehicle. For each variable, enter 1 if bandlimited white noise is to be added to that variable; enter 0 if no noise is to be added. The white noise is modelled by a set of Gaussian distributed random numbers; the white noise is bandlimited by digital filtering with a low pass filter.

h)   Noise characteristics: For each state variable which is to have noise included, enter a single line of data containing two numbers representing the standard deviation of the noise and its desired cut-off frequency in Hertz.

i)   Number of nonzero commanded deviation (feedforward) inputs (up to 4).

j)   The feedforward facet of the control law allows the user to command changes to the vehicle configuration (roll, pitch, and yaw angles) and the depth of the mass center of the vehicle. These variables may be specified in one of two ways:

24

1) by using a precoded function, or 2) by using a profile of data values. In the latter case, linear interpolation is used between data values; this is similar to an acceleration profile, except that the data values represent the variable itself and **not** its second derivative.

For each commanded input, enter the following data lines:

    i)   The first line contains two integers identifying the commanded variable and the mode of specification. These integers are defined as follows:

Integer	Commanded Variable
1	yaw angle
2	pitch angle
3	roll angle
4	depth

Integer	Specification Mode
1	precoded function
2	profile of data points

    ii)   If precoded function is specified, enter five numbers representing the constants f_0, A, b, p, and ϕ on the next line. See **DEFINITIONS OF TERMS**, Section 9 (PRECODED FUNCTIONS).

    iii)   If a profile of data points is specified, first enter the number of data points on the next line. Then, on subsequent lines, enter the data point pairs, each pair on a single line. Each data pair consists of two numbers representing the time (seconds) and the commanded input (angles in degrees and depth in feet or meters) at that time.

The commanded variables of the vehicle are the entries of its commanded variable vector; the variables appear in the order of their identifying integers defined above.

19)   Hydrodynamic coefficients for the towed body: The next 56 lines of input contain the hydrodynamic coefficients used to calculate the hydrodynamic forces on the vehicle (See **DEFINITIONS OF TERMS**, Section 19 (FLUID FORCES ON TOWED VEHICLES)). Enter them as follows:

Line 1:	$X'_{\dot{u}}$	$X'_{\dot{w}}$	$X'_{\dot{q}}$
Line 2:	X'_{uu}	X'_{uv}	X'_{uw}
Line 3:	X'_{up}	X'_{uq}	X'_{ur}
Line 4:	X'_{vv}	X'_{vw}	
Line 5:	X'_{vp}	X'_{vq}	X'_{vr}
Line 6:	X'_{ww}		
Line 7:	X'_{wp}	X'_{wq}	X'_{wr}
Line 8:	X'_{pp}	X'_{pq}	X'_{pr}

Line 9: $\quad X'_{qq} \qquad X'_{qr} \qquad X'_{rr}$

Line 10: $\quad X'_{uu\delta_s} \qquad X'_{uw\delta_s} \qquad X'_{uq\delta s}$

Line 11: $\quad X'_{ww\delta_s} \qquad X'_{wq\delta_s} \qquad X'_{qq\delta_s}$

Line 12: $\quad X'_{uu\delta_r\delta_r} \qquad X'_{uq\delta_r\delta_r} \qquad X'_{qq\delta_r\delta_r}$

Line 13: $\quad X'_{uu\delta_s\delta_s} \qquad X'_{uw\delta_s\delta_s} \qquad X'_{uq\delta_s\delta_s}$

Line 14: $\quad X'_{ww\delta_s\delta_s} \qquad X'_{wq\delta_s\delta_s} \qquad X'_{qq\delta_s\delta_s}$

Line 15: $\quad Y'_{\dot{v}} \qquad Y'_{\dot{p}} \qquad Y'_{\dot{r}}$

Line 16: $\quad Y'_{uv} \qquad Y'_{up} \qquad Y'_{ur}$

Line 17: $\quad Y'_{vq} \qquad Y'_{wp}$

Line 18: $\quad Y'_{pq} \qquad Y'_{qr}$

Line 19: $\quad Y'_{uu\delta_r} \qquad Y'_{uq\delta_r} \qquad Y'_{qq\delta_r}$

Line 20: $\quad Z'_{\dot{u}} \qquad Z'_{\dot{w}} \qquad Z'_{\dot{q}}$

Line 21: $\quad Z'_{uu} \qquad Z'_{uv} \qquad Z'_{uw}$

Line 22: $\quad Z'_{up} \qquad Z'_{uq} \qquad Z'_{ur}$

Line 23: $\quad Z'_{vv} \qquad Z'_{vw}$

Line 24: $\quad Z'_{vp} \qquad Z'_{vq} \qquad Z'_{vr}$

Line 25: $\quad Z'_{ww}$

Line 26: $\quad Z'_{wp} \qquad Z'_{wq} \qquad Z'_{wr}$

Line 27: $\quad Z'_{pp} \qquad Z'_{pq} \qquad Z'_{pr}$

Line 28: $\quad Z'_{qq} \qquad Z'_{qr} \qquad Z'_{rr}$

Line 29: $\quad Z'_{uu\delta_s} \qquad Z'_{uw\delta_s} \qquad Z'_{uq\delta_s}$

Line 30: $\quad Z'_{ww\delta_s} \qquad Z'_{wq\delta_s} \qquad Z'_{qq\delta_s}$

Line 31: $\quad Z'_{uu\delta_s\delta_s} \qquad Z'_{uw\delta_s\delta_s} \qquad Z'_{uq\delta_s\delta_s}$

Line 32: $\quad Z'_{ww\delta_s\delta_s} \qquad Z'_{wq\delta_s\delta_s} \qquad Z'_{qq\delta_s\delta_s}$

Line 33: $\quad K'_{\dot{v}} \qquad K'_{\dot{p}} \qquad K'_{\dot{r}}$

Line 34: $\quad K'_{uv} \qquad K'_{up} \qquad K'_{ur}$

Line 35: $\quad K'_{vq} \qquad K'_{wp} \qquad K'_{wr}$

Line 36: $\quad K'_{pq} \qquad K'_{qr}$

Line 37: $\quad K'_{uu\delta_r} \qquad K'_{uq\delta_r} \qquad K'_{qq\delta_r}$

Line 38: $\quad M'_{u} \qquad M'_{w} \qquad M'_{\dot{q}}$

Line 39: $\quad M'_{uu} \qquad M'_{uv} \qquad M'_{uw}$

Line 40: $\quad M'_{up} \qquad M'_{uq} \qquad M'_{ur}$

Line 41: $\quad M'_{vv} \qquad M'_{vw}$

26

Line 42: M'_{vp} $\quad$ M'_{vq} $\quad$ M'_{vr}

Line 43: M'_{ww}

Line 44: M'_{wp} $\quad$ M'_{wq} $\quad$ M'_{wr}

Line 45: M'_{pp} $\quad$ M'_{pq} $\quad$ M'_{pr}

Line 46: M'_{qq} $\quad$ M'_{qr} $\quad$ M'_{rr}

Line 47: $M'_{uu\delta_s}$ $\quad$ $M'_{uw\delta_s}$ $\quad$ $M'_{uq\delta_s}$

Line 48: $M'_{ww\delta_s}$ $\quad$ $M'_{wq\delta_s}$ $\quad$ $M'_{qq\delta_s}$

Line 49: $M'_{uu\delta_s\delta_r}$ $\quad$ $M'_{uq\delta_s\delta_r}$ $\quad$ $M'_{qq\delta_s\delta_r}$

Line 50: $M'_{uu\delta_s\delta_s}$ $\quad$ $M'_{uw\delta_s\delta_s}$ $\quad$ $M'_{uq\delta_s\delta_s}$

Line 51: $M'_{ww\delta_s\delta_s}$ $\quad$ $M'_{wq\delta_s\delta_s}$ $\quad$ $M'_{qq\delta_s\delta_s}$

Line 52: $N'_{\dot{v}}$ $\quad$ $N'_{\dot{p}}$ $\quad$ $N'_{\dot{r}}$

Line 53: N'_{uv} $\quad$ N'_{up} $\quad$ N'_{ur}

Line 54: N'_{vq} $\quad$ N'_{wp} $\quad$ N'_{wr}

Line 55: N'_{pq} $\quad$ N'_{qr}

Line 56: $N'_{uu\delta_r}$ $\quad$ $N'_{uq\delta_r}$ $\quad$ $N'_{qq\delta_r}$

SYSTEM CONTROL LAW GAIN MATRICES

If a nonlinear dynamic analysis (options 2 or 5) **with** closed-loop control has been specified, enter the system feedback and feed-forward gain matrices as follows:

    a.   Enter the feedback control gain matrix by rows.
           Start each row on a new input line.

    b.   Enter the feed-forward control gain matrix by rows.
           Start each row on a new input line.

Note that the system control surface vector, the system state vector, and the system commanded variable vectors for the control law are defined by concatenating the appropriate vectors for each of the towed vehicles. The order in which these individual vehicle vectors appear in the system vectors is the same as the order in which they were input. See **DEFINITIONS OF TERMS**, Section 20 (CLOSED-LOOP CONTROL LAW).

To determine the units of a particular entry of these matrices, use the following guidelines. If these values multiply an angular deviation, they are unitless; if they multiply an angular rate deviation, they have the units of seconds; if they multiply a depth deviation, they have the units of ft^{-1}; and, if they multiply a depth rate deviation, they have the units of seconds/ft.

MOTION OF THE MEAN SHIP FRAME AND SYSTEM REFERENCE POINT

The mean ship frame may exhibit planar motion relative to the inertial reference frame; this motion is described by two variables representing the forward (or reverse) speed and the turning angle of the ship. Also, Q the system reference point may have arbitrary motion relative to the mean ship frame; this motion is described by three variables representing the forward, starboard, and vertical (downward) displacement of Q.

1)   Analysis options 1 and 4: If analysis options 1 (linear dynamic analysis) or 4 (steady-state followed by linear dynamic analysis) has been specified, enter the following lines of data (See **DEFINITIONS OF TERMS**, Sections 7 (MEAN SHIP FRAME, INERTIAL FRAME, AND COORDINATE SYSTEMS) and 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state mean ship frame motion: Enter the steady-state ship speed (ft/sec or m/sec) and turning rate (degrees/second).

b)   Steady-state system reference point position: Enter the steady-state X, Y, and Z coordinates of the system reference point relative to the mean ship frame. Recall that initially the mean ship frame is aligned with the inertial reference frame.

c)   For analysis option 4 only, enter the maximum number of iterations (minimum of 6) and the maximum system error allowed in the calculation of the steady-state configuration of the system. Note that 20-30 iterations may be needed for convergence for partially submerged systems and systems undergoing steady turns.

d)   System tow point motion as external input: Enter 1 to include the tow point motion as an external input. Enter 0 to **not** to include this motion as external input. If this option is to be included, enter the following lines of input:

Line 1:   Enter three numbers representing the increments of the forward, starboard, and downward displacements of the system tow point relative to the origin of the mean-ship-frame used for numerical calculation of the partial derivatives in the [B] matrix in the linear equations of motion.

Line 2:   Enter three numbers representing the increments of the derivatives of the forward, starboard, and downward displacements of the system tow point relative to the origin of the mean-ship-frame used for numerical calculation of the partial derivatives in the [B] matrix in the linear equations of motion.

