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6 A MATHEMATICAL MODEL OF WATER ENTRY.

9 Technical note,

BY

10 A. M. MACKEY

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A MATHEMATICAL MODEL OF WATER ENTRY. (U/U)

by

A M Mackey

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A MATHEMATICAL MODEL OF WATER ENTRY. (U/U)PRÉCIS

1. A computer simulation of the water entry of an axisymmetric body with or without a cruciform tail and with or without a parachute delivery system is described. The predictions of the simulation are shown to agree with experimental observations of water entry motion. The Fortran program which implements this model is listed.

CONCLUSIONS

2. Over the range of impact velocities (20 to 40 m/sec) which were experimentally investigated using a full scale dummy torpedo, the simulation gave reasonable agreement with the measured water entry behaviour. In addition a limited comparison at higher impact velocities indicated that the possibility of applying the simulation to a wider range of entry velocities was promising.

3. The principal areas in which future work could be carried out are in improving the model of the splash, the cavity and the interaction of both the body and the parachute with the cavity flow field particularly at low Froude numbers.

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INTRODUCTION

4. During the passage of a body from air into water a complex series of forces act upon the body. The experimentally observed phenomena associated with this water entry are described in detail by Waugh and Stubstad (Ref 1). These various phases of water entry are summarised in figure 1.

5. At initial impact and during the subsequent flow formation momentum is rapidly transferred from the body to the water in order to create a velocity field in the water. During initial impact very high local pressures are experienced, the amplitudes of which are dependent upon the physical properties, including compressibility, of the body, of the water, and of the air. However the actual force and moment impulses are comparatively independent of compressibility effects.

6. The flow field contains regions of low pressure and consequently cavitation occurs. Initially, figure 1b, the cavity is open to the atmosphere. During this open cavity phase the pressure in the cavity under the body may be significantly lower than the, near atmospheric, pressure in the upper part of the cavity. As the cavitation number increases the cavity closes, figure 1c, and progressively decreases in size.

7. Some of the air which was originally sucked into the cavity is lost by entrainment at the rear of the cavity. Depending upon the initial entry conditions of the body, the tail may momentarily, intermittently, or continuously contact the wall of the cavity, figure 1d. Finally the cavity collapses, the body slips out of any remaining air bubble, figure 1e, and becomes fully wet.

8. The work which is described here seeks to predict the forces which are applied to the body during these various phases and thus to predict the resulting motion of a body during water entry. Although the mathematical model is of an analytical nature many of the coefficients and functional relationships have been determined empirically by comparison with the work of other experimenters and by comparison with a series of measurements which were made specifically to assist in forming and validating this model.

9. It is intended that this mathematical model should be applicable to the water entry of any axisymmetric body, with or without an axisymmetric parachute. However the actual simulation was derived with particular reference to a lightweight torpedo. A torpedo may be launched from a surface ship using above water torpedo tubes and a typical torpedo is shown in figure 2. The torpedo may also be delivered by an aircraft using a parachute as shown in figure 3. In addition a torpedo may be fitted with a frangible nose cap which is designed to attenuate the initial shock at water impact.

THE MATHEMATICAL MODEL

Reference frames

10. The orientation of a body in space is usually defined by the three Euler angles, roll (ϕ), pitch (θ), and yaw (ψ), however this representation possesses a singularity when the body is pitched at ninety degrees. The quaternion four parameter system, first described by the Irish mathematician Sir W R Hamilton (Ref 2), which also may be used to define the attitude of a body in space overcomes this singularity.

11. If a moving set of right handed axes (x, y, z) , fixed in a body, are obtained from the n co-ordinate axes (x_s, y_s, z_s) , fixed in space, by

rotating the space frame of reference through the angle μ about the unit vector $(\alpha_s, \beta_s, \gamma_s)$ then the quaternion parameters, e , describing the orientation of the body axes relative to the space axes are defined as:-

$$\begin{aligned} e_0 &= \cos \frac{\mu}{2} \\ e_1 &= \alpha_s \sin \frac{\mu}{2} \\ e_2 &= \beta_s \sin \frac{\mu}{2} \\ e_3 &= \gamma_s \sin \frac{\mu}{2} \end{aligned} \quad (1)$$

It may be seen that:-

$$\sum e^2 = 1 \quad (2)$$

12. In terms of the three Euler angles the quaternion parameters are given by:-

$$\begin{aligned} e_0 &= \cos \frac{\phi}{2} \cos \frac{\theta}{2} \cos \frac{\psi}{2} + \sin \frac{\phi}{2} \sin \frac{\theta}{2} \sin \frac{\psi}{2} \\ e_1 &= \sin \frac{\phi}{2} \cos \frac{\theta}{2} \cos \frac{\psi}{2} - \cos \frac{\phi}{2} \sin \frac{\theta}{2} \sin \frac{\psi}{2} \\ e_2 &= \cos \frac{\phi}{2} \sin \frac{\theta}{2} \cos \frac{\psi}{2} + \sin \frac{\phi}{2} \cos \frac{\theta}{2} \sin \frac{\psi}{2} \\ e_3 &= \cos \frac{\phi}{2} \cos \frac{\theta}{2} \sin \frac{\psi}{2} - \sin \frac{\phi}{2} \sin \frac{\theta}{2} \cos \frac{\psi}{2} \end{aligned} \quad (3)$$

13. The transformation matrix, which relates the body frame of reference to the space frame of reference, is:-

$$T = \begin{bmatrix} e_0^2 + e_1^2 - e_2^2 - e_3^2 & 2e_1e_2 - 2e_0e_3 & 2e_0e_2 + 2e_1e_3 \\ 2e_3e_0 + 2e_1e_2 & e_0^2 - e_1^2 + e_2^2 - e_3^2 & 2e_2e_3 - 2e_0e_1 \\ 2e_1e_3 - 2e_0e_2 & 2e_0e_1 + 2e_2e_3 & e_0^2 - e_1^2 - e_2^2 + e_3^2 \end{bmatrix} \quad (4)$$

14. The terminology:-

$$T = \begin{bmatrix} \underline{x}, \underline{y}, \underline{z} \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix} \quad (5)$$

will be used for convenience. In the space frame of reference the unit vector $\underline{X}$ is the body x axis, the unit vector $\underline{Y}$ is the body y axis and the unit vector $\underline{Z}$ is the body z axis.

The equations of motion

15. The origin of the body fixed axes is chosen so that the x axis is the axis of symmetry of the body and so that the co-ordinates of the position of the centre of gravity are $(0, y_g, z_g)$. If the body, of mass m , axial moment of inertia I_x and transverse moment of inertia I_y , is moving with linear velocity (u, v, w) and angular velocity (p, q, r) under the influence of external forces (F_x, F_y, F_z) and moments (L_x, L_y, L_z) in a gravitational field g then the equations of motion are:-

$$\begin{aligned}
 m(\dot{u} - vr + wq + y_g(pq - \dot{r}) + z_g(pr + \dot{q}) - gX_3) &= F_x \\
 m(\dot{v} - wp + ur - y_g(r^2 + p^2) + z_g(qr - \dot{p}) - gY_3) &= F_y \\
 m(\dot{w} - uq + vp + y_g(rq + \dot{p}) - z_g(p^2 + q^2) - gZ_3) &= F_z \\
 I_x \dot{p} + m(y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur) + g(z_g Y_3 - y_g Z_3)) &= L_x \\
 I_y \dot{q} + (I_x - I_y)rp + m z_g(\dot{u} - vr + wq - gX_3) &= L_y \\
 I_z \dot{r} + (I_y - I_x)pq + m y_g(\dot{v} - wp + ur - gY_3) &= L_z
 \end{aligned} \quad (6)$$

The geometry of water entry

16. In order to predict the external forces and moments applied to the body it is first necessary to determine which parts of the body are in contact with water.

17. The shape of the axially symmetric body is defined by a table of axial distances, x , and the corresponding radii, R , so that the body is divided into a number of segments, one of which is shown in figure 4. From this table of values the following segment parameters are defined:-

$$\begin{aligned}
 \text{segment 'x' co-ordinate} &= x = (x_n + x_{n+1})/2 \\
 \text{segment radius} &= R = (R_n + R_{n+1})/2 \\
 \text{segment width} &= dx = x_n - x_{n+1} \\
 \text{segment angle} &= \alpha = \tan^{-1}((R_{n+1} - R_n)/dx)
 \end{aligned} \quad (7)$$

18. The geometrical problem which must be solved in order to determine which areas of the body surface are wet is shown in figure 5. For an area of the body to be in contact with water it is necessary that the area be both beneath the sea surface and not in a region of cavitation.

Sea surface condition

19. If the unit vector in space out of the sea surface is $\underline{n}_s$, then in the body co-ordinate system this is:-

$$\underline{n} = \underline{n}_s \begin{bmatrix} T \end{bmatrix} \quad (8)$$

The body segment, in body co-ordinates relative to the centre of the segment may be defined as $(0, R \cos \beta, R \sin \beta)$. Hence the intersection of the segment with the sea surface is defined by the two roots β_1, β_2 of:-

$$(0, R \cos \beta, R \sin \beta) \cdot \underline{n} = d \quad (9)$$

where d is the normal distance between the plane of the sea surface and the centre of the segment. Equation 9 has a solution if:-

$$\left| \frac{d}{R(n_y^2 + n_z^2)^{\frac{1}{2}}} \right| < 1 \quad (10)$$

When there is no solution the sign of d determines whether the segment is completely above or completely below the sea surface.