Line 3:   Enter three numbers representing the increments of the second derivatives of the forward, starboard, and downward displacements of the system tow point relative to the origin of the mean-ship-frame used for numerical calculation of the partial derivatives in the [B] matrix in the linear equations of motion.

Note that the actual deviations of the tow point motion are calculated in SUBROUTINE TPMOTN a user-supplied routine. See **DEFINITIONS OF TERMS**, Section 27 (DEVIATIONS OF EXTERNAL INPUTS AND LINEAR SYSTEM DYNAMICS).

2)   Analysis options 3 and 5: If analysis options 3 (steady-state analysis) or 5 (steady-state analysis followed by nonlinear dynamic analysis) is specified, then enter the following three lines of data (See **DEFINITIONS OF TERMS**, Section 26 (EQUATIONS OF MOTION AND STEADY-STATE EQUILIBRIUM CONFIGURATIONS)):

a)   Steady-state mean ship frame motion: Enter the steady-state ship speed (ft/sec or m/sec) and turning rate (degrees/second).

b)	Steady-state system reference point position: Enter the steady-state forward, starboard, and vertically downward displacements of the system reference point relative to the mean ship frame.

c)	Enter the maximum number of iterations (minimum of 6) and the maximum error allowed in the calculation of the steady-state configuration of the system. Note that 20-30 iterations may be needed for convergence for partially submerged systems or systems undergoing a steady turn.

3)	Analysis options 2 and 5: If the analysis option 2 (nonlinear dynamic analysis) or 5 (steady-state analysis followed by nonlinear dynamic analysis) is specified, five variables are used to describe the motion of the mean ship frame and system reference point during the dynamic analysis. They are identified by the following integers:

Identifying Integer	Variable
1	Forward displacement (X) of the system reference point relative to the mean ship frame (backward, if negative).
2	Starboard displacement (Y) of the system reference point relative to the mean ship frame.
3	Vertical (downward) displacement (Z) of the system reference point relative to the mean ship frame.
4	Forward speed of the mean ship frame relative to the inertial reference frame.
5	Turning angle of the mean ship frame relative to the inertial reference frame (positive for starboard turning).

The data describing these variables can be specified in two ways: 1) by using precoded functions, or 2) by using acceleration profiles. The specific data for these options should be input as follows:

a)	Number of nonzero variables: Enter the number of these variables that are to have nonzero values.

b)	For each nonzero motion variable, the following data lines must be entered. If 0 was entered for the number of nonzero variables, skip these lines.

i)	Identifying integer and specification mode: On the next line, enter the variable's identifying integer and specification mode. A specification mode of 1 indicates that a precoded function will be used to specify the variable; a mode of 2 indicates that an acceleration profile will be used.

ii)	If a precoded function is selected, enter the values of the precoded function constants on the next line (See **DEFINITIONS OF TERMS**, Section 9 (**PRECODED FUNCTIONS**)). For variables 1-3, six values are entered representing

the values of the constants f_0, A, b, p, ϕ, and m. For variables 4 and 5, five values are entered representing the values of the constants f_0, A, b, p, and ϕ. If an acceleration profile is selected, skip this line.

iii)   If an acceleration profile is selected, enter the number of data points in the profile on the next line. Next, enter a set of data lines equal in number to the number of data pairs. The first line of this set contains: (1) the initial time, (2) the initial second derivative of the data value, (3) the initial first derivative of the data value, and (4) the initial data value. Each subsequent line contains: 1) the time, and 2) the corresponding second derivative of the data value. Note that the second derivative of the data value is defined as the second derivative of variables 1-3 and 5, and the first derivative of variable 4. As defined these are all either linear or angular acceleration values.

INTEGRATION OPTION AND PARAMETERS:

        The next set of data has two lines of input. On the first line, enter a single integer value to indicate the numerical integration scheme to be used. Enter 1 for a fixed-step Runge-Kutta method; enter 2 for a fixed-step predictor-corrector (PC) method. Note that the PC method is generally preferred over the Runge-Kutta method in that it requires only half as much computation time. Since the PC algorithm is not self-starting, the fixed-step Runge-Kutta algorithm is used to initiate the integration process. On the next line, enter three numbers: 1) the integration starting time, 2) the integration ending time, and 3) the integration time increment.

CONTROL LAW SAMPLING TIME

        If the closed-loop control law was specified, then on the next line, enter a single data entry representing the sampling time increment of the control law. For best operation of DYNTOCABS, this value should be an integer multiple of the integration time increment. The control law will be employed and the control surface angular positions will be updated as the integration process passes over each sampling time; these times are defined to be the initial integration time and all integer multiples of the sampling time increment beyond that time.

OUTPUT OPTIONS

        1)   The next line contains the time increment for printing the computed data to an output file. Since printing this data at each integration step can produce an excessive amount of output, the print time increment is usually greater than the integration time increment. For best operation of DYNTOCABS, the print time increment should be an integer multiple of the integration time increment.

        2)   At the beginning of the output data, DYNTOCABS lists a copy (or echo) of the input data. The extent of the listing of computed data is a user option. To exercise this option, enter an integer (0,1,2,3,4) in column 1 according to the following printing priority:

        0 - Prints all computed data: the X-Y position, forward speed, turning angle, and turning rate of the mean ship frame; the position, velocity, and acceleration of Q the system reference point; the control surface angular positions for each towed vehicle; the position, velocity, and acceleration of the mass center of each towed vehicle relative to the inertial reference frame and the mean ship frame; the orientation angles and their derivatives for each towed vehicle (in degrees, degrees/second, and degrees/second^2); the vehicle-fixed X,

Y, and Z components of the tension force acting on each towed vehicle; the inertial X, Y, and Z components of the cable tension force acting at Q the system reference point; the tensions in each cable link; the position, velocity, and acceleration of the reference point of each link and towed vehicle relative to the inertial reference frame and to the mean ship frame; and the orientation angles and their derivatives for each cable link (in degrees, degrees/second, and degrees/second^2).

1 - Prints as above for option 0, except for the second derivatives of the orientation angles of the cable links and the accelerations of the reference points of the cable links and towed vehicles.

2 - Prints as above for option 1, except for the first derivatives of the orientation angles of the cable links and the velocities of the reference points of the cable links and towed vehicles.

3 - Prints as above for option 2, except for the orientation angles of and the tensions in the cable links.

4 - Prints as above for option 3, except for the positions of the reference points of the cable links and towed vehicles.

 3) During the execution of a nonlinear time-domain dynamic analysis (analysis options 2 or 5), DYNTOCABS stores information to a file for later use (for example, by a plotting program). On this, the last line of input, enter an integer value representing the number of integration time increments between writes to this file. For example, if this value is specified to be 100 and the integration increment is 0.0025 seconds, then information will be written to this file every 0.25 seconds.

EXAMPLE INPUT DATA

 The purpose of this section is to provide the user with a sample data set that illustrates many of the features of DYNTOCABS. To this end, consider the cable link system shown in Figure 15. The system is made up of 15 cable links, a towed vehicle, and a sphere; let them be numbered as shown. The cable links have varying lengths beginning with link number 1 at 100 feet and progressing to links at the free end of the cable of 5 feet. The main cable from the system tow point to the towed vehicle is 5/8 (0.625) inches in diameter, weighs 0.65 lb/ft, and has a buoyancy force of 0.127 lb/ft. The shorter cable connecting the sphere to the main tow cable has the same characteristics, except it weighs only 0.2 lb/ft. The towed vehicle is 2.85 feet in length and weighs 60 lb (in air); the towed sphere is 3.5 inches in diameter and weighs 1 lb in air. The system is fully submerged in still water.

 DYNTOCABS will first determine the steady-state configuration of the system traveling in a straight line at 10 knots (16.87 ft/sec), and then perform a nonlinear time-domain analysis on the system for 20 seconds as it moves into a turn and undergoes tow point excitation. The angular acceleration of the ship is given by the profile shown in Figure 16; the initial angular displacement and angular velocity are zero. This profile results in a constant angular velocity of 0.5 deg/sec for the mean ship frame after 7 seconds. The vertical motion of the system tow point is prescribed through a precoded function to be $z = 5.0 + 0.5 \cos(\pi t) \tanh(0.5t)$.

The sternplane of the towed vehicle is controlled by a closed loop control law of the form:

$$\delta_s = K_{b1} \delta z + K_{b2} \delta \dot{z} + K_f \delta z_c$$

A depth change of 5 feet is commanded beginning at time zero. The sternplane will be driven with an actuator. The actuator has a natural frequency of 0.63 Hertz, a damping ratio of 0.9, minimum and maximum operating angles of -20 deg and +20 deg, respectively, minimum and maximum operating rates of -100 deg/sec and +100 deg/sec, respectively, and no backlash.

The input for this analysis is shown on the following pages. Note that comments have been included to the right of the data to add clarity.

```
DYNTOCABS - EXAMPLE INPUT DATA
5                                          STEADY STATE & NONLINEAR DYNAMIC ANALYSIS
0                                          USE CLOSED LOOP CONTROL
0                                          NO RESTART
1                                          USE ENGLISH UNITS
1                                          INCLUDE NORMAL DRAG
1                                          INCLUDE TANGENTIAL DRAG
1                                          USE LOADING FUNCTIONS
1                                          ONE LOADING FUNCTION
0.00699   0.0000   0.0000                  LOADING FUNCTION CONSTANTS
0.5000    0.0000   0.0000
1.6145    0.0955   -3.3081
1                                          INCLUDE ADDED MASS
1                                          INCLUDE BUOYANCY
1                                          INCLUDE GRAVITY
0                                          NO POINT LOADS
0                                          USE DEFAULT FLUID PROPERTIES
0                                          NO FLUID VELOCITIES
1                                          FLUID INTERFACE ABOVE TOW POINT
5.0                                        INTERFACE BELOW TOW POINT
15                                         NUMBER OF LINKS
1                                          INPUT FOR BODY 1
        L1                                 LINK LABEL
A    0                                     LINK REFERENCE POINT LABEL
                                           LOWER LINK BODY NUMBER
0.65                                       WEIGHT/UNIT LENGTH
0.127                                      BUOYANT FORCE/UNIT LENGTH
100.0                                      LENGTH
10.0                                       DIAMETER
0.0      0.0      0.0                      GUESS FOR STEADY-STATE ANGLES
0.0      0.0                               INITIAL ANGLE DEVIATIONS
0.0      1.82                              INITIAL DEVIATIONS OF ANGLE DERIVATIVES
        1    L2                            LOADING FUNCTION NO., DRAG COEFF, LIFT COEFF
        2    B                             INPUT FOR BODY 2
2.65
0.127
90.0
0.625
12.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L3
        3    C                             INPUT FOR BODY 3
0.65
0.127
80.0
0.625
14.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L4
        4    D                             INPUT FOR BODY 4
0.65
0.127
70.0
0.625
16.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L5
        5    E                             INPUT FOR BODY 5
0.65
0.127
60.0
0.625
18.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1
```

```
L6    6                                    INPUT FOR BODY 6
F     5
0.65
0.127
50.0
0.625
20.0
0.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L7
        7    G                             INPUT FOR BODY 7
0.65
0.127
50.0
0.625
30.0
0.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L8
        8    H                             INPUT FOR BODY 8
0.65
0.127
50.0
0.625
35.0
0.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L9
        9    I                             INPUT FOR BODY 9
0.65
0.127
25.0
0.625
40.0
0.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L10
        10   J                             INPUT FOR BODY 10
0.65
0.127
10.0
0.625
45.0
0.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L11
        11   K                             INPUT FOR BODY 11
0.65
0.127
10.0
0.625
50.0
0.0
0.0      0.0
0.0      0.0
0.0      1.82     0.0
        1    L12
        12   L                             INPUT FOR BODY 12
0.65
0.127
5.0
0.625
70.0
0.0
```