Cavitation condition

20. The pressure distribution, cavity detachment angles, and cavity shapes, described by Knapp, Daily and Hammitt (Ref 3), for a number of axisymmetric bodies were studied. The empirical conditions for cavity detachment are chosen to be that the cavitation number, σ , is less than 0.3 and that the local angle of incidence, i , of the body surface to the flow is:-

$$\begin{aligned} \sin(i) = & 0.152 \sin(i_m) + 0.608 \sin^3(i_m) - 0.34 \exp(-R \cos \alpha \frac{da}{dx}) \\ & - 0.36\sigma + 0.28 \sin^2(i_b) \end{aligned} \quad (11)$$

where i_m is the maximum local angle of incidence and i_b is the incidence of the whole body.

21. If the velocity is assumed to be constant over each segment of the body then the local incidence, i_β , of a point at angular position β on a segment is:-

$$\sin(i_\beta) = (u_s \sin \alpha + (v_s \cos \beta + w_s \sin \beta) \cos \alpha) / (u_s^2 + v_s^2 + w_s^2)^{\frac{1}{2}} \quad (12)$$

where (u_s, v_s, w_s) is the velocity of the centre of the segment. By equating i_β to i from equation (11) the cavitating sector is found in terms of β . However in:-

$$u_s \sin \alpha - (v_s^2 + w_s^2)^{\frac{1}{2}} \cos \alpha > \sin(i) (u_s^2 + v_s^2 + w_s^2)^{\frac{1}{2}} \quad (13)$$

then there is no cavitation and if:-

$$u_s \sin \alpha + (v_s^2 + w_s^2)^{\frac{1}{2}} \cos \alpha < \sin(i) (u_s^2 + v_s^2 + w_s^2)^{\frac{1}{2}} \quad (14)$$

then the whole segment is cavitating and a cavity is assumed to be thrown off from the body at this segment.

22. This cavity is assumed to be an ellipsoid of revolution with its major axis aligned to the flow direction and with:-

$$\text{semi major axis} = a = 0.4 \sin(i) R_{ef} (1 + R \cos \alpha \frac{d\alpha}{dx})/\sigma \quad (15)$$

$$\text{semi minor axis} = b = R_{ef} + 0.13a \quad (16)$$

where the effective segment radius R_{ef} is

$$R_{ef} = R(u_s^2 + v_s^2 + w_s^2)^{\frac{1}{2}} / (u_s - (v_s^2 + w_s^2)^{\frac{1}{2}} \tan \alpha) \quad (17)$$

The origin of this ellipsoid is found by fitting the radius of the cavity to the effective radius of the segment. Initially, after impact, the size of this cavity and the pressure of the air entrained within it are defined as empirical functions of the distance travelled in water.

23. If an ellipsoidal cavity is present then the wetted sectors of segments which are downstream of the inception of this cavity are determined by solving for the intersection of each body segment with the cavity.

The external forces and moments

24. The external forces on the body are divided into those forces resulting from quasi steady state pressures and those forces which are associated with 'added mass' effects.

Steady state pressure forces

25. The mass of water, of density ρ , displaced by each wetted sector is:-

$$dm = \rho R^2 dx (\beta_2 - \beta_1 - \sin(\beta_2 - \beta_1))/2 \quad (18)$$

therefore, in the body frame of reference, the buoyancy force on each segment is:-

$$dF = dm g (X_3, Y_3, Z_3) \quad (19)$$

26. The dynamic pressure on the surface of the body is defined to be proportional to the square of the normal component of the velocity of the surface. The normal component of velocity, V_β , at angular position β on a segment is the scalar product of the velocity of the surface and the unit vector normal to the surface at that position ie:-

$$V_\beta = ((u,v,w) + ((p,q,r) \times (x,R\cos\beta,R\sin\beta))) \cdot (\sin\alpha, \cos\beta\cos\alpha, \sin\beta\cos\alpha) \quad (20)$$

The magnitude of the pressure force, dF , on the elemental area, $Rd\beta dx/\cos \alpha$, is:-

$$dF = \frac{1}{2} \rho V_\beta^2 C_D \frac{Rd\beta dx}{\cos \alpha} \quad (21)$$

where C_D is the force coefficient.

27. If a constant velocity, V_{β_0} , is chosen to be of the same order as V_{β} .
then to a first approximation:-

$$V_{\beta}^2 = V_{\beta_0} (2V_{\beta} - V_{\beta_0}) \quad (22)$$

Substituting this linear expression for V_{β}^2 into equation (21), resolving dF into the body frame of reference and integrating over the whole segment yields:-

$$\begin{aligned} dF_x &= \frac{1}{2} \rho C_D V_{\beta_0} R dx \tan \alpha \int_{\beta_1}^{\beta_2} (2V_{\beta} - V_{\beta_0}) d\beta \\ dF_y &= \frac{1}{2} \rho C_D V_{\beta_0} R dx \int_{\beta_1}^{\beta_2} (2V_{\beta} - V_{\beta_0}) \cos \beta d\beta \\ dF_z &= \frac{1}{2} \rho C_D V_{\beta_0} R dx \int_{\beta_1}^{\beta_2} (2V_{\beta} - V_{\beta_0}) \sin \beta d\beta \end{aligned} \quad (23)$$

The moment, dL , of dF about the origin is:-

$$dL = (x, R \cos \beta, R \sin \beta) \times dF \quad (24)$$

$$\text{ie } dL = (h \tan \alpha - x) (0, dF_z, -dF_y) \quad (25)$$

The external forces and moments applied to the body by quasi steady state pressures are obtained by summing dF and dL over all of the segments of the body.

Aided mass forces

28. The importance of forces associated with the momentum of the flow field surrounding the partially wet body during water entry was first emphasised by von Kármán (Ref 4). The linear momentum M , and the angular momentum, H , of the flow field surrounding the body may be defined by:-

$$\begin{bmatrix} M_x \\ M_y \\ M_z \\ H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} X_u & X_v & X_w & X_p & X_q & X_r \\ Y_u & Y_v & Y_w & Y_p & Y_q & Y_r \\ Z_u & Z_v & Z_w & Z_p & Z_q & Z_r \\ K_u & K_v & K_w & K_p & K_q & K_r \\ M_u & M_v & M_w & M_p & M_q & M_r \\ N_u & N_v & N_w & N_p & N_q & N_r \end{bmatrix} \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} \quad (26)$$

The six by six array is the added mass matrix which is discussed in detail by Imlay (Ref 5). The resulting forces and moments acting on a moving body are:-

$$\underline{F} = \frac{d\mathbf{M}}{dt} + ((p, q, r) \times \underline{M}) \quad (27)$$

$$\text{and } \underline{L} = \frac{d\mathbf{H}}{dt} + ((u, v, w) \times \underline{M}) + ((p, q, r) \times \underline{H}) \quad (28)$$

29. In order to evaluate the added mass matrix it is assumed that associated with every element of area, $R d\beta dx / \cos \alpha$, is a volume of fluid, $R h d\beta dx / \cos \alpha$, so that h is a measure of the distribution of added mass upon the body. In addition it is assumed that only the component of velocity normal to the surface imparts momentum to the associated volume of water. The element of linear momentum normal to the surface at angular position β on a segment is therefore:-

$$dM = V_{\beta} \rho R h d\beta dx / \cos \alpha \quad (29)$$

where V_{β} is given by equation (20). Integrating over a whole segment gives the fluid linear momentum associated with the wetted sector of the segment expressed in the body frame of reference:-

$$\begin{aligned} dM_x &= \rho R h dx \tan \alpha \int_{\beta_1}^{\beta_2} V_{\beta} d\beta \\ dM_y &= \rho R h dx \int_{\beta_1}^{\beta_2} V_{\beta} \cos \beta d\beta \\ dM_z &= \rho R h dx \int_{\beta_1}^{\beta_2} V_{\beta} \sin \beta d\beta \end{aligned} \quad (30)$$

Angular momentum about the body origin is:-

$$d\mathbf{H} = (x, R \cos \beta, R \sin \beta) \times d\mathbf{M} \quad (31)$$

$$\text{ie } d\mathbf{H} = (R \tan \alpha - x) (0, dM_z, -dM_y) \quad (32)$$

30. The coefficients of u, v, w, p, q and r in equations (30) and (32) are equated to the identical coefficients, comprising the added mass matrix, in equation (26) and hence the contributions of each wetted sector to all 36 of the added mass derivatives are obtained. The total added mass matrix is formed by summing the individual contributions from each segment of the body.

The solution of the equations of motion

31. Noting that $\frac{d\mathbf{M}}{dt}$ and $\frac{d\mathbf{H}}{dt}$ contain the rates of change of the added masses in addition to acceleration terms, the total forces and moments both due to the

added mass effects, equations (27) and (28), and due to the steady state pressures, equations (19), (23) and (25), are summed linearly and substituted into the equations of motion, equation (6), which may then be expressed in the form:-

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} du \\ dv \\ dw \\ dp \\ dq \\ dr \end{bmatrix} = \begin{bmatrix} B \end{bmatrix} dt + \begin{bmatrix} C \end{bmatrix} \quad (33)$$

where A is a six by six matrix defining the total inertias of the system, B is a six by one matrix defining the steady state external forces and C is a six by one matrix defining the changes of momentum which have occurred during the time interval, dt. The equations of motion are expressed with dt as a multiplicand in order that the stable numerical integration of these equations may be performed through the indeterminate accelerations associated with the wetting of an incompressible body by an incompressible liquid.

32. At each cycle of the numerical integration of the equations of motion the six simultaneous linear equations (33) are solved to yield the velocity increments from which the linear and angular velocities of the body are updated. In addition the orientation and position in space (x_o, y_o, z_o) of the body are obtained by integrating the kinematic relationships:-

$$\dot{\underline{e}} = \frac{1}{2} \begin{bmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{bmatrix} \underline{e} \quad (34)$$

and

$$\begin{bmatrix} \dot{x}_o \\ \dot{y}_o \\ \dot{z}_o \end{bmatrix} = \begin{bmatrix} T \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \quad (35)$$

Discussion of the numerical simulation

33. A FORTRAN program which generates and integrates equations 33, 34 and 35 is listed in the appendix.

34. This program requires the shape of the body and the added mass distribution to be supplied as input data. The added mass distribution is somewhat subjective, however it is helpful to consider some examples which will assist in estimating the added mass distribution parameter, h. Lamb (Ref 6, p 144) indicates that on each side of a flat disc the added mass distribution is given by:-

$$h = \frac{2}{\pi} (R^2 - R_h^2)^{\frac{1}{2}} \quad (36)$$

where R is the radius of the disc and R_h is the radial position at which h is defined. On p.155 of the same reference it is shown that:-

$$h = R/2 \quad (37)$$

for a sphere of radius R and that

$$h = R \quad (38)$$

for the sides of a long cylinder of radius R .

35. In addition to the basic model described in the previous paragraphs the simulation also includes the effects of a horizontal steady wind and a simple sea motion. It is assumed that the body is small compared to velocity gradients in the sea and that the sea velocity potential, ϕ , may be represented by (Ref 6):-

$$\phi = ac \exp(-wz_0) \cos w(x_0 - ct) \quad (39)$$

where a is the wave amplitude, c is the wave celerity, and w is the wave frequency. Typical values of a , c and w are tabulated by Lofft and Price (Ref 7).

36. The model allows the addition of cruciform tail fins and/or a shroud ring tail. These tail surfaces are assumed to have a linear relationship between force and incidence at small angles of incidence.

37. The underpressure effect which occurs during the initial period of oblique water entry is represented in the simulation by a local pressure reduction in the cavity on the underside of the nose of the body.

38. It was experimentally observed that the tail, when in contact with the cavity wall, experiences an upward force which is thought to be due to the gravity effect described by Knapp, Daily and Hammitt (Ref 3, p.251). This effect is represented in the simulation by an additional upward velocity field superimposed on the rear of the cavity at low Froude numbers.

39. When the body is fully surrounded by a single fluid, before impact or after deep cavity collapse, then the external forces on the body are represented by force derivatives in the usual way (eg Ref 8, p.196).

40. The simulation has a provision for the shape of the body to change after a prescribed amount of kinetic energy has been dissipated during water entry. This facility may be used to represent a frangible nose cap.

41. The simulation, as listed, will not be valid for body angles of incidence greater than about 135° as any axial cavity from the tail will not be modelled correctly.

42. The mathematical model described on the previous pages may be applied to an axisymmetric parachute. The simulation listed in the appendix allows a parachute to be attached to the body via elastic rigging lines.

43. The additional forces applied by the rigging lines to both the parachute and the body are obtained by deriving the strain and strain rate of each line

from the known position and velocity of the body relative to the parachute. The equations of motion of the body and of the parachute are then evaluated independently.

44. In the previous paragraphs the principles of the water entry simulation were described. The reader who wishes to explore the detailed implementation of these principles may do so by studying the appendix.

THE EXPERIMENTAL MEASUREMENTS

45. The difficulties associated with scaling water entry behaviour are discussed by Knapp, Daily and Hammitt (Ref 3, p.548). In view of the many uncertainties associated with extrapolating small scale model measurements up to full scale the experimental measurements required to improve and validate the mathematical model were carried out at full scale.

46. An instrumentation system, designed to record the motion of the body and described by Coman (Ref 9), was fully contained within the dummy torpedo and comprised, three rate gyroscopes to measure the angular velocity vector, three accelerometers to measure the linear acceleration vector, and a solid state digital recorder. The trajectory of the body was obtained by integrating the recorded angular velocity and linear acceleration as described by Coman (Ref 10). The sensor signals were also recorded for a ten second period before release and this data was filtered to provide the attitude of the body at release for the initial conditions of the attitude integration. The initial conditions for the velocity integration were measured optically.

47. In order to isolate the influence of the parachute and determine the characteristics of the body alone the first set of measurements were carried out by projecting the dummy torpedo alone, without any parachute, into the sea. A second series of measurements were then made with parachutes, the torpedo and parachute being released from a helicopter. It was interesting to note that by commencing with the buoyant dummy torpedo, assumed stationary, on the sea surface at the end of a drop and then integrating the measured motion backwards through water entry and through the flight in air it was possible to determine the velocity of the delivery aircraft and that this value agreed within 1 m/sec with the optically measured aircraft velocity.

MODEL VALIDATION

48. Some typical results of the experimental measurements along with the predictions of the simulation are shown in figures 6, 7 and 8. The body's pitch angle, θ , in degrees and axial component of velocity, u , in metres per second are both plotted against time in these figures.

49. Figure 6 shows the water entry behaviour of the bare torpedo projected into a calm sea at approximately 30 m/sec, at a trajectory angle of 20° below the horizontal, and with zero incidence to this trajectory. Water impact occurs at approximately 0.3 seconds and during the initial phases of water entry a nose down rate of turn is imparted to the body by the reduced pressure region under the nose. At approximately 0.6 seconds the tail hits the top of the cavity, in this region the simulation diverges a little from the measurements however this particular tail slapping behaviour was found to be not experimentally repeatable in detail.

50. In the drops described in figures 7 and 8 the torpedo was fitted with a parachute. In figure 7 a conical ribbon parachute of approximately 2 metres flying diameter fitted with 7.0 metres long rigging lines was employed, the

torpedo was released at a height of 225 metres above sea level, water impact occurred approximately 9.5 seconds after release, and the pitch angle at impact is almost vertical. In figure 8 a ringshot parachute of 2 metres flying diameter fitted with 3.5 metres long rigging lines was used, the torpedo was released at a height of 60 metres, water impact occurred approximately 4 seconds after release and the pitch angle at impact is about 55 degrees.

51. In figures 7 and 8 and, indeed, in all of the parachute drops which were made it was found that the simulation predicted higher frequencies of oscillation of the body in air than were observed. It was not possible to offer a satisfactory explanation for this inaccuracy of the simulation.

52. All of the measurements which were carried out in support of the mathematical model described in this note were at impact velocities of between 20 and 40 m/sec, however a limited amount of work was carried out to compare the simulation with the 150 m/sec entry velocity full scale measurements described by Waugh and Stubstad (Ref 1, chap 5). At this higher impact velocity it is to be expected that the influence of the underpressure effect will be reduced. Head shapes 'a', 'g', 'l' and 'n' were simulated and good agreement with the water entry whip (Ref 1, fig 5.9) and with the zero cavitation number drag coefficient (Ref 1, fig 5.11) were obtained indicating that this simulation may be applicable to a wide range of impact velocities.

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53. Grateful acknowledgement is made to the staff of AUWE, Helston, and of AMTE, Glen Fruin, who assisted in carrying out the measurements.