COEFFICIENTS FOR LATERAL FORCE

COEFFICIENTS FOR NORMAL FORCE

COEFFICIENTS FOR ROLL MOMENT

COEFFICIENTS FOR PITCH MOMENT

COEFFICIENTS FOR YAW MOMENT

FEEDBACK GIANS
FEED FORWARD GIAN
STEADY STATE SHIP SPEED AND TURN RATE
SS CYS REF PT PCS REL TO SHIP FRAME
SYSTEM ITERATION AND MAX ERROR
NUMBER OF NONZERO MOTIONS
X DISPLACEMENT OF SYS REF PT   PRECOMED FCT
FUNCTION CONSTANTS
Z DISPLACEMENT OF SYS REF PT   PRECOMED FCT
FUNCTION CONSTANTS
SHIP SEED   PRECOMED FCT
FUNCTION CONSTANTS
SHIP ANGULAR ACCELERATION PROFILE
NUMBER OF POINTS IN PROFILE
DATA VALUES

FIXED STEP PREDICTOR CORRECTOR
INTEGRATION PARAMETERS
CONTROL LAW SAMPLING TIME
DELTA TIME TO PRINT
OUTPUT OPTION
OUTPUT FREQUENCY TO PLOT FILE

COEFFICIENTS FOR AXIAL FORCE

INPUT FOR BODY 14

INPUT FOR BODY 15

INPUT FOR BODY 16

NUMBER OF TOWED SPHERES
INPUT FOR BODY 13
TOWED SPHERE LABEL
LOWER LINK NUMBER
DRY WEIGHT
DIAMETER
NUMBER OF TOWED VEHICLES
INPUT FOR BODY 13
TOWED BODY LABEL
TOWED BODY REFERENCE POINT LABEL
LOWER LINK NUMBER
TOWED BODY NUMBER
TOWED BODY WEIGHT
TOWED BODY LENGTH
TOWED BODY VOLUME
Ixx,Iyy,Izz
Ixy,Ixz,Iyz
MASS CENTER POSITION VECTOR
BUOYANCY POSITION VECTOR
HYDRODYNAMIC CENTER POSITION VECTOR
TOWED BODY SS ANGLES GUESS
SS CONTROL SURFACE ANGLES
INITIAL ANGLE DEVIATIONS
DEVIATIONS OF INITIAL ANGLE DERIVATIVES
USE CLOSED LOOP CONTROL FOR VEHICLE
OF ACTIVE CONTROL SURFACES
STERNPLANE
DRIVE STERNPLANE WITH ACTUATOR
NAT BRAL FREQ & DAMPING RATIO
MIN/MAX OPER ANGLES & BACKLASH
MIN/MAX OPER RATES
OF STATE VARIABLES
DEPTH & DEPTH RATE
NO NOISE
OF NONZERO COMMANDS
DEPTH DEVIATION BY PROFILE
OF POINTS IN PROFILE
DATA VALUES

34

EXAMPLE OUTPUT

Before performing any analyses, DYNTOCABS provides an "echo" of the input data. This may be used to verify the user's inputs. In addition to this, DYNTOCABS provides output data at specified instants of time. Steady-state configuration data is given (if calculated) at time zero. An example output at time t=20 seconds for a printing priority of 0 is given below for the example input data shown above. Along with the time value and number of integration steps, DYNTOCABS provides kinematic data for the mean ship frame, the system reference point, the towed vehicles, the references points of the links and towed vehicles, and the cable links. It also provides the force required at the system tow point, the forces acting on the cable at the vehicle tow points, and the tensions in each of the cable links. Both the printing interval size and the printing priority are user options; the printing priority controls the amount of data printed at the end of each printing interval.

DYNTOCABS -- EXAMPLE INPUT DATA

TIME = 20.000 SECONDS
NUMBER OF INTEGRATION STEPS = 8001
NUMBER OF CALLS TO FORMLD = 16010

MEAN SHIP FRAME

X-POSITION COORDINATE =	336.44
Y-POSITION COORDINATE =	20.186
FORWARD SPEED =	16.870
TURNING ANGLE =	8.2500
TURNING RATE =	0.50000

SYSTEM REFERENCE POINT (RELATIVE TO MEAN SHIP FRAME)

POSITION COORDINATES =	-10.000	0.00000E+00	5.5000
VELOCITY COMPONENTS =	0.00000E+00	0.00000E+00	0.20628E-08
ACCELERATION COMPONENTS =	0.00000E+00	0.00000E+00	-4.9348
TENSION COMPONENTS =	-1889.4	142.78	290.56

TOWED VEHICLES

CONTROL SURFACE DEFLECTIONS (DEGREES)

DEPRESSOR	0.00000E+00	0.00000E+00	0.00000E+00	11.647

MASS CENTER POSITION, VELOCITY, ACCELERATION (RELATIVE TO INERTIA SPACE)

POSITION VECTOR COMPONENTS

DEPRESSOR	-219.73	0.62510	201.20

VELOCITY COMPONENTS

DEPRESSOR	16.790	0.18367	0.28494E-01

ACCELERATION COMPONENTS

DEPRESSOR	0.80284	0.48348E-01	-0.55126E-02

MASS-CENTER POSITION, VELOCITY, ACCELERATION (RELATIVE TO MEAN SHIP FRAME)

POSITION VECTOR COMPONENTS

DEPRESSOR	-552.98	60.417	200.86

VELOCITY COMPONENTS

DEPRESSOR	0.29969	2.6004	0.28494E-01

ACCELERATION COMPONENTS

DEPRESSOR	0.80145	-0.21530	-0.11869E-01

ORIENTATION ANGLES RELATIVE TO MEAN SHIP FRAME
(3-2-1 ROTATION SEQUENCE IN DEGREES)

DEPRESSOR	-7.6341	-0.79413	-0.67750E-01

DERIVATIVES OF THE ORIENTATION ANGLES (DEGREES/SECOND)

DEPRESSOR	-0.36918	0.30185E-01	-0.12572E-01

SECOND DERIVATIVES OF THE ORIENTATION ANGLES (DEGREES/SECOND**2)

DEPRESSOR	0.39017E-01	-0.16431	-0.48169E-02

TENSION AT VEHICLE REFERENCE (TOW) POINTS
(VEHICLE FIXED COMPONENTS)

DEPRESSOR	-290.78	-0.16547	1661.0

REFERENCE POINTS OF THE LINKS AND TOWED VEHICLES

RELATIVE TO INERTIA SPACE

POSITION VECTOR COMPONENTS

A	326.54	18.752	5.5000
B	228.00	12.820	21.453
C	139.62	8.8150	37.979
D	61.402	6.0454	54.535
E	-6.5891	4.1340	71.073
F	-64.145	2.8564	87.974
G	-111.11	2.0099	105.12
H	-156.06	1.3377	126.99
I	-195.55	0.85310	157.66
J	-210.65	0.69942	177.58
K	-215.12	0.65961	186.53
L	-218.38	0.63403	195.98
TB	-219.49	0.62730	200.86
M	-156.06	1.3377	126.99
N	-176.04	0.99648	128.00
O	-186.02	0.84934	128.50
SPHERE	-191.02	0.78051	128.76

VELOCITY COMPONENTS

A	16.208	2.3364	0.20629E-08
B	16.856	1.7798	0.70742
C	16.673	1.2735	-0.39445
D	16.763	1.0455	-0.62160E-02
E	16.792	0.79404	0.83124E-01
F	16.771	0.57531	-0.54952E-02
G	16.789	0.43494	-0.55992E-02
H	16.789	0.32322	-0.26869E-01
I	16.794	0.23258	-0.31201E-01
J	16.792	0.20020	0.29300E-01
K	16.793	0.19144	0.28724E-01
L	16.790	0.18574	0.28410E-01
TB	16.789	0.18415	0.28366E-01
M	16.784	0.32322	0.26869E-01
N	16.791	0.26709	0.35507E-01
O	16.791	0.23648	0.35606E-01
SPHERE	16.791	0.22208	0.32980E-01

ACCELERATION COMPONENTS

A	-0.20371E-01	0.14580	-4.9348
B	1.0015	0.52933	1.4676
C	0.84509	0.10359	0.43715
D	0.60981	0.19574E 01	-0.70130
E	0.79408	0.15903	0.68063E-01
F	0.78254	0.14496	-0.24358E-01
G	0.75541	0.84078E-01	-0.54095E-01
H	0.76377	0.56266E-01	-0.38363E-01
I	0.78304	0.54422E-01	-0.13855E-01
J	0.78959	0.51449E-01	-0.89671E-01
K	0.79005	0.49792E-01	-0.87501E-02
L	0.79693	0.48704E-01	-0.63884E-02
TB	0.80387	0.48404E-01	-0.48163E-02
M	0.76377	0.56366E-01	-0.38363E-01
N	0.76374	0.66060E-01	-0.38832E-01
O	0.76458	0.60870E-01	-0.25563E-01
SPHERE	0.76347	0.55068E-01	-0.49088E-01

RELATIVE TO MEAN SHIP FRAME

POSITION VECTOR COMPONENTS

A	-10.000	0.00000E+00	5.5000
B	-108.37	8.2698	21.453
C	196.41	16.988	37.979
D	-274.22	25.471	54.535
E	-341.78	33.336	71.073
F	-398.92	40.330	87.974
G	-445.52	46.2?	105.12
H	-490.11	52.017	126.99
I	-529.26	57.204	157.66
J	-544.22	59.217	177.58
K	-548.65	59.820	186.53
L	-551.88	60.262	195.98
TB	-552.98	60.415	200.86
M	-490.11	52.017	126.99
N	-509.92	54.545	128.00
O	-519.83	55.832	128.50
SPHERE	524.78	56.481	128.76

10.632	-5.5589
12.012	-6.0869
13.754	-6.4510
16.476	-6.6994
20.202	-6.7776
26.177	-6.6451
38.072	-5.9543
53.104	-4.6204
63.635	-3.4530
71.150	-2.5353
77.254	-1.7544
2.9166	-7.2618
2.8805	-7.3966
3.0085	-7.4500

VELOCITY COMPONENTS

A	0.00000E+00	0.00000E+00	0.20620E-08
B	0.13897	0.28842	0.70742
C	0.91820E-01	0.58136	-0.39445
D	0.15287	1.0224	0.62160E-02
E	0.16157	1.3589	0.81124E-01
F	0.19943	1.6442	0.54852E-01
G	0.24579	1.9109	0.55992E-02
H	0.28248	2.1878	0.26868E-01
I	0.29325	2.4391	0.31201E-01
J	0.29618	2.5379	0.29306E-01
K	0.29836	2.5681	0.28724E-01
L	0.29929	2.5907	0.28410E-01
TB	0.24579	2.1878	0.28166E-01
M	0.76118	2.5988	0.2686RE-01
N	0.26647	2.3610	0.35606E-01
O	0.27212	2.3899	0.32980E-01
SPHERE			

DERIVATIVES OF THE ORIENTATION ANGLES (DEGREES/SECOND)

L1	0.41426	-0.16582
L2	-0.71367	-0.18775
L3	0.29309	-0.31721
L4	-0.83433E-01	-0.27426
L5	-0.79324E-01	-0.30784
L6	0.27092E-01	-0.31937
L7	0.45579E-01	-0.28953
L8	0.29994E-01	-0.22722
L9	0.17205E-01	-0.17317
L10	0.13551E-01	-0.12991
L11	0.11279E-01	-0.92592E-01
L12	0.10261E-01	-0.33884
L14	0.27176E-01	-0.32395
L15	0.26933E-02	-0.33452
L16	-0.28097E-01	

SECOND DERIVATIVES OF THE ORIENTATION ANGLES (DEGREES/SECOND**2)

L1	3.7213	-0.23292
L2	-0.67470	0.25767
L3	-0.83870	0.36553E-01
L4	0.65487	0.91616E-01
L5	-0.44560E-01	0.11272E-01
L6	-0.99594E-02	0.65084E-02
L7	0.18064E-01	0.32779E-01
L8	0.35011E-01	0.59862E-02
L9	0.17390E-01	0.89340E-02
L10	0.13189E-02	0.97904E-02
L11	0.40196E-01	0.11847E-01
L12	0.79107E-01	0.13758E-01
L14	0.11905E-02	0.26609E-01
L15	0.76516E-01	0.30289E-01
L16	-0.27278	0.64433E-01

ACCELERATION COMPONENTS

A	0.00000E+00	0.00000E+00	-4.9348
B	1.0638	0.23113	1.4672
C	0.84626	-0.16399	0.43628
D	0.60295	-0.21500	-0.70294
E	0.87589	-0.10389	0.65740E-01
F	0.79287	-0.11578	-0.21358E-01
G	0.75812	-0.20094	-0.51850E-01
H	0.76344	-0.20627	-0.43073E-01
I	0.78274	-0.21019	-0.19630E-01
J	0.78884	-0.21190	-0.15156E-01
K	0.78904	-0.21397	-0.15044E-01
L	0.79566	-0.21517	-0.12742E-01
TB	0.80243	-0.20094	-0.11186E-01
M	0.76344	-0.19181	-0.43594E-01
N	0.76528	-0.19710	-0.30350E-01
O	0.76559	-0.20270	-0.53888E-01
SPHERE	0.76379		

CABLE LINKS

TENSION MAGNITUDES

L1	1902.4	L8	1714.4
L2	1874.6	L9	1698.1
L3	1848.9	L10	1696.7
L4	1825.0	L11	1689.1
L5	1802.9	L12	1686.9
L6	1782.4	L14	7.7532
L7	1759.6	L15	4.8376
	3.3796		

ORIENTATION ANGLES RELATIVE TO MEAN SHIP FRAME
(2-3 ROTATION SEQUENCE IN DEGREES)

L1   9.2115   -4.7437

REFERENCES

1. Walton, T.S., And Polacheck, H., "Calculation of Transient Motion of Submerged Cables," **Mathematics of Computation**, Vol. 14, pp. 27-46, 1960.

2. Wilson, H., And Wang, L.C., "Computational Methods for 3D Dynamics of Cables," BER Report No. 414-58, Bureau of Engineering Research, University of Alabama, University, AL, 1987.

3. Kamman, J.W., And Nguyen, T.C., "Modeling Towed Cable System Dynamics," NCSC TM 492-88, Naval Coastal Systems Center, Panama City, FL, September 1988.

4. Kamman, J.W., And Huston, R.L., "Modeling of Submerged Cable Dynamics," **Computers and Structures**, Vol. 20, pp. 623-629, 1985.

5. Huston, R.L., And Kamman, J.W., "A Representation of Fluid Forces in Finite Segment Cable Models," **Computers and Structures**, Vol. 14, No. 3-4, pp. 281-287, 1981.

6. Huston, R.L., And Kamman, J.W., "Validation of Finite Segment Cable Models," **Computers and Structures**, Vol. 15, pp. 653-660, 1982.

7. Springston, G.B., Jr., "Generalized Hydrodynamic Loading Functions for Bare and Faired Cables in Two-Dimensional Steady-State Cable Configurations," NSRDC Report No. 2424, Washington, D.C., June 1967.

8. Horton, K.J., Ferrer, C.M., Watson, K.P., And Charvoz, D., "Measurements of the Hydrodynamic Force and Strum Characteristics of Stranded Cables," NCSC TM 471-87, Naval Coastal Systems Center, December 1987.

9. Webster, R.L., "An Application of the Finite Element Method to the Determination of Nonlinear Static and Dynamic Responses of Underwater Cable Structures," General Electric Technical Information Series Report No. R76EMH2, Syracuse, NY, January 1976.

10. Gertler, M., And Hagen, G.R., "Standard Equations of Motion for Submarine Simulation," NSRDC Report 2510, Naval Ship Research and Development Center, Washington, D.C., 1967.

11. Newman, J.N., **Marine Hydrodynamics**, MIT Press, Cambridge, MA, 1977.

12. Reid, R.O. And Wilson, B.W., "Boundary Flow Along a Circular Cylinder," Technical Report No. 204-4, National Engineering Science Company, February 1962.

13. Granville, P.S., "The Frictional Resistance and Turbulent Layer of Rough Surfaces," Report No. 1024, David Taylor Model Basin, June 1958.

14. Whang, J.H. And Dobeck, G.J., "Control System Design Study for Mechanical Minesweep Systems," NCSC TN 963-90, Naval Coastal Systems Center, April 1990.
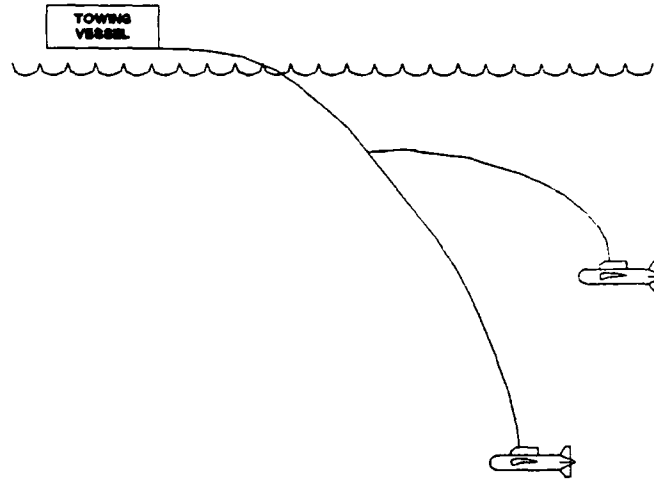
FIGURE 1. TYPICAL MULTIPLE BRANCHED TOWED SYSTEM
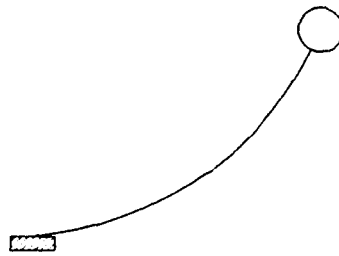
FIGURE 2. A SIMPLE MOORING SYSTEM
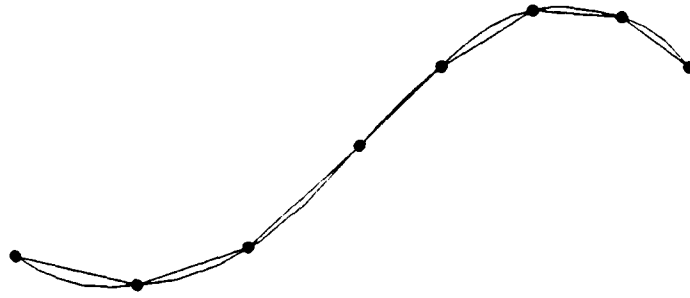
FIGURE 3. A FINITE-SEGMENT MODEL OF A CABLE
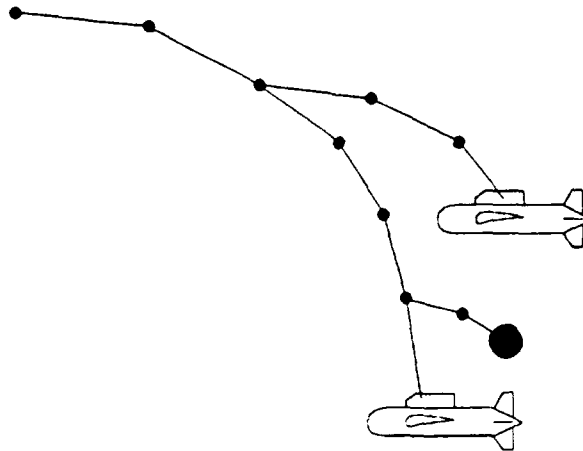
FIGURE 4. A FINITE-SEGMENT TOWED SYSTEM MODEL
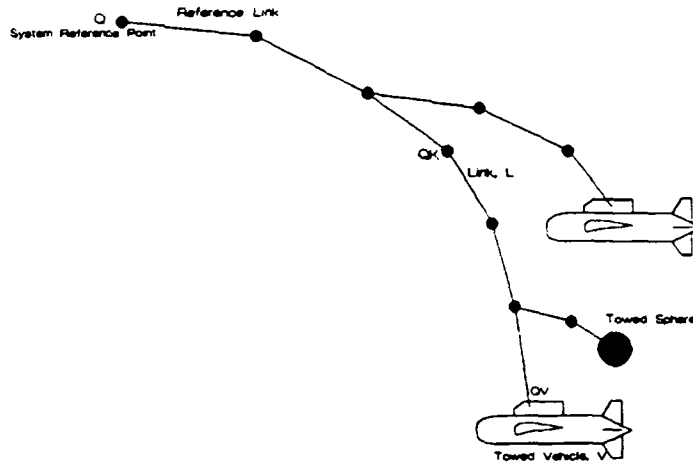
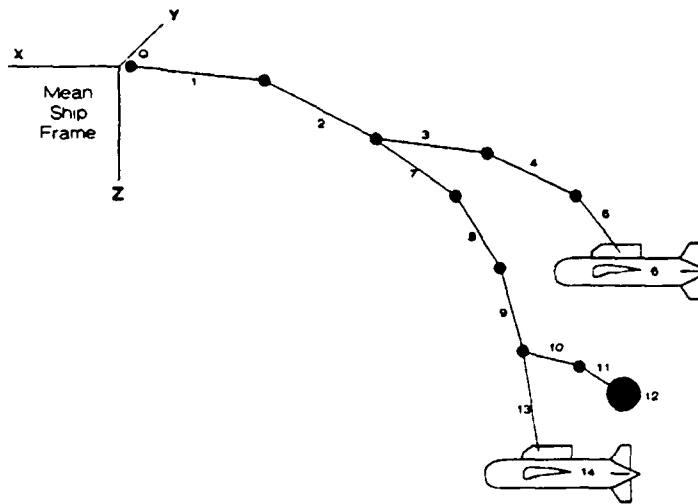**FIGURE 5. REFERENCE LINK, REFERENCE POINTS, AND TOWED VEHICLES**