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FORTRAN LISTING OF WATER ENTRY SIMULATION

S.I. UNITS ARE USED
 LENGTH IN METRES
 TIME IN SECONDS
 FORCE IN NEWTONS
 MASS IN KILOGRAMS
 ANGLE IN RADIANS

THE PRINCIPAL VARIABLES IN THIS PROGRAMME ARE:-

NAME OF VARIABLE	DESCRIPTION
BODY	PARACHUTE
VBOD(1)	VPAR(1) U)
VBOD(2)	VPAR(2) V) COMPONENTS OF LINEAR VELOCITY
VBOD(3)	VPAR(3) W)
VBOD(4)	VPAR(4) P)
VBOD(5)	VPAR(5) Q) COMPONENTS OF ANGULAR VELOCITY
VBOD(6)	VPAR(6) R)
VBOD(7)	VPAR(7) E0)
VBOD(8)	VPAR(8) E1) QUATERNION ATTITUDE REPRESENTATION
VBOD(9)	VPAR(9) E2)
VBOD(10)	VPAR(10) E3)
VBOD(11)	VPAR(11) X)
VBOD(12)	VPAR(12) Y) POSITION OF C.G. IN SPACE
VBOD(13)	VPAR(13) Z)
XBOD	XPAR)
YBOD	YPAR) TRANSFORMATION MATRIX
ZBOD	ZPAR)
ADMBOD	ADMPAR (THE FIRST 6 COLUMNS IS THE MASS MATRIX
	(THE 7TH COLUMN IS THE EXTERNAL FORCES
BDMBOD	BDMPAR OLD VALUES OF ADMBOD AND ADMPAR
PWBOD(1)	PWPAR(1) X/U2)
PWBOD(2)	PWPAR(2) Y/V)
PWBOD(3)	PWPAR(3) Y/R)
PWBOD(4)	PWPAR(4) M/W) IN WATER FORCE DERIVATIVES
PWBOD(5)	PWPAR(5) M/Q)
PWBOD(6)	PWPAR(6) X/UDOT)
PWBOD(7)	PWPAR(7) Y/VDOT) *****NOTE*****
PWBOD(8)	PWPAR(8) Y/RDOT) P****(4)=M/W EXCLUDES PERFECT
PWBOD(9)	PWPAR(9) N/RDOT) FLUID MOMENT WHICH IS CALCULATED
PWBOD(10)	PWPAR(10) Y/V2) IN SUBROUTINE ENERT
PWBOD(11)	PWPAR(11) Y/RV) I.E.P(4)=M/W(TOTAL)+X/UDOT-Y/VDOT
PWBOD(12)	PWPAR(12) M/W2)
PWBOD(13)	PWPAR(13) M/QW)
PWBOD(14)	PWPAR(14) MASS OF DISPLACED FLUID
PWBOD(15)	PWPAR(15) (DISPLACED MASS)*(X CO-ORD OF C.B.)
PWBOD(16)	PWPAR(16) K/P ROLL DAMPING
PABOD	PAPAR IN AIR EQUIVALENT TO PWBOD,PWPAR
	PAPBR FULLY DEPLOYED VALUES OF PAPAR
	PWPBR FULLY DEPLOYED VALUES OF PWPAR


```

      READ(1,20)SEAA
C      SEA WAVE FREQUENCY(1/METRES)
      READ(1,20)SEAW
C      SEA WAVE CELERITY(M./SEC)
      READ(1,20)SEAC
C      UNIT VECTOR IN DIRECTION OF SEAC
      READ(1,20)COMX
      READ(1,20)COMY
20     FORMAT(F13.5)
21     FORMAT(2F13.5)
      DO30I=1,16
C      BODY FORCE DERIVATIVES
30     READ(2,21)FABOD(I),FWBOD(I)
C      (TAIL IN CAVITY LIFT COEFFICIENT)*0.5
      READ(2,20)CLBOD
C      (BODY IN CAVITY DRAG COEFFICIENT)*0.5
      READ(2,20)CDBOD
C      MASS OF BODY
      READ(2,20)PMBOD
C      Y CO-ORD OF BODY C.G.
      READ(2,20)PYBOD
C      Z CO-ORD OF BODY C.G.
      READ(2,20)PZBOD
C      BODY AXIAL MOMENT OF INERTIA
      READ(2,20)PIXBOD
C      BODY TRANSVERSE MOMENT OF INERTIA
      READ(2,20)PIYBOD
C      MAXIMUM BODY RADIUS
      READ(2,20)BODRAD
C      X CO-ORD OF POINT OF ATTACHMENT OF PARACHUTE
      READ(2,20)BODTL
C      MEASURE OF ENERGY TO DESTROY NOSE CAP
      READ(2,20)PIMP
      TRAV=0.0
      IFIMP=1
      T=0.0
      FPOINT=TMAX/POINUM
      IFIRST=1
      ISECON=1
      DO75I=1,6
      DO75J=1,6
      BDMFAR(I,J)=0.0
75     BDMBOD(I,J)=0.0
58     NBOD=0
C      BODY GEOMETRY TEM2=X CO-ORD, TEM4=RADIUS,
C      TEM8=ADDED MASS HEIGHT
C      I1=0 AND J1=1 ORDINARY BUOYANT SECTION
C      I1=1 AND J1=1 FLOODED SECTION EG PARACHUTE CONTAINER
C      I1=1 AND J1=0 CRUCIFORM TAIL
C      I1=0 AND J1=0 SHROUD RING TAIL
C      SET TEM4=-1.0 AT END OF COMPLETE BODY DATA BLOCK
C      TWO DATA BLOCKS ARE REQUIRED FIRST WITH NOSE CAP
C      SECOND WITHOUT NOSE CAP
C      IF PIMP<=0.0 THE FIRST BLOCK IS IRRELEVANT
60     READ(2,62)TEM2,TEM4,TEM8,I1,J1

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```

62  FORMAT(3F13.5,2I2)
    IF(TEM4.LT.-0.1)GOTO200
    IF(I1.NE.I.OR.J1.NE.J)GOTO67
    TEM5=TEM1-TEM2
    TEM6=TEM4-TEM3
    TEM7=SQRT(TEM5*TEM5+TEM6*TEM6)
    IF((TEM5/TEM7).GT.0.002)GOTO65
    TEM5=0.002*ABS(TEM6)
    TEM7=SQRT(TEM5*TEM5+TEM6*TEM6)
65  NBOD=NBOD+1
    XAXBOD(NBOD)=(TEM1+TEM2)/2.0
    RADBOD(NBOD)=(TEM3+TEM4)/2.0
    HTTBOD(NBOD)=(TEM8+TEM9)/2.0
    DAXBOD(NBOD)=TEM5
    SINBOD(NBOD)=TEM6/TEM7
    COSBOD(NBOD)=TEM5/TEM7
    ISW1BOD(NBOD)=I1
    ISW2BOD(NBOD)=J1
67  I=I1
    J=J1
    TEM1=TEM2
    TEM3=TEM4
    TEM9=TEM8
    GOTO60
6000 ISECON=0
C    PARACHUTE INITIAL CONDITIONS
    VPAR(1)=VBOD(1)
    VPAR(2)=VBOD(2)+BODTL*VBOD(6)
    VPAR(3)=VBOD(3)-BODTL*VBOD(5)
    DO6050I=4,10
6050 VPAR(I)=VBOD(I)
    VPAR(11)=VBOD(11)+BODTL*XBOD(1)
    VPAR(12)=VBOD(12)+BODTL*XBOD(2)
    VPAR(13)=VBOD(13)+BODTL*XBOD(3)
C    SY:WEFF.DAT CONTAINS THE DESCRIPTION OF THE PARACHUTE
    CALL ASSIGN(4,'SY:WEFF.DAT',0,'OLD','NC',1)
C    NUMBER OF SHROUD LINES
    READ(4,50)NSHD
50  FORMAT(I2)
C    TORSIONAL STIFFNESS OF SHROUD LINE SYSTEM
    READ(4,20)TWIST
C    LENGTH OF EACH SHROUD LINE
    READ(4,20)TLFL
C    TEAR STRIP YIELD LOAD
    READ(4,20)TLFT
C    TEAR STRIP EXPIRED LENGTH + TLFL
    READ(4,20)TLFTL
C    TEAR STRIP BREAKING LOAD
    READ(4,20)TLFF
C    TLFA,TLFB,TLFC,TLFF DESCRIBE SHROUD LINE STRESS/STRAIN
C    CHARACTERISTIC SEE 7000
    READ(4,20)TLFA
    READ(4,20)TLFB
    READ(4,20)TLFC
    READ(4,20)TLFF

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C      IN WATER VALUE OF TLFC
      READ(4,20)TLCWET
C      IN WATER VALUE OF TLFP
      READ(4,20)TLPWET
C      SHROUD LINE BREAKING LOAD
      READ(4,20)TLFBR
C      RATE OF DEPLOYMENT PARAMETER
      READ(4,20)SDLPAR
      DO2030I=1,16
C      PARACHUTE FORCE DERIVATIVES
2030  READ(4,21)PAPBR(I),PWPBR(I)
C      PARACHUTE ADDED MASS HEIGHT
      READ(4,20)HTPAR
C      PARACHUTE PARTIALLY WET DRAG COEFFICIENT*0.5
      READ(4,20)CDPAR
C      MASS OF PARACHUTE
      READ(4,20)PMPAR
C      PARACHUTE AXIAL MOMENT OF INERTIA
      READ(4,20)PIXPAR
C      PARACHUTE TRANSVERSE MOMENT OF INERTIA
      READ(4,20)PIYPAR
C      MAXIMUM RADIUS OF FULLY DEPLOYED PARACHUTE
      READ(4,20)PBRRAD
C      X CO-ORD OF POINT OF ATTACHMENT OF SHROUD LINES TO CANOPY
      READ(4,20)PARTL
C      RADIUS OF PARACHUTE AT RELEASE AS FRACTION OF PBRRAD
      READ(4,20)SCLMIN
C      RADIUS OF DROGUE AS FRACTION OF PBRRAD
      READ(4,20)SCLMAX
C      RADIUS OF REEFED PARACHUTE AS FRACTION OF PBRRAD
      READ(4,20)SCL2
      NPAR=0
C      FULLY DEPLOYED PARACHUTE GEOMETRY TEM1=X CO-ORD, TEM3=RADIUS
      READ(4,2002)TEM1,TEM3
2000  READ(4,2002)TEM2,TEM4
2002  FORMAT(2F13.5)
      IF(TEM4,LT,-0.1)GOTO2060
      TEM5=TEM1-TEM2
      TEM6=TEM4-TEM3
      TEM7=SQRT(TEM5*TEM5+TEM6*TEM6)
      IF((TEM5/TEM7).GT.0.002)GOTO2005
      TEM5=0.002*ABS(TEM6)
      TEM7=SQRT(TEM5*TEM5+TEM6*TEM6)
2005  NPAR=NPAR+1
      XAXPAR(NPAR)=(TEM1+TEM2)/2.0
      RADPAR(NPAR)=(TEM3+TEM4)/2.0
      DAXPAR(NPAR)=TEM5
      SINPAR(NPAR)=TEM6/TEM7
      COSPAR(NPAR)=TEM5/TEM7
      TEM1=TEM2
      TEM3=TEM4
      GOTO2000
2060  SHIANG=6.283185/LOAT(NSHD)
      DO2065I=1,NSHD
2065  ISHD(I)=0

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20.

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SCLPAR=SCLMIN
DT=0.0
GOTO6005
C   FROM 200 TO 1500 IS FORCES ON BODY
C   TEST FOR PRESENCE OF NOSE CAP
200 IF(IPIMP.EQ.0)GOTO202
   IF(TRAU*VEL2.LT.PIMP)GOTO202
   IPIMP=0
   GOTO58
202 DO205I=1,6
   DO205J=1,7
   ADMFAR(I,J)=0.0
205 ADMBOD(I,J)=0.0
   CALL XYZ(VBOD,XBOD,YBOD,ZBOD)
   CALL SEA(WATER,XBOD,YBOD,ZBOD,VBOD(11),VBOD(12),VBOD(13))
C   DEPTH OF EXTREMITIES OF BODY
   DEF=SURECG-XAXBOD(1)*DURECG
   TEM2=SURECG-XAXBOD(NBOD)*DURECG
   DEFME=(DEF+TEM2)/2.0
   TEM7=BODRAD*SQTEM1
   TEM3=DEF-TEM7
   TEM4=TEM2-TEM7
   TEM1=DEF+TEM7+BODRAD
   TEM2=TEM2+TEM7+BODRAD
C   FIRST ESTIMATE OF TIME INCREMENT
   DT=BODRAD/SQRT(VBOD(1)*VBOD(1)+VBOD(2)*VBOD(2)+VBOD(3)*VBOD(3))
   IF(DT.GT.0.02)DT=0.02
   IF(DEFME.GT.0.0)GOTO208
C   RELATIVE MOTION FIELD IN AIR
   RBOD(1)=VBOD(1)-WINDX*XBOD(1)-WINDY*XBOD(2)
   RBOD(2)=VBOD(2)-WINDX*YBOD(1)-WINDY*YBOD(2)
   RBOD(3)=VBOD(3)-WINDX*ZBOD(1)-WINDY*ZBOD(2)
   RBOD(4)=-9.81*XBOD(3)