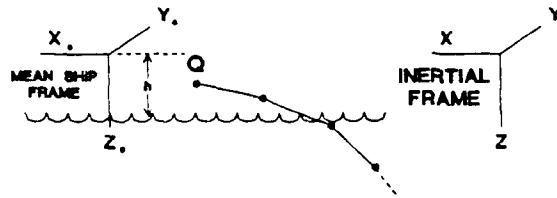**FIGURE 6. NUMBERING OF THE TOWED SYSTEM MODEL OF FIGURES 4 AND 5**

41

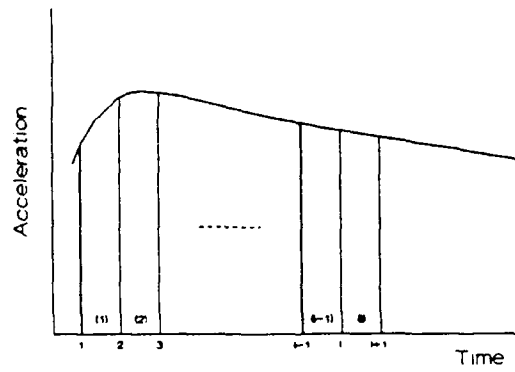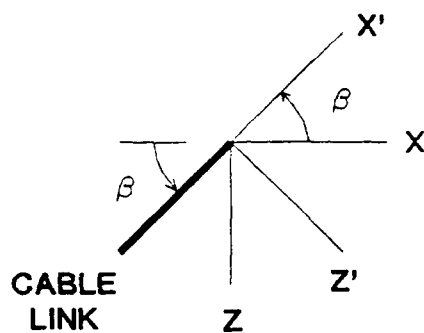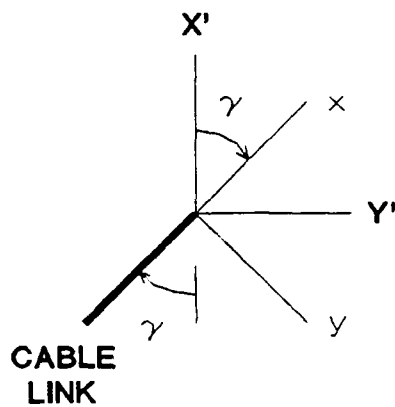**FIGURE 7. INERTIAL FRAME, MEAN SHIP FRAME, AND TOWED SYSTEM
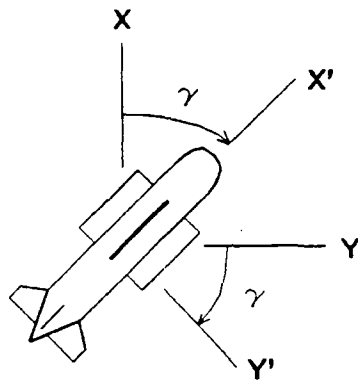MODEL**

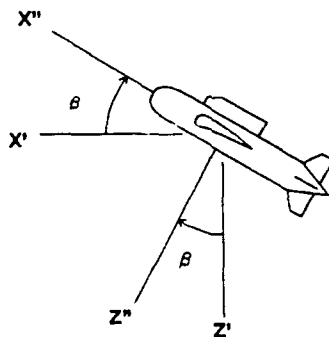**FIGURE 8. ACCELERATION PROFILE APPROXIMATION**

a. POSITIVE β ROTATION

b. POSITIVE γ ROTATION

FIGURE 9. ORIENTATION ANGLES FOR CABLE LINKS

43

a. POSITIVE γ ROTATION

b. POSITIVE β ROTATION

FIGURE 10. ORIENTATION ANGLES FOR TOWED VEHICLES
(Sheet 1 of 2)

44
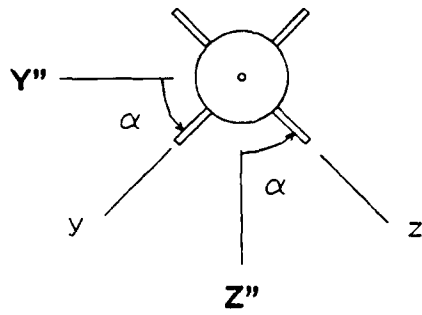
c. POSITIVE α ROTATION

FIGURE 10. (Sheet 2 of 2)
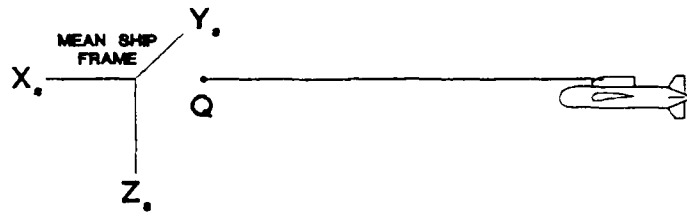
FIGURE 11. ZERO INITIAL CONFIGURATION OF A SINGLE BRANCHED SYSTEM
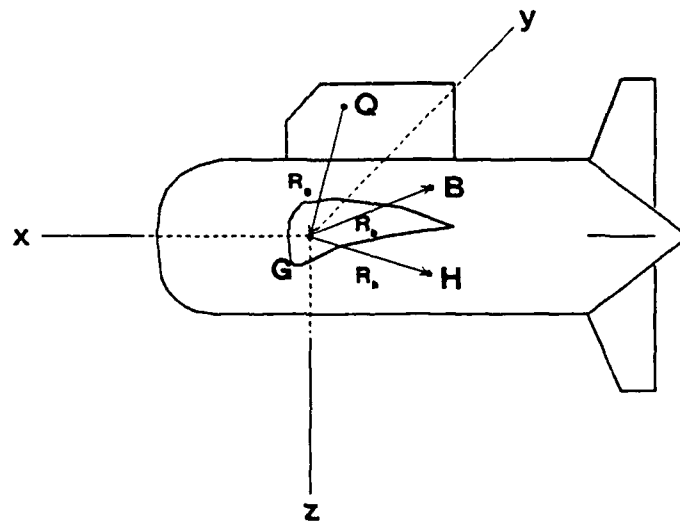
FIGURE 12. TYPICAL VEHICLE WITH POSITION VECTORS AND AXES

TANGENTIAL DRAG PROPERTIES
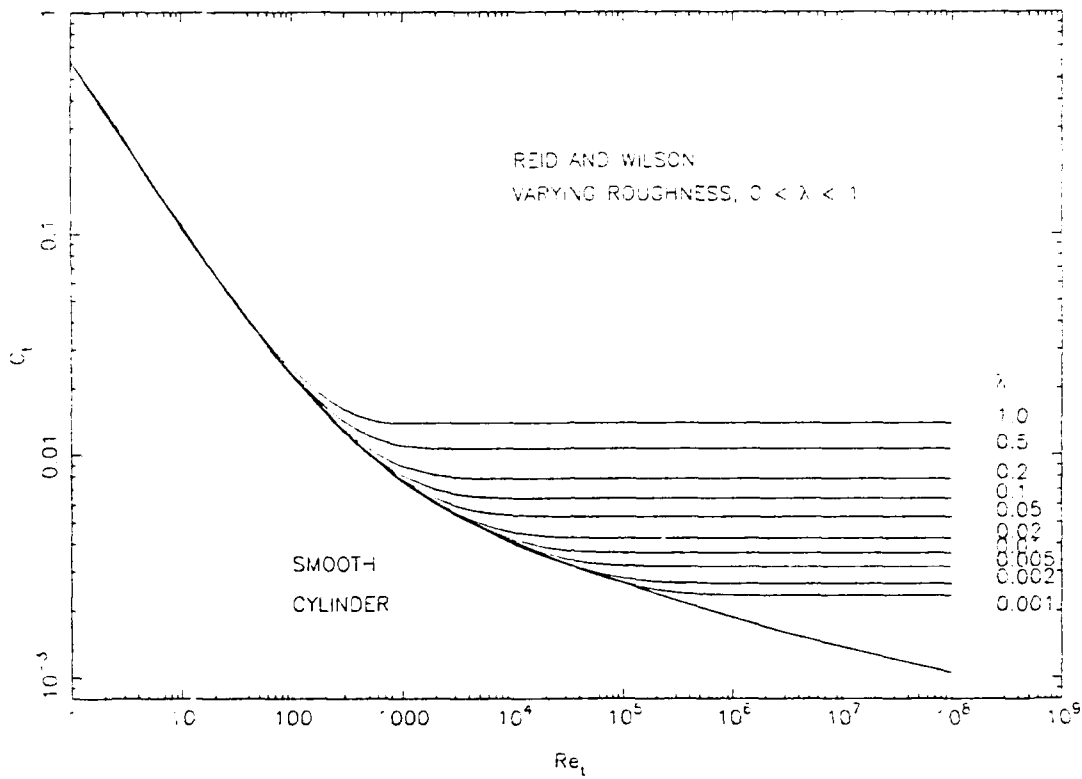
FIGURE 13. TANGENTIAL DRAG COEFFICIENT FOR VARIOUS SURFACE
ROUGHNESSES

47
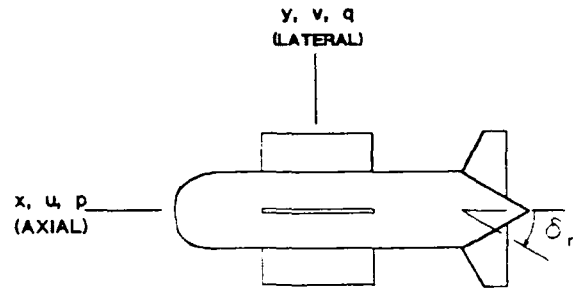
a. TOP VIEW
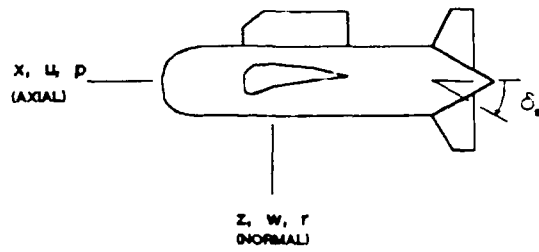
b. SIDE VIEW
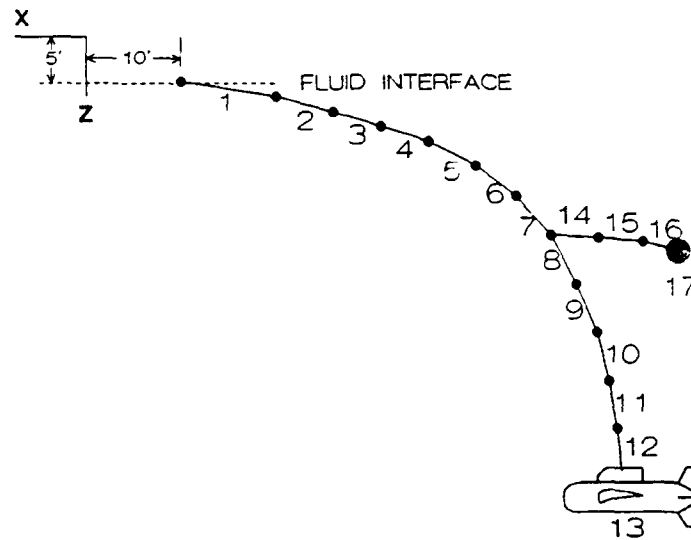
FIGURE 14. TYPICAL VEHICLE WITH CONTROL SURFACES

48

FIGURE 15. SEGMENTED MODEL OF EXAMPLE TOWED SYSTEM
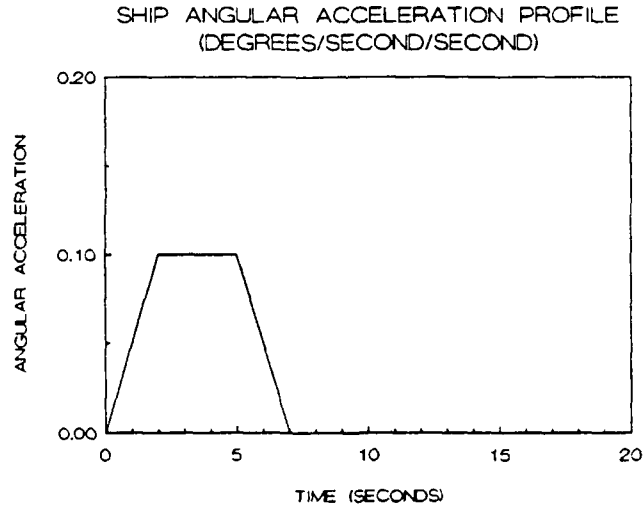

FIGURE 16. ANGULAR ACCELERATION PROFILE FOR MEAN SHIP FRAME

49

APPENDIX A

SUMMARY OF INPUT DATA REQUIREMENTS

APPENDIX A

SUMMARY OF INPUT DATA REQUIREMENTS

This appendix provides an abbreviated summary of the input data requirements for quick reference. Unless otherwise specified, all data is free-formatted input, that is, each line must contain the necessary data items separated by one or more spaces; the column location of each item is arbitrary.

1.   HEADING: Enter a heading or title of up to 75 characters.

2.   OPTIONS:

     a.   Analyses:

         Enter 1 for linear dynamic analysis.
         Enter 2 for nonlinear dynamic analysis.
         Enter 3 for steady-state analysis (SSA).
         Enter 4 for SSA followed by linear dynamic analysis.
         Enter 5 for SSA followed by nonlinear dynamic analysis.

     b.   Closed-loop control:

         Enter 1 to include closed-loop control.
         Enter 0 to neglect closed-loop control.

         Note: Closed-loop control is for analysis options 2 and 5, only.

     c.   Restart Option:

         Enter 1 to activate the restart option.
         Enter 0 to suppress the restart option.

     d.   Units:

         Enter 1 for the English system of units.
         Enter 2 for the MKS system of units.

     e.   Normal drag forces:

         Enter 1 to include these forces.
         Enter 0 to neglect these forces.

     f.   Tangential drag forces:

         Enter 1 to include these forces.

Enter 0 to neglect these forces.

    g.   Cable drag/lift formulation:

Enter 0 to use velocity-dependent normal and tangential drag coefficients (default method). Then, on the next line, enter the surface roughness factor.

Enter 1 to use loading functions for normal, tangential, and side (lift) forces, then enter the following data:
- i)   Enter the number of loading function sets.
- ii)   For each set enter the following three lines of data:
  - (1) Values of A_{t0}, A_{t1}, B_{t1}, A_{t2}, and B_{t2}
  - (2) Values of A_{n0}, A_{n1}, B_{n1}, A_{n2}, and B_{n2}
  - (3) Values of A_{s0}, A_{s1}, B_{s1}, A_{s2}, and B_{s2}

    h.   Added mass forces: (functional for vehicles and spheres)

Enter 1 to include these forces.
Enter 0 to neglect these forces.

    i.   Buoyancy forces:

Enter 1 to include these forces.
Enter 0 to neglect these forces.

    j.   Gravitational forces:

Enter 1 to include these forces.
Enter 0 to neglect these forces.

    k.   Point loads on the cable:

Enter 1 to include these forces.
Enter 0 to neglect these forces.

    l.   Viscosities and fluid mass densities:

Enter 0 to use the default values.
Enter 1 to use substitute values. Next, enter four additional data lines:
    (1) Viscosity of the first fluid

        (2) Mass density of the first fluid
        (3) Viscosity of the second fluid
        (4) Mass density of the second fluid

m.   Fluid velocities:

Enter 0 for zero fluid velocities.
Enter 1 for constant fluid velocities. Then, on the next two
lines, enter the inertial X, Y, and Z components of the
velocitiesof the fluids.

n.   Fluid interface level:

Enter 0 for a zero interface level.
Enter 1 for a nonzero interface level. Then enter the vertical
distance on the next line.

3.   NUMBER OF LINKS: Enter the total number of links in the cable system.

4.   INDIVIDUAL LINK DATA: For each link, enter the following data:

a.   Body number.

b.   Link label: Up to 10 characters (A10 format).

c.   Link reference point label: Up to 10 characters (in A10 format).

d.   Body number of adjacent lower numbered link.

e.   Link dry weight density per unit length. (lb/ft or N/m)

f.   Link buoyant force (in Fluid 2) per unit length. (lb/ft or N/m)

g.   Link length. (ft or m)

h.   Link diameter. (in or cm)

i.   Point Load: If point loads are to be included, enter the inertial
X, Y, and Z components of the point load. (lb or N)

j.   For analysis options 1 and 4, enter the following:

1) Steady-state configuration of the link: Enter the two steady
state orientation angles (these are estimates for analysis type
4). (deg)

2) Initial deviation from steady-state configuration: Enter the
deviations of the two orientation angles. (deg)

3) Initial deviation of the link motion from zero: Enter the first derivatives of the deviations of the two orientation angles. (deg/sec)

4) Increment of the link configuration: Enter the increments of the two orientation angles used for calculating the linear equations of motion. (deg)

5) Increment of the link motion: Enter the increments of the derivatives of the two link orientation angles used for calculation of the linear equations of motion. (deg/sec)

k.   For analysis option 2 **without** closed-loop control, enter the following lines of data:

1) Initial configuration of the link: Enter the two orientation angles. (deg)

2) Initial motion of the link: Enter the derivatives of the two orientation angles. (deg/sec)

l.   For analysis option 2 **with** closed-loop control, enter the following lines of data:

1) Steady-state configuration of the link: Enter the two steady-state orientation angles. (deg/sec)

2) Initial deviation of steady-state configuration: Enter the deviations of the two steady-state orientation angles. (deg/sec)

3) Initial deviation of the link motion from zero: Enter the first derivatives of the deviations of the two orientation angles. (deg/sec)

m.   For analysis option 3, enter the initial estimates of the two steady-state orientation angles of the link. (deg)

n.   For analysis option 5, enter the following lines of data:

1) Steady-state configuration of the link: Enter the initial estimates of the steady-state orientation angles. (deg)

2) Initial deviation of steady-state configuration: Enter the deviations of the two steady-state orientation angles from their steady-state values. (deg)

3) Initial deviation of the link motion from zero: Enter the derivatives of the deviations of the two orientation angles. (deg/sec)

A-4

o.   Loading function and coefficients: If loading functions are
to be used, enter the set number, the normal drag coefficient, and
the side (lift) coefficient for the link.

5.   NUMBER OF TOWED SPHERES: Enter the total number of spheres.

6.   INDIVIDUAL TOWED SPHERE DATA: For each towed sphere, enter the
following data:

a.   Body number.

b.   Towed sphere label: Up to 10 characters (A10 format).

c.   Body number of adjacent lower numbered link.

d.   Towed sphere dry weight. (lb or N)

e.   Towed sphere diameter. (in or cm)

7.   NUMBER OF TOWED VEHICLES: Enter the total number of towed vehicles.

8.   INDIVIDUAL TOWED VEHICLE DATA: For each towed vehicle, enter the
following data:

a.   Body number.

b.   Towed body label: Up to 15 characters (A15 format).

c.   Towed body reference point label: Up to 15 characters (A15 format).

d.   Body number of adjacent lower numbered link.

e.   Towed body dry weight. (lb or N)

f.   Towed body axial length. (ft or m)

g.   Towed body volume. (ft^3 or m^3)

h.   Towed body moments of inertia: I_{xx}, I_{yy}, I_{zz}. (slug-ft^2 or N-m^2)

i.   Towed body products of inertia: I_{xy}, I_{xz}, I_{yz}. (slug-ft^2 or N-m^2)

j.   Towed body mass center position vector: Enter the vehicle-fixed
X, Y, and Z components of the position vector of the vehicle's mass
center relative to cable attachment point. (ft or m)

k.   Towed body buoyancy center position vector: Enter the vehicle-
fixed X, Y, and Z components of the position vector of the vehicle's
buoyancy center relative to its mass center. (ft or m)

l.   Towed body hydrodynamic center position vector: Enter the vehicle-fixed X, Y, and Z components of the position vector of the vehicle's hydrodynamic center relative to its mass center. (ft or m)

m.   For analysis options 1 and 4, enter the following lines of data:

    1)   Steady-state configuration of the vehicle: Enter the three steady-state orientation angles (estimates for option 4). (deg)

    2)   Steady-state control surface angles: Enter the four steady-state angles of the control surfaces A and B, the rudder, and the sternplane. (deg)

    3)   Initial deviation from the steady-state configuration: Enter the deviations of the three vehicle orientation angles from their steady-state values. (deg)

    4)   Initial deviation of the link motion from zero: Enter the derivatives of the deviations of the three vehicle orientation angles. (deg/sec)

    5)   Increment of the vehicle configuration: Enter the increments of the three vehicle orientation angles used for calculating the linear equations of motion. (deg)

    6)   Increment of the vehicle motion: Enter the increments of the derivatives of the three vehicle orientation angles used for calculating the linear equations of motion. (deg/sec)

    7)   Increment of control surface angles: Enter the increments of the derivatives of the four vehicle control surface angles used for calculating the linear equations of motion. (deg)

n.   For an analysis option 2 **without** closed-loop control, enter the following lines of data:

    1)   Initial configuration of the vehicle: Enter the initial values of the three orientation angles. (deg)

    2)   Initial motion of the vehicle: Enter the initial values of the first derivatives of the three orientation angles. (deg/sec)

    3)   Initial control surface angles: Enter the initial values of the angles of the four control surfaces A and B, the rudder, and the sternplane of the vehicle. (deg)

o.   For an analysis option 2 **with** closed-loop control, enter the following lines of data:

1)   Steady-state configuration of the vehicle: Enter the three steady-state orientation angles. (deg)

2)   Steady-state control surface angles: Enter the steady-state values of the angles of the four control surfaces A and B, the rudder, and the sternplane. (deg)

3)   Initial deviation from the steady-state configuration: Enter the deviations of the three orientation angles from their steady-state values. (deg)

4)   Initial deviation of the vehicle motion from zero: Enter the derivatives of the deviations of the three orientation angles. (deg/sec)

p.   For an analysis option 3, enter the following lines of data:

1)   Steady-state configuration of the vehicle: Enter initial estimates of the three steady-state orientation angles. (deg)

2)   Steady-state control surface angles: Enter the steady-state values of the angles of the four control surfaces A and B, the rudder, and the sternplane of the vehicle. (deg)

q.   For an analysis option 5, enter the following lines of data:

1)   Steady-state configuration of the vehicle: Enter initial estimates of the three steady-state orientation angles. (deg)

2)   Steady-state control surface angles: Enter the steady-state values of the angles of the four control surfaces A and B, the rudder, and the sternplane. (deg)

3)   Initial deviation from the steady-state configuration: Enter the deviations of the three orientation angles from their steady-state values. (deg)

4)   Initial deviation of the vehicle motion from zero: Enter the derivatives of the deviations of the three orientation angles. (deg/sec)

r.   Vehicle closed-loop control: If the closed-loop control option is specified, the user must indicate whether or not the vehicle is to use a control law. If the closed-loop control option is **not** specified, skip this input.