   RBOD(5)=-9.81*YBOD(3)
   RBOD(6)=-9.81*ZBOD(3)
   CALL HYDRO(ADMBOD,PABOD,VBOD,RBOD)
   IF(T.LT.TRELAN)ADMBOD(5,7)=ADMBOD(5,7)+TORLAN
   IF(TEM1.GT.0.0.OR.TEM2.GT.0.0)GOTO210
C   BODY IS FULLY IN AIR
   PCAV=101000.0
   TRAU=0.0
   IIM=0
   GOTO400
208 IIM=1
C   RELATIVE MOTION FIELD IN WATER
210 RBOD(1)=VBOD(1)-WATER(1)*XBOD(1)-WATER(2)*XBOD(2)-WATER(3)*XBOD(3)
   RBOD(2)=VBOD(2)-WATER(1)*YBOD(1)-WATER(2)*YBOD(2)-WATER(3)*YBOD(3)
   RBOD(3)=VBOD(3)-WATER(1)*ZBOD(1)-WATER(2)*ZBOD(2)-WATER(3)*ZBOD(3)
   RBOD(4)=WATER(4)*XBOD(1)+WATER(5)*XBOD(2)+(WATER(6)-9.81)*XBOD(3)
   RBOD(5)=WATER(4)*YBOD(1)+WATER(5)*YBOD(2)+(WATER(6)-9.81)*YBOD(3)
   RBOD(6)=WATER(4)*ZBOD(1)+WATER(5)*ZBOD(2)+(WATER(6)-9.81)*ZBOD(3)
C   OBTAIN CAVITATION NUMBER
   V2W2=RBOD(2)*RBOD(2)+RBOD(3)*RBOD(3)
   VEL2=V2W2+RBOD(1)*RBOD(1)
   FAMB=10100.0*WDEF

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IF(FCAV.EQ.0.0)GOTO216
FCAV=FAMB-TRAV*300.0/BODRAD
IF(FCAV.LT.0.0)PCAV=0.0
FAMB=FAMB-PCAV
216 CAV=FAMB/(515.0*VEL2)
IF(TEM3.LT.0.0.OR.TEM4.LT.0.0)GOTO240
C BODY IS FULLY IMMERSED IN WATER
IF(CAV.LT.0.3)GOTO250
C THERE IS NO CAVITY
CALL HYDRO(ADMBOD,FWBOD,VBOD,VBOD,VBOD)
TRAV=9999.0
PCAV=0.0
GOTO400
C BODY IS PARTIALY WET
240 DT=DT/5.0
250 ICROS=1
ICS=0
IUP=0
SINMAX=SQRT(V2W2/VEL2)
IF(DEPME.GT.0.0)CALL HYDRO(ADMBOD,PAROD,VBOD,VBOD,VBOD)
IF(IIM.EQ.0.OR.FCAV.EQ.0.0)GOTO256
C TRAV=DISTANCE TRAVELLED AFTER IMPACT
TEM8=VBOD(11)-TORX
TEM9=VBOD(12)-TORY
TEM10=VBOD(13)-TORZ
TRAV=SQRT(TEM8*TEM8+TEM9*TEM9+TEM10*TEM10)
C CALCULATE UNDERPRESSURE
256 DUNPE=101000.0*(1.0-(0.2-0.07*XBOD(3))*TRAV/BODRAD)
C CALCULATE FORCES AND ADDED MASSES FOR EACH BODY SEGMENT
DO1500J=1,NBOD
ITES=0
XAX=XAXBOD(J)
RAD=RADBOD(J)
DAX=DAXBOD(J)
SINA=SINBOD(J)
COSA=COSEBOD(J)
ISW1=ISW1BOD(J)
ISW2=ISW2BOD(J)
PROT=VBOD(4)
BODU=RBOD(1)
BODV=RBOD(2)+XAX*VBOD(6)
BODW=RBOD(3)-XAX*VBOD(5)
IF(IUP.EQ.0.OR.XAX.GT.CGOUF)GOTO1110
C UPWARD VELOCITY ON REAR OF CAVITY
TEM1=(CGOUF-XAX)/CAVUP
IF(TEM1.GT.1.0)TEM1=1.0
BODV=BODV+TEM1*UPVEL
BODW=BODW+TEM1*UPWEL
1110 BOFU=BODU*SINA
BOFV=BODV*COSA-RAD*VBOD(6)*SINA
BOFW=BODW*COSA+RAD*VBOD(5)*SINA
CALL DEPTH
IF(IDRY.EQ.1)GOTO1500
IF(IIM.EQ.1)GOTO1120
C SET UP IMPACT POSITION

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IIM=1
TORX=VBOD(11)
TORY=VBOD(12)
TORZ=VBOD(13)
C      IF ICROS=1 AXIAL ELLIPSOID CAVITY NOT FORMED
C      IF ICROS=0 AXIAL ELLIPSOID CAVITY EXISTS
1120  IF(ICROS.EQ.0)GOTO1170
      IF(ISW2.EQ.0)GOTO1150
C      TEST SEGMENT FOR CAVITATION
C      BET1C TO BET2C WILL BE THE WETTED SECTOR OF THE SEGMENT
1130  TEM7=BODV*BODV+BODW*BODW
      U2V2W2=TEM7+BODU*BODU
      IF(PCAV.GT.0.0)GOTO1132
      PAMB=10100.0*(WDEF-XAX*RBOD(4)/9.81)
1132  CAUSEG=PAMB/(515.0*U2V2W2)
      IF(CAUSEG.GT.1.0)GOTO1150
      IF(CAUSEG.LT.0.001)CAUSEG=0.001
      TEM6=SQRT(U2V2W2)
      TEM27=SQRT(TEM7)
      TEM1=COSA*TEM27
      TEM4=(BOFU+TEM1)/TEM6
      IF(SINMAX.LT.TEM4)SINMAX=TEM4
      J1=J-1
      IF(J.EQ.1)J1=1
C      CALCULATE INCIDENCE CONDITION FOR CAVITATION
      TEM28=RAD*(SINBOD(J1)*COSA-COSBOD(J1)*SINA)
      TEM28=TEM28*(COSBOD(J1)+COSA)/(DAXBOD(J1)+DAX)
      TEM2=0.25*TRAV/RAD
      IF(TEM2.GT.0.76)TEM2=0.76
      TEM2=TEM2*(0.2+0.8*SINMAX*SINMAX)
      CONINC=TEM2*SINMAX-0.34*EXP(-TEM28)-0.36*CAUSEG+0.28*TEM7/U2V2W2
      TEM2=CONINC*TEM6
      IF((BOFU+TEM1).GT.TEM2)GOTO1140
C      SEGMENT IS ALL DRY
C      CALCULATE GEOMETRY OF AXIAL CAVITY IF PRESENT
      TEM2=TEM27/TEM6
      TEM3=ABS(BODU)/TEM6
      TEM4=TEM3-ABS(TEM2*SINA/COSA)
      IF(TEM4.LE.0.0)GOTO1400
      TEM1=RAD/TEM4
      CAVA=0.4*SINMAX*(1.0+TEM28)*TEM1/CAUSEG
      CAVB=TEM1+0.13*CAVA
      TEM9=1/5*TEM1+0.09*TRAV
      IF(TEM9.LT.CAVB)CAVB=TEM9
      ICS=0
      IF((CAVA+CAVB).LT.TRAV)GOTO1135
      CAVA=0.84*TRAV
      CAVC=0.21*TRAV
      ICS=1
1135  IF(CAVA.LE.0.0)GOTO1400
C      FIT CAVITY TO NOSE
      TEM4=TEM1/CAVB
      CXOR=CAVA*SQRT(1.0-TEM4*TEM4)
      TEM4=TEM4*CAVA*CAVA/CAVB
      TEM5=CXOR/SQRT(CXOR*CXOR+TEM4*TEM4)

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TEM4=TEM2*COXA+ABS(TEM3*SINA)
IF(TEM5.LE.TEM4)GOTO1400
CAVY=-BODV/TEM6
CAVZ=-BODW/TEM6
CGOR=CXOR-XAX
XAXOR=XAX
SQVYZ=SQRT(CAVY*CAVY+CAVZ*CAVZ)
ATVZY=ATAN2(CAVZ,CAVY)
ICRS=0
IF(XAX.LT.0.0.OR.ICRS.EQ.1)GOTO1400
C      UPWARD VELOCITY ON REAR OF CAVITY
CGOR=-CGOR
CAVUP=CAVA
IUP=1
UPVEL=-TEM6*(0.005*RBOD(5)+SIGN(0.025,RBOD(5)))
UPWEL=-TEM6*(0.005*RBOD(6)+SIGN(0.025,RBOD(6)))
IF(ABS(XBOD(3)).LT.0.96)GOTO1400
UPVEL=TEM6*SIGN(0.025,VBOD(6))
UPWEL=-TEM6*SIGN(0.025,VBOD(5))
GOTO1400
1140 IF((BOFU-TEM1).GE.TEM2)GOTO1150
C      SEGMENT IS PARTIALLY WET BY CAVITATION CONDITION
TEM2=(TEM2-BOFU)/TEM1
TEM1=ATAN2(BODV,BODW)
TEM3=SQRT(1.0-TEM2*TEM2)
TEM4=ATAN2(TEM2,TEM3)
BET1C=TEM4-TEM1
BET2C=3.1416-TEM4-TEM1
GOTO1200
C      SEGMENT IS COMPLETELY WET BY CAVITATION CONDITION
1150 BET1C=0.0
BET2C=6.2831
ITES=1
GOTO1200
C      TEST FOR INTERSECTION WITH CAVITY
1170 TEM1=CGOR+XAX
TEM8=CAVA
IF(TEM1.GT.0.0.OR.ICRS.EQ.0)GOTO1175
TEM8=CAVC
1175 TEM1=TEM1/TEM8
TEM1=TEM1*TEM1
IF(TEM1.GE.1.0)GOTO1180
CAVR=CAVB*SQRT(1.0-TEM1)
CAVD=ABS(XAXOR-XAX)*SQVYZ
TEM1=CAVR+RAD
IF(CAVD.GE.TEM1)GOTO1180
TEM1=CAVR-RAD
IF(CAVD.LE.TEM1)GOTO1400
TEM1=-TEM1
IF(CAVD.LE.TEM1)GOTO1180
TEM1=(CAVD*CAVD+RAD*RAD-CAVR*CAVR)/(2.0*CAVD*RAD)
TEM2=SQRT(1.0-TEM1*TEM1)
TEM3=ATAN2(TEM2,TEM1)
BET1C=ATVZY+TEM3
BET2C=ATVZY-TEM3

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      GOTO1200
1180  IF(ISW2.EQ.0)GOTO1150
      ICROS=1
      SINMAX=SQRT(V2W2/VEL2)
      GOTO1130
1200  CALL FORCES(ADMBOD,RROD,HTTBOD(J),CLBOD,CDBOD)
      IF(ICROS.EQ.1.AND.ICS.EQ.0)GOTO1500
1400  IF(IDEF.EQ.1.OR.DUNPE.LT.0.0.OR.ISW2.EQ.0)GOTO1500
      C    UNDERPRESSURE FORCE
      TEM4=DUNPE*DAX*RAD
      TEM1=TEM4*(COS(BET1D)-COS(BET2D))
      TEM2=TEM4*(SIN(BET2D)-SIN(BET1D))
      TEM3=XAX-RAD*SINA/COSA
      ADMBOD(2,7)=ADMBOD(2,7)+TEM2
      ADMBOD(3,7)=ADMBOD(3,7)+TEM1
      ADMBOD(5,7)=ADMBOD(5,7)-TEM3*TEM1
      ADMBOD(6,7)=ADMBOD(6,7)+TEM3*TEM2
1500  CONTINUE
400   IF(ISECON.EQ.1)GOTO5500
      C    UP TO 4500 IS FORCES ON PARACHUTE
      CALL XYZ(VPAR,XPAR,YPAR,ZPAR)
      CALL SEA(WATER,XPAR,YPAR,ZPAR,VPAR(11),VPAR(12),VPAR(13))
      C    DEPTH OF EXTREMITIES OF PARACHUTE
      DEF=SURECO-XAXPAR(1)*DIURECG
      TEM2=SURECG-XAXPAR(NPAR)*DIURECG
      TEM7=FARRAD*SQRT(TEM1)
      TEM1=DEF+TEM7
      TEM13=DEF-TEM7
      TEM14=TEM2-TEM7
      DEFME=(TEM1+TEM14)/2.0
      IF(DEFME.GT.0.0)GOTO3210
      C    RELATIVE MOTION FIELD IN AIR
      RPAR(1)=VPAR(1)-WINDX*XPAR(1)-WINDY*XPAR(2)
      RPAR(2)=VPAR(2)-WINDX*YPAR(1)-WINDY*YPAR(2)
      RPAR(3)=VPAR(3)-WINDX*ZPAR(1)-WINDY*ZPAR(2)
      RPAR(4)=-9.81*XPAR(3)
      RPAR(5)=-9.81*YPAR(3)
      RPAR(6)=-9.81*ZPAR(3)
      CALL HYDRO(ADMPAR,PAFAR,VPAR,RPAR)
      IF(TEM1.LT.0.0)GOTO3400
      C    PARACHUTE COULD BE WET
      C    RELATIVE MOTION FIELD IN WATER
3210  RPAR(1)=VPAR(1)-WATER(1)*XPAR(1)-WATER(2)*XPAR(2)-WATER(3)*XPAR(3)
      RPAR(2)=VPAR(2)-WATER(1)*YPAR(1)-WATER(2)*YPAR(2)-WATER(3)*YPAR(3)
      RPAR(3)=VPAR(3)-WATER(1)*ZPAR(1)-WATER(2)*ZPAR(2)-WATER(3)*ZPAR(3)
      RPAR(4)=WATER(4)*XPAR(1)+WATER(5)*XPAR(2)+(WATER(6)-9.81)*XPAR(3)
      RPAR(5)=WATER(4)*YPAR(1)+WATER(5)*YPAR(2)+(WATER(6)-9.81)*YPAR(3)
      RPAR(6)=WATER(4)*ZPAR(1)+WATER(5)*ZPAR(2)+(WATER(6)-9.81)*ZPAR(3)
      IF(TEM13.GT.0.0.AND.TEM14.GT.0.0.AND.CAV.GT.0.3)GOTO3240
      C    PARACHUTE COULD BE PART WET
      C    SET UP TEST FOR INTERSECTION WITH CAVITY FROM BODY
      IF(ICROS.EQ.0)GOTO3220
      IF(CAV.LT.0.001)CAV=0.001
      CAVA=2.0*BODRAD/CAV
      CAVB=BODRAD+0.13*CAVA

```

```

3220 TEM1=TORX-VBOD(11)
    TEM2=TORY-VBOD(12)
    TEM3=TORZ-VBOD(13)
    TEM15=TEM1*XP(1)+TEM2*XP(2)+TEM3*XP(3)
    IF(TEM15.EQ.0.0)GOTO3230
    TEM4=VBOD(11)-V(11)
    TEM5=VBOD(12)-V(12)
    TEM6=VBOD(13)-V(13)
    TEM16=TEM4*XP(1)+TEM5*XP(2)+TEM6*XP(3)
    TEM17=-TEM16/TEM15
    IF(TEM17.LE.0.0)GOTO3230
    TEM18=SQRT(TEM1*TEM1+TEM2*TEM2+TEM3*TEM3)
    TEM1=TEM4+TEM1*TEM17
    TEM2=TEM5+TEM2*TEM17
    TEM3=TEM6+TEM3*TEM17
    CAVY=TEM1*Y(1)+TEM2*Y(2)+TEM3*Y(3)
    CAUZ=TEM1*Z(1)+TEM2*Z(2)+TEM3*Z(3)
    CAVD=SQRT(CAVY*CAVY+CAUZ*CAUZ)
    TEM1=1.0-TEM17*TEM18/CAV
    TEM1=TEM1*TEM1
    IF(TEM1.GE.1.0)GOTO3230
    CAVR=CAV*SQRT(1.0-TEM1)
    TEM1=CAVR+PARRAD
    IF(CAVD.GE.TEM1)GOTO3230
    TEM1=CAVR-PARRAD
    IF(CAVD.LE.TEM1)GOTO3225
    ATUZVY=ATAN2(CAUZ,CAVY)
    ICAV=1
    GOTO3250
3225 IF(DEPME.GT.0.0)CALL HYDRO(ADMPAR,PAPAR,V(1),RPAR)
    GOTO3400
3230 ICAV=0
    IF(TEM13.LT.0.0.OR.TEM14.LT.0.0)GOTO3250
C    PARACHUTE IS FULLY WET
3240 CALL HYDRO(ADMPAR,P(1),V(1),RPAR)
    GOTO3400
3250 IF(DEPME.GT.0.0)CALL HYDRO(ADMPAR,PAPAR,V(1),RPAR)
C    CALCULATE FORCES AND ADDED MASSES ON EACH SEGMENT
    ID04300J=1,NPAR
    ITES=0
    XAX=XAXPAR(J)
    RAD=SCLPAR*RADPAR(J)
    DAX=SCLPAR*DAXPAR(J)
    SINA=SINPAR(J)
    COSA=COSPAR(J)
    ISW1=1
    ISW2=1
    BODU=RPAR(1)
    BOFU=BODU*SINA
    TEM1=XAX*COSA-RAD*SINA
    LOFU=RPAR(2)*COSA+V(6)*TEM1
    BOFW=RPAR(3)*COSA-V(5)*TEM1
    CALL DEPTH
    IF(IDRY.EQ.1)GOTO4500
    IF(ICAV.EQ.0)GOTO4350