Enter 1 if the towed vehicle contains active control surfaces piloted by a closed-loop control law. Enter 0 if no closed-loop control law is to be used for this vehicle. If a closed-loop control law is to be used, enter the following additional lines of data to define the form of the control law:

i) Number of active control surfaces

ii) Active control surfaces identifications: For each active control surface, enter its identifying integer:

1-bowplane A
2-bowplane B
3-rudder
4-sternplane

iii) Actuator Switches: On a single line, enter 1 or 0 for each active control surface indicating whether an actuator will be used (1) or not (0).

iv) Actuator Characteristics: For each act' 'e control surface that is to use an actuator model, enter the following three lines of data:

Line 1: Natural frequency (Hz.) and damping ratio.
Line 2: Minimum and maximum operating angles and mechanical backlash (deg).
Line 3: Minimum and maximum operating rates (deg/sec).

v) Number of towed body state variables

vi) State variable identifiers: For each state variable, enter its identifying integer:

1-yaw angle
2-pitch angle
3-roll angle
4-yaw rate
5-pitch rate
6-roll rate
7-depth
8-depth rate

vii) Noise Switches: On a single line, enter 1 or 0 for each state variable indicating whether noise will be added to that variable (1) or not (0).

viii) Noise Characteristics: For each state variable that is
to have noise added, enter one line of data containing the
standard deviation of the noise (units same as state
variable) and its cut-off frequency (Hz.).

ix)　Number of nonzero commanded deviation inputs

x)　For each commanded input, enter the following lines of
data:

1) Commanded input and specification mode identifiers:

Commanded Input	Specification Mode
1-yaw angle	1-precoded function
2-pitch angle	2-profile of data points
3-roll angle	
4-depth	

2)　If precoded function is specified, enter constants f_0, A, b,
p, and ϕ. If profile of data points is specified, first enter the
number of data points, then enter the data point pairs,
each on single line. Each data point pair consists of
a time value and the value of the commanded input at
that time. Linear interpolation is used between the
data values. (Angles in degrees; depth in ft or m)

s.　Hydrodynamic coefficients for the towed body: Enter the 56 lines
of hydrodynamic coefficients as follows:

Line 1:	$X'_{\dot{u}}$	$X'_{\dot{w}}$	$X'_{\dot{q}}$
Line 2:	X'_{uu}	X'_{uv}	X'_{uw}
Line 3:	X'_{up}	X'_{uq}	X'_{ur}
Line 4:	X'_{vv}	X'_{vw}	
Line 5:	X'_{vp}	X'_{vq}	X'_{vr}
Line 6:	X'_{ww}		
Line 7:	X'_{wp}	X'_{wq}	X'_{wr}
Line 8:	X'_{pp}	X'_{pq}	X'_{pr}
Line 9:	X'_{qq}	X'_{qr}	X'_{rr}
Line 10:	$X'_{uu\delta_s}$	$X'_{uw\delta_s}$	$X'_{uq\delta s}$
Line 11:	$X'_{ww\delta_s}$	$X'_{wq\delta_s}$	$X'_{qq\delta_s}$

Line 12: $\quad X'_{uu\delta_r\delta_r} \qquad X'_{uq\delta_r\delta_r} \qquad X'_{qq\delta_r\delta_r}$

Line 13: $\quad X'_{uu\delta_s\delta_s} \qquad X'_{uw\delta_s\delta_s} \qquad X'_{uq\delta_s\delta_s}$

Line 14: $\quad X'_{ww\delta_s\delta_s} \qquad X'_{wq\delta_s\delta_s} \qquad X'_{qq\delta_s\delta_s}$

Line 15: $\quad Y'_{\dot{v}} \qquad Y'_{\dot{p}} \qquad Y'_{\dot{r}}$

Line 16: $\quad Y'_{uv} \qquad Y'_{up} \qquad Y'_{ur}$

Line 17: $\quad Y'_{vq} \qquad Y'_{wp}$

Line 18: $\quad Y'_{pq} \qquad Y'_{qr}$

Line 19: $\quad Y'_{uu\delta_r} \qquad Y'_{uq\delta_r} \qquad Y'_{qq\delta_r}$

Line 20: $\quad Z'_{\dot{u}} \qquad Z'_{\dot{w}} \qquad Z'_{\dot{q}}$

Line 21: $\quad Z'_{uu} \qquad Z'_{uv} \qquad Z'_{uw}$

Line 22: $\quad Z'_{up} \qquad Z'_{uq} \qquad Z'_{ur}$

Line 23: $\quad Z'_{vv} \qquad Z'_{vw}$

Line 24: $\quad Z'_{vp} \qquad Z'_{vq} \qquad Z'_{vr}$

Line 25: $\quad Z'_{ww}$

Line 26: $\quad Z'_{wp} \qquad Z'_{wq} \qquad Z'_{wr}$

Line 27: $\quad Z'_{pp} \qquad Z'_{pq} \qquad Z'_{pr}$

Line 28: $\quad Z'_{qq} \qquad Z'_{qr} \qquad Z'_{rr}$

Line 29: $\quad Z'_{uu\delta_s} \qquad Z'_{uw\delta_s} \qquad Z'_{uq\delta_s}$

Line 30: $\quad Z'_{ww\delta_s} \qquad Z'_{wq\delta_s} \qquad Z'_{qq\delta_s}$

Line 31: $\quad Z'_{uu\delta_s\delta_s} \qquad Z'_{uw\delta_s\delta_s} \qquad Z'_{uq\delta_s\delta_s}$

Line 32: $\quad Z'_{ww\delta_s\delta_s} \qquad Z'_{wq\delta_s\delta_s} \qquad Z'_{qq\delta_s\delta_s}$

Line 33: $\quad K'_{\dot{v}} \qquad K'_{\dot{p}} \qquad K'_{\dot{r}}$

Line 34: $\quad K'_{uv} \qquad K'_{up} \qquad K'_{ur}$

Line 35: $\quad K'_{vq} \qquad K'_{wp} \qquad K'_{wr}$

Line 36: $\quad K'_{pq} \qquad K'_{qr}$

Line 37: $\quad K'_{uu\delta_r} \qquad K'_{uq\delta_r} \qquad K'_{qq\delta_r}$

Line 38: $\quad M'_{\dot{u}} \qquad M'_{\dot{w}} \qquad M'_{\dot{q}}$

Line 39: $\quad M'_{uu} \qquad M'_{uv} \qquad M'_{uw}$

Line 40: $\quad M'_{up} \qquad M'_{uq} \qquad M'_{ur}$

A-10

Line 41: $\quad M'_{vv} \qquad M'_{vw}$

Line 42: $\quad M'_{vp} \qquad M'_{vq} \qquad M'_{vr}$

Line 43: $\quad M'_{ww}$

Line 44: $\quad M'_{wp} \qquad M'_{wq} \qquad M'_{wr}$

Line 45: $\quad M'_{pp} \qquad M'_{pq} \qquad M'_{pr}$

Line 46: $\quad M'_{qq} \qquad M'_{qr} \qquad M'_{rr}$

Line 47: $\quad M'_{uu\delta_s} \qquad M'_{uw\delta_s} \qquad M'_{uq\delta_s}$

Line 48: $\quad M'_{ww\delta_s} \qquad M'_{wq\delta_s} \qquad M'_{qq\delta_s}$

Line 49: $\quad M'_{uu\delta_r\delta_r} \qquad M'_{uq\delta_r\delta_r} \qquad M'_{qq\delta_r\delta_r}$

Line 50: $\quad M'_{uu\delta_s\delta_s} \qquad M'_{uw\delta_s\delta_s} \qquad M'_{uq\delta_s\delta_s}$

Line 51: $\quad M'_{ww\delta_s\delta_s} \qquad M'_{wq\delta_s\delta_s} \qquad M'_{qq\delta_s\delta_s}$

Line 52: $\quad N'_{\dot{v}} \qquad N'_{\dot{p}} \qquad N'_{\dot{r}}$

Line 53: $\quad N'_{uv} \qquad N'_{up} \qquad N'_{ur}$

Line 54: $\quad N'_{vq} \qquad N'_{wp} \qquad N'_{wr}$

Line 55: $\quad N'_{pq} \qquad N'_{qr}$

Line 56: $\quad N'_{uu\delta r} \qquad N'_{uq\delta r} \qquad N'_{qq\delta r}$

9.   CONTROL GAIN MATRICES: For analysis type 2 **with** closed-loop control, enter the control gain matrices:

   a.   Feedback control gain matrix: Enter one row of the feedback gain matrix on each data line.

   b.   Feedforward control gain matrix: Enter one row of the feedforward gain matrix on each data line.

If these values multiply an angular deviation, they are unitless; if they multiply an angular rate deviation, they have the units of seconds (s); if they multiply a depth deviation, they have the units of ft^{-1}; and, if they multiply a depth rate deviation, they have the units of s/ft.

10.   MOTION OF THE MEAN SHIP FRAME AND SYSTEM REFERENCE POINT:

   a.   For analysis options 1 and 4 enter the following lines of data:

   1) Steady-state mean ship frame motion: Enter the steady-state ship speed and turning rate. (ft/sec or m/sec; deg/sec)

   2) Steady-state system reference point position: Enter the forward, starboard, and downward coordinates of the steady-state position vector of the system reference point relative to the mean ship frame. (ft or m)

   3) For analysis option 4 only, enter the maximum number of system iterations (minimum of 6) and the maximum system error allowed for the calculation of the steady-state configuration of the system.

   4) System tow point as external input: Enter 1 to include the tow point motion as an external input; enter 0 **not** to include this option. If this option is to be included, enter the following lines of input:

      Line 1:   Enter the increments in the forward, starboard, and downward displacements of the system reference point relative to the mean ship frame use for calculating the linear equations of motion. (ft or m)

      Line 2:   Enter the increments in the derivatives of the forward, starboard, and downward displacements of the system reference point relative to the mean ship frame used for calculating the linear equations of motion. (ft/sec or m/sec)

      Line 3:   Enter the increments in the second derivatives forward, starboard, and downward displacements of the system reference point relative to the mean ship frame used

A-12

for calculating the linear equations of motion. (ft/sec^2 or m/sec^2)

b.   For analysis options 3 and 5, enter steady-state data on three lines:

Line 1:   Steady-state ship speed and turning rate. (ft/sec or m/sec; deg/sec)

Line 2:   Steady-state forward, starboard, and downward displacements of the system reference point Q relative to the mean ship frame. (ft or m)

Line 3:   Maximum number of system iterations and error allowed for calculation of steady-state configuration of the system.

c.   For analysis options 2 and 5, enter data only for the non-zero variables among the following:

Identifying Integer	Variable
1	Forward displacement of system reference point Q relative to the mean ship frame (ft or m)
2	Starboard displacement of system reference point Q relative to the mean ship frame (ft or m)
3	Downward (vertical) displacement of system reference point Q relative to the mean ship frame (ft or m)
4	Forward speed of the mean ship frame (ft/sec or m/sec)
5	Turning angle of the mean ship frame relative to the inertial frame (positive for a starboard turn) (deg)

To do this, enter the following data:

1)   Enter the number of variables with non-zero values.