```

```

TEM1=CAVR+RAD
IF(CAVD.GE.TEM1)GOTO4350
TEM1=CAVR-RAD
IF(CAVD.LE.TEM1)GOTO4500
TEM1=-TEM1
IF(CAVD.LE.TEM1)GOTO4350
TEM1=(CAVD*CAVD+RAD*RAD-CAVR*CAVR)/(2.0*CAVD*RAD)
TEM2=SQRT(1.0-TEM1*TEM1)
TEM3=ATAN2(TEM2,TEM1)
RET1C=ATVZVY+TEM3
RET2C=ATVZVY-TEM3
GOTO4400
C    ALL WET BY CAVITY INTERSECTION
4350  RET1C=0.0
      RET2C=6.2831
      ITES=1
4400  CALL FORCES(ADMPAR,RPAR,HTPAR,0.0,CDPAR)
      TLFC=TLCWET
      TLFP=TLPWET
4500  CONTINUE
C    CALCULATE FORCES IN SHROUD LINES
C    FIRST OBTAIN BODY TO PARACHUTE TRANSFORMATION MATRIX
3400  S1=XBOD(1)*XPAR(1)+XBOD(2)*XPAR(2)+XBOD(3)*XPAR(3)
      S2=YBOD(1)*XPAR(1)+YBOD(2)*XPAR(2)+YBOD(3)*XPAR(3)
      S3=ZBOD(1)*XPAR(1)+ZBOD(2)*XPAR(2)+ZBOD(3)*XPAR(3)
      S4=XBOD(1)*YPAR(1)+XBOD(2)*YPAR(2)+XBOD(3)*YPAR(3)
      S5=YBOD(1)*YPAR(1)+YBOD(2)*YPAR(2)+YBOD(3)*YPAR(3)
      S6=ZBOD(1)*YPAR(1)+ZBOD(2)*YPAR(2)+ZBOD(3)*YPAR(3)
      S7=XBOD(1)*ZPAR(1)+XBOD(2)*ZPAR(2)+XBOD(3)*ZPAR(3)
      S8=YBOD(1)*ZPAR(1)+YBOD(2)*ZPAR(2)+YBOD(3)*ZPAR(3)
      S9=ZBOD(1)*ZPAR(1)+ZBOD(2)*ZPAR(2)+ZBOD(3)*ZPAR(3)
C    RELATIVE VELOCITY AND POSITION OF BODY W.R.T. PARACHUTE
      TEM1=VBOD(2)+VBOD(6)*BODTL
      TEM2=VBOD(3)-VBOD(5)*BODTL
      BODU=VBOD(1)*S1+TEM1*S2+TEM2*S3
      BODV=VBOD(1)*S4+TEM1*S5+TEM2*S6
      BODW=VBOD(1)*S7+TEM1*S8+TEM2*S9
      TEM1=VBOD(11)-VPAR(11)
      TEM2=VBOD(12)-VPAR(12)
      TEM3=VBOD(13)-VPAR(13)
      TLX=TEM1*XPAR(1)+TEM2*XPAR(2)+TEM3*XPAR(3)+BODTL*S1
      TLY=TEM1*YPAR(1)+TEM2*YPAR(2)+TEM3*YPAR(3)+BODTL*S4
      TLZ=TEM1*ZPAR(1)+TEM2*ZPAR(2)+TEM3*ZPAR(3)+BODTL*S7
C    CALCULATE AND SUM TENSIONS IN SHROUD LINES
7000  TFX=0.0
      TPY=0.0
      TPZ=0.0
      TEM12=-SHDANG
      DO7500I=1,NSHD
      TEM12=TEM12+SHDANG
      IF(ISHD(I).EQ.1)GOTO7450
C    EXTENSION OF LINE
      TEM1=TLX-PARTL
      TEM6=PARRAD*COS(TEM12)
      TEM2=TLY-TEM6

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```

TEM7=PARRAD*SIN(TEM12)
TEM3=TLZ-TEM7
TEM4=SQRT(TEM1*TEM1+TEM2*TEM2+TEM3*TEM3)
TEM5=TEM4-TLFL
IF(TEM5.LE.0.0)GOTO7500
C    RATE OF EXTENSION OF LINE
TEM8=BODU-(VPA(1)+VPA(5)*TEM7-VPA(6)*TEM6)
TEM9=BODU-(VPA(2)+VPA(6)*PARTL-VPA(4)*TEM7)
TEM10=BODU-(VPA(3)+VPA(4)*TEM6-VPA(5)*PARTL)
TEM1=TEM1/TEM4
TEM2=TEM2/TEM4
TEM3=TEM3/TEM4
C    TENSION IN LINE
TEM4=(TEM8*TEM1+TEM9*TEM2+TEM10*TEM3)*TLFC
TEM8=(TLFA+TLFB*TEM5)*TEM5
TEM9=TEM8*TLFF
IF(TEM4.GT.TEM9)TEM4=TEM9
IF(TEM4.LT.-TEM9)TEM4=-TEM9
TEM8=TEM8+TEM4
IF(TEM8.GT.TLFB)ISHD(I)=1
TPX=TPX+TEM8*TEM1
TPY=TPY+TEM8*TEM2
TPZ=TPZ+TEM8*TEM3
GOTO7500
7450  ITEM=0
C    AT LEAST ONE SHROUD LINE IS BROKEN
DO7455J=1,NSHD
7455  ITEM=ITEM+ISHD(J)
IF(ITEM.EQ.NSHD)GOTO7550
7500  CONTINUE
C    TEAR STRIP BEHAVIOUR
TEM1=SQRT(TPX*TPX+TPY*TPY+TPZ*TPZ)
IF(TEM1.LT.TLFT)GOTO7600
IF(TLFL.GT.TLFTL)GOTO7530
C    TEAR STRIP YIELDS
TLFL=1.001*TLFL
GOTO7000
7530  IF(TEM1.LT.TLFF)GOTO7600
C    PARACHUTE HAS BROKEN FREE FROM BODY
7550  TREL=10000.0
ISECON=1
GOTO5500
C    TORSIONAL TORQUE
7600  TEM2=TWA
IF(TEM2.GT.3.0)TEM2=3.0
IF(TEM2.LT.-3.0)TEM2=-3.0
TEM1=TEM1*TEM2*TWIST*SCLPAR*SCLPAR
C    ADD SHROUD LINE FORCES TO PARACHUTE AND BODY
ADMPAR(1,7)=ADMPAR(1,7)+TPX
ADMPAR(2,7)=ADMPAR(2,7)+TPY
ADMPAR(3,7)=ADMPAR(3,7)+TPZ
ADMPAR(4,7)=ADMPAR(4,7)+TEM1
ADMPAR(5,7)=ADMPAR(5,7)-TPZ*TLX+TPX*TLZ
ADMPAR(6,7)=ADMPAR(6,7)+TPY*TLX-TPX*TLY
TBX=-TPX*S1-TPY*S4-TPZ*S7

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    TBY=-TPX*S2-TPY*S5-TPZ*S8
    TBZ=-TPX*S3-TPY*S6-TPZ*S9
    ADMBOD(1,7)=ADMBOD(1,7)+TBX
    ADMBOD(2,7)=ADMBOD(2,7)+TBY
    ADMBOD(3,7)=ADMBOD(3,7)+TBZ
    ADMBOD(4,7)=ADMBOD(4,7)-TEM1*S1
    ADMBOD(5,7)=ADMBOD(5,7)-TBZ*BODTL-TEM1*S2
    ADMBOD(6,7)=ADMBOD(6,7)+TRY*BODTL-TEM1*S3
    CALL ENERT(ADMBOD,BDMBOD,RBOD,VBOD,DBOD,XBOD,YBOD,ZBOD,FMBOD,
1PYBOD,FZBOD,PIXBOD,PIYBOD,DT)
    CALL ENERT(ADMPAR,BDMPAR,RPAR,VPAR,DPAR,XPAR,YPAR,ZPAR,FMPAR,
10.0,0.0,PIXPAR,PIYPAR,DT)
    CALL DERIV(ADMBOD,VBOD,DBOD,XBOD,YBOD,ZBOD,DT)
    CALL DERIV(ADMPAR,VPAR,DPAR,XPAR,YPAR,ZPAR,DT)
C     PARACHUTE DEPLOYMENT
    SCLPAR=SCLPAR+SCLPAR*(RPAR(1)-ABS(RPAR(2))-ABS(RPAR(3)))*DT
    TWA=TWA+(VBOD(4)-VPAR(4))*DT
    IF(SCLPAR.GT.SCLMAX)SCLPAR=SCLMAX
    IF(SCLPAR.LT.SCLMIN)SCLPAR=SCLMIN
    IF(SCLOLD.EQ.SCLMAX.AND.SCLPAR.EQ.SCLMAX)GOTO5700
6005  TEM2=SCLPAR*SCLPAR
    DO6100I=1,16
    PAFAR(I)=PAFBR(I)*TEM2
6100  PWFAR(I)=PWFBR(I)*TEM2
    SCLOLD=SCLPAR
    PARRAD=SCLPAR*PBRRAD
    GOTO5700
C     BODY ALONE
5500  CALL ENERT(ADMBOD,BDMBOD,RBOD,VBOD,DBOD,XBOD,YBOD,ZBOD,FMBOD,
1PYBOD,FZBOD,PIXBOD,PIYBOD,DT)
    IF(IFIRST.EQ.0)GOTO5505
C     FIRST PASS THROUGH PROGRAMME TO SET UP BDMBOD ETC.
    IFIRST=0
    GOTO5705
5505  CALL DERIV(ADMBOD,VBOD,DBOD,XBOD,YBOD,ZBOD,DT)
C     INCREMENT TIME
5700  T=T+DT
C     CHECK PARACHUTE STATUS
    IF(T.GT.TREL.AND.ISECON.EQ.1)GOTO6000
    IF(T.GT.TREL1)SCLMAX=SCL2
    IF(T.GT.TREL2)SCLMAX=1.0
    IF(T.LT.POIT)GOTO200
C     OUTPUT A RECORD
C     THE WRITE STATEMENTS AND NEED TO CALL EULER SHOULD BE
C     VARIED AS REQUIRED
5705  POIT=T+POIDT
    CALL EULER(TEM1,TEM2,TEM3,XBOD,YBOD,ZBOD)
    IF(ISECON.EQ.1)GOTO5900
    CALL EULER(TEM4,TEM5,TEM6,XPAR,YPAR,ZPAR)
    WRITE(3,199)T,VBOD(1),VPAR(1),TEM2,TEM5,VBOD(11),VBOD(12),VBOD(13)
    WRITE(7,199)T,VBOD(1),VPAR(1),TEM2,TEM5,VBOD(11),VBOD(12),VBOD(13)
    GOTO5950
5900  WRITE(3,199)T,VBOD(1),0.0,TEM2,0.0,VBOD(11),VBOD(12),VBOD(13)
    WRITE(7,199)T,VBOD(1),0.0,TEM2,0.0,VBOD(11),VBOD(12),VBOD(13)
199   FORMAT(F9.4,7F10.3)