2)   For each non-zero variable:

i)   Enter its identifying integer; then enter: 1 for a precoded function; 2 for an acceleration profile.

ii)   If a precoded function is selected, enter the necessary constants.

For variables 1-3, enter f_0, A, b, p, ϕ, and m.
For variables 4 and 5, enter f_0, A, b, p, and ϕ.

iii)   If an acceleration profile is selected, enter the
number of data points in the profile on the first line.
Next, enter a set of data lines, one for each of the data
pairs. The first line of this set contains the: 1) initial
time; 2) initial acceleration; 3) initial velocity; and 4)
initial displacement value. Each subsequent line contains
the; 1) time; and 2) corresponding acceleration value.
Note that the acceleration represents the second derivative
of variables 1-3 and 5 and the first derivative of variable
4; all of these are acceleration values.

11.   INTEGRATION OPTION AND PARAMETERS:

a.   Integration option:

Enter 1 for the fixed-step Runge-Kutta integrator.
Enter 2 for the fixed-step predictor-corrector integrator.

b.   Integration parameters: Enter the: 1) starting time; 2) ending
time; and 3) time increment. All input in seconds.

12.   CONTROL LAW SAMPLING TIME:

If the closed-loop control option has been selected, enter the time
increment at which the control law is to be sampled. For best
operation of DYNTOCABS, this number should be an integer multiple of
the integration step size. (seconds)

13.   OUTPUT OPTIONS:

a.   Enter print time increment. (seconds)

b.   Output option:

Enter 0 to print all data

Enter 1 to print all except the second derivatives of the
orientation angles of the cable links and the accelerations of
the reference points of the cable links and towed vehicles.

Enter 2 to print as in option 1 except first derivatives of the
orientation angles of the cable links and the velocities of the
reference points of the cable links and towed vehicles.

Enter 3 to print as in option 2 except for the orientation angles
of and the tensions in the cable links.

A-14

Enter 4 to print as in option 3 except for the positions of the reference points and towed vehicles.

c.   Enter the number of integration steps between each set of output written to the plot file.

APPENDIX B

HYDRODYNAMIC LOADS ON TOWED VEHICLES

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HYDRODYNAMIC LOADS ON TOWED VEHICLES

This appendix gives the form of the hydrodynamic loads on towed vehicles as calculated in the present version of DYNTOCABS. In these equations, note that: 1) ρ represents the mass density of the fluid; 2) l represents the axial length of the vehicle; 3) u, v, and w represent the axial, lateral, and normal components of the velocity of the vehicle; 4) p, q, and r represent the axial, lateral, and normal components of the angular velocity of the vehicle; 5) δ_r and δ_s represent the angular deflections of the rudder and sternplane in radians; and 6) the X', Y', Z', K', M', and N' coefficients with the appropriate subscripts represent the user-supplied hydrodynamic coefficients.

Axial Force:

$$
\begin{aligned}
F_{axial} = \frac{\rho}{2}l^2 \{ & X'_{uu}u^2 + X'_{uv}uv + X'_{uw}uw + X'_{vv}v^2 + X'_{vw}vw + \\
& X'_{ww}w^2 + X'_{uu\delta_s}u^2\delta_s + X'_{uw\delta_s}uw\delta_s + X'_{ww\delta_s}w^2\delta_s + \\
& X'_{uu\delta_r\delta_r}u^2\delta_r^2 + X'_{uu\delta_s\delta_s}u^2\delta_s^2 + X'_{uw\delta_s\delta_s}uw\delta_s^2 + X'_{ww\delta_s\delta_s}w^2\delta_s^2 \} + \\[6pt]
\frac{\rho}{2}l^3 \{ & X'_{\dot{u}}\dot{u} + X'_{\dot{w}}\dot{w} + \\
& X'_{up}up + X'_{uq}uq + X'_{ur}ur + X'_{vp}vp + X'_{vq}vq + \\
& X'_{vr}vr + X'_{wp}wp + X'_{wq}wq + X'_{wr}wr + X'_{uq\delta_s}uq\delta_s + \\
& X'_{wq\delta_s}wq\delta_s + X'_{uq\delta_r\delta_r}uq\delta_r^2 + X'_{uq\delta_s\delta_s}uq\delta_s^2 + X'_{wq\delta_s\delta_s}wq\delta_s^2 \} + \\[6pt]
\frac{\rho}{2}l^4 \{ & X'_{\dot{q}}\dot{q} + X'_{pp}p^2 + X'_{pq}pq + X'_{pr}pr + X'_{qq}q^2 + X'_{qr}qr + \\
& X'_{rr}r^2 + X'_{qq\delta_s}q^2\delta_s + X'_{qq\delta_r\delta_r}q^2\delta_r^2 + X'_{qq\delta_s\delta_s}q^2\delta_s^2 \}
\end{aligned}
$$

Lateral Force:

$$F_{lateral} = \frac{\rho}{2}l^2 \left\{ Y'_{uv}uv + Y'_{uu\delta_r}u^2\delta_r \right\} +$$

$$\frac{\rho}{2}l^3 \{Y'_{\dot{v}}\dot{v} + Y'_{up}up + Y'_{ur}ur + Y'_{vq}vq + Y'_{wp}wp + Y'_{uq\delta_r}uq\delta_r\} +$$

$$\frac{\rho}{2}l^4 \{Y'_{\dot{p}}\dot{p} + Y'_{\dot{r}}\dot{r} + Y'_{pq}pq + Y'_{qr}qr + Y'_{qq\delta_r}q^2\delta_r\}$$

Normal Force:

$$F_{normal} = \frac{\rho}{2}l^2 \{Z'_{uu}u^2 + Z'_{uv}uv + Z'_{uw}uw + Z'_{vv}v^2 +$$

$$Z'_{vw}vw + Z'_{ww}w^2 + Z'_{uu\delta_s}u^2\delta_s + Z'_{uw\delta_s}uw\delta_s +$$

$$Z'_{ww\delta_s}w^2\delta_s + Z'_{uu\delta_s\delta_s}u^2\delta_s^2 + Z'_{uw\delta_s\delta_s}uw\delta_s^2 + Z'_{ww\delta_s\delta_s}w^2\delta_s^2\} +$$

$$\frac{\rho}{2}l^3 \{Z'_{\dot{u}}\dot{u} + Z'_{\dot{w}}\dot{w} +$$

$$Z'_{up}up + Z'_{uq}uq + Z'_{ur}ur + Z'_{vp}vp + Z'_{vq}vq +$$

$$Z'_{vr}vr + Z'_{wp}wp + Z'_{wq}wq + Z'_{wr}wr + Z'_{uq\delta_s}uq\delta_s +$$

$$Z'_{wq\delta_s}wq\delta_s + Z'_{uq\delta_s\delta_s}uq\delta_s^2 + Z'_{wq\delta_s\delta_s}wq\delta_s^2\} +$$

$$\frac{\rho}{2}l^4 \{Z'_{\dot{q}}\dot{q} + Z'_{pp}p^2 + Z'_{pq}pq + Z'_{pr}pr + Z'_{qq}q^2 + Z'_{qr}qr +$$

$$Z'_{rr}r^2 + Z'_{qq\delta_s}q^2\delta_s\}$$

Roll Moment:

$$M_{roll} = \frac{\rho}{2}l^3 \left\{ K'_{uv}uv + K'_{uu\delta_r}u^2\delta_r \right\} +$$

$$\frac{\rho}{2}l^4 \{ K'_{\dot{v}}\dot{v} + K'_{up}up + K'_{ur}ur + K'_{vq}vq + K'_{wp}wp +$$

$$K'_{wr}wr + K'_{uq\delta_r}uq\delta_r \} +$$

$$\frac{\rho}{2}l^5 \{ K'_{\dot{p}}\dot{p} + K'_{\dot{r}}\dot{r} + K'_{pq}pq + K'_{qr}qr + K'_{qq\delta_r}q^2\delta_r \}$$

Pitch Moment:

$$M_{pitch} = \frac{\rho}{2}l^3 \{ M'_{uu}u^2 + M'_{uv}uv + M'_{uw}uw + M'_{vv}v^2 + M'_{vw}vw +$$

$$M'_{ww}w^2 + M'_{uu\delta_s}u^2\delta_s + M'_{uw\delta_s}uw\delta_s + M'_{ww\delta_s}w^2\delta_s +$$

$$M'_{uu\delta_r\delta_r}u^2\delta_r^2 + M'_{uu\delta_s\delta_s}u^2\delta_s^2 + M'_{uw\delta_s\delta_s}uw\delta_s^2 + M'_{ww\delta_s\delta_s}w^2\delta_s^2 \} +$$

$$\frac{\rho}{2}l^4 \{ M'_{\dot{u}}\dot{u} + M'_{\dot{w}}\dot{w} +$$

$$M'_{up}up + M'_{uq}uq + M'_{ur}ur + M'_{vp}vp + M'_{vq}vq +$$

$$M'_{vr}vr + M'_{wp}wp + M'_{wq}wq + M'_{wr}wr + M'_{uq\delta_s}uq\delta_s +$$

$$M'_{wq\delta_s}wq\delta_s + M'_{uq\delta_r\delta_r}uq\delta_r^2 + M'_{uq\delta_s\delta_s}uq\delta_s^2 + M'_{wq\delta_s\delta_s}wq\delta_s^2 \} +$$

$$\frac{\rho}{2}l^5 \{ M'_{\dot{q}}\dot{q} + M'_{pp}p^2 + M'_{pq}pq + M'_{pr}pr + M'_{qq}q^2 + M'_{qr}qr +$$

$$M'_{rr}r^2 + M'_{qq\delta_s}q^2\delta_s + M'_{qq\delta_r\delta_r}q^2\delta_r^2 + M'_{qq\delta_s\delta_s}q^2\delta_s^2 \}$$

Yaw Moment:

$$M_{yaw} = \frac{\rho}{2}l^3 \left\{ N'_{uv}uv + N'_{uu\delta_r}u^2\delta_r \right\} +$$

$$\frac{\rho}{2}l^4 \left\{ N'_{\dot{v}}\dot{v} + N'_{up}up + N'_{ur}ur + N'_{vq}vq + N'_{wp}wp + \right.$$

$$\left. N'_{wr}wr + N'_{uq\delta_r}uq\delta_r \right\} +$$

$$\frac{\rho}{2}l^5 \left\{ N'_{\dot{p}}\dot{p} + N'_{\dot{r}}\dot{r} + N'_{pq}pq + N'_{qr}qr + N'_{qq\delta_r}q^2\delta_r \right\}$$

B-4

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