```

```

5950 IF(T.LT.TMAX)GOTO200
C      RUN COMPLETE
      WRITE(3,199)-1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0
      STOP
      END
      SUBROUTINE XYZ(V,X,Y,Z)
C      GENERATES THE TRANSFORMATION MATRIX X,Y,Z FROM QUATERNIONS
      DIMENSION V(13),X(3),Y(3),Z(3)
      X(1)=1.0-2.0*(V(9)*V(9)+V(10)*V(10))
      X(2)=2.0*(V(10)*V(7)+V(8)*V(9))
      X(3)=2.0*(V(8)*V(10)-V(7)*V(9))
      Y(1)=2.0*(V(8)*V(9)-V(7)*V(10))
      Y(2)=1.0-2.0*(V(8)*V(8)+V(10)*V(10))
      Y(3)=2.0*(V(7)*V(8)+V(9)*V(10))
      Z(1)=2.0*(V(7)*V(9)+V(8)*V(10))
      Z(2)=2.0*(V(9)*V(10)-V(7)*V(8))
      Z(3)=1.0-2.0*(V(8)*V(8)+V(9)*V(9))
      RETURN
      END
      SUBROUTINE SEA(W,X,Y,Z,XPOS,YPOS,ZPOS)
C      MOTION AND GEOMETRY OF THE SEA
      DIMENSION W(6),X(3),Y(3),Z(3)
      COMMON/BLOCK1/ T,SEAA,SEAW,SEAC,COMX,COMY,WDEF,SURMY,SURMZ,
1SQTEM1,ATSYSZ,SURECG,DURECG,BET1D,BET2D,CGOR,XAXOR,CAVA,CAVB,
2SQVYZ,ATVZY,BET1C,BET2C,BOFU,BOFV,BOFW,PCAV,XAX,RAD,DAX,SINA,
3COSA,ISW1,ISW2,ITES,ICROS,IDEF,IDRY,BODU,BODV,BODW,PROT
      ANG=SEAW*(XPOS*COMX+YPOS*COMY-SEAC*T)
      S=SIN(ANG)
      C=COS(ANG)
      ZEXP=SEAA*S
      IF(ZPOS.GT.ZEXP)ZEXP=ZPOS
      E=EXP(-SEAW*ZEXP)
      A1=SEAA*SEAC*SEAW
      A2=A1*SEAC*SEAW
C      SEA MOTION AT XPOS,YPOS,ZPOS
      U=-A1*E*S
      W(1)=U*COMX
      W(2)=U*COMY
      W(3)=-A1*E*C
      UDOT=A2*E*C
      W(4)=UDOT*COMX
      W(5)=UDOT*COMY
      W(6)=-A2*E*S
      WDEF=10.0+ZPOS-SEAA*E*S
C      SEA SURFACE GEOMETRY
      DZDX=SEAA*SEAW*C
      A1=SQRT(1.0+DZDX*DZDX)
      A2=DZDX/A1
      XN=A2*COMX
      YN=A2*COMY
      ZN=-1.0/A1
      SURMY=XN*Y(1)+YN*Y(2)+ZN*Y(3)
      SURMZ=XN*Z(1)+YN*Z(2)+ZN*Z(3)
      TEM1=SURMY*SURMY+SURMZ*SURMZ
      IF(TEM1.LT.0.00001)TEM1=0.00001

```

```

SQTEM1=SQRT(TEM1)
ATSYSZ=ATAN2(SURMY,SURMZ)
SURECG=ZN*(SEAA*S-ZPOS)
DURECG=XN*X(1)+YN*X(2)+ZN*X(3)
RETURN
END

```

```

C   SUBROUTINE HYDRO(A,P,V,R)
C   FULLY IMMERSED FORCES AND ADDED MASSES

```

```

DIMENSION P(16),A(6,7),V(13),R(6)

```

```

U=ABS(R(1))

```

```

U2=R(1)*U

```

```

UP=V(4)*U

```

```

UQ=U*V(5)

```

```

UR=U*V(6)

```

```

UV=U*R(2)

```

```

UW=U*R(3)

```

```

VWAB=SQRT(R(2)*R(2)+R(3)*R(3))

```

```

V2=R(2)*VWAB

```

```

W2=R(3)*VWAB

```

```

QA2=V(5)*VWAB

```

```

RA2=V(6)*VWAB

```

```

C   FORCES

```

```

A(1,7)=P(1)*U2+P(14)*R(4)

```

```

A(2,7)=P(3)*UR+P(2)*UV+P(10)*V2+P(11)*RA2+P(14)*R(5)

```

```

A(3,7)=-P(3)*UQ+P(2)*UW+P(10)*W2-P(11)*QA2+P(14)*R(6)

```

```

A(4,7)=P(16)*UP

```

```

A(5,7)=-P(15)*R(6)+P(4)*UW+P(5)*UQ+P(12)*W2+P(13)*QA2

```

```

A(6,7)=P(15)*R(5)-P(4)*UV+P(5)*UR-P(12)*V2+P(13)*RA2

```

```

C   ADDED MASSES

```

```

A(1,1)=P(6)

```

```

A(2,2)=P(7)

```

```

A(2,6)=P(8)

```

```

A(3,3)=P(7)

```

```

A(3,5)=-P(8)

```

```

A(5,5)=P(9)

```

```

A(6,6)=P(9)

```

```

RETURN

```

```

END

```

```

C   SUBROUTINE IEPTH

```

```

C   CALCULATES THE INTERSECTION OF A SEGMENT WITH THE SEA SURFACE

```

```

C   BET1D TO BET2D IS THE INTERSECTION SECTOR

```

```

COMMON/BLOCK1/ T,SEAA,SEAW,SEAC,COMX,COMY,WDEF,SURMY,SURMZ,
1SQTEM1,ATSYSZ,SURECG,DURECG,BET1D,BET2D,CGOR,XAXOR,CAVA,CAVB,
2SQVYVZ,ATVZVY,BET1C,BET2C,BOFU,BOFV,BOFW,PCAV,XAX,RAD,DAX,SINA,
3COSA,ISW1,ISW2,ITES,ICROS,IDEF,IDRY,BODU,BODV,BODW,PROT

```

```

IDEP=0

```

```

IDRY=0

```

```

SURE=SURECG-XAX*DURECG

```

```

SURE=SURE/SQTEM1

```

```

IF(SURE.LE,RAD)GOTO120

```

```

IDEP=1

```

```

RETURN

```

```

120 IF(SURE.LE,-RAD)GOTO500

```

```

SURE=SURE/RAD

```

```

TEM1=SQRT(1.0-SURE*SURE)

```

```

      TEM2=ATAN2(SURE,TEM1)
      BET1D=TEM2-ATSYSZ
      BET2D=3.1416-TEM2-ATSYSZ
      TEM1=(BET1D+BET2D)/2.0
      TEM2=COS(TEM1)*SURMY+SIN(TEM1)*SURMZ
      IF(TEM2.LT.0.0)RETURN
      TEM1=BET1D
      BET1D=BET2D
      BET2D=TEM1
      RETURN
500  IDRY=1
      RETURN
      END
      SUBROUTINE FORCES(A,R,HT,CLIFT,CDRAG)
C      FORCES AND ADDED MASSES FOR EACH WET SECTOR
      DIMENSION A(6,7),R(6)
      COMMON/BLOCK1/ T,SEAA,SEAW,SEAC,COMX,COMY,WDEF,SURMY,SURMZ,
      1SQTEM1,ATSYSZ,SURECG,DURECG,BET1D,BET2D,CGOR,XAXOR,CAVA,CAVB,
      2SQVYZ,ATVZVY,BET1C,BET2C,BOFU,BOFV,BOFW,PCAV,XAX,RAD,IAX,SINA,
      3COSA,ISW1,ISW2,ITES,ICROS,IDEF,IDRY,BODU,BODV,BODW,PROT
C      SORT OUT ACTUAL WETTED SECTOR FROM DEPTH AND CAVITATION DATA
      ISEG=0
      IF(IDEF.EQ.1)GOTO300
      IF(ITES.EQ.0)GOTO205
      BET1C=BET1D
      BET2C=BET2D
      GOTO300
205  TEM2=SCALE(BET2D-BET1D)
      TEM3=SCALE(BET1C-BET1D)
      TEM4=SCALE(BET2C-BET1D)
220  IF(TEM4.LT.TEM3)GOTO240
      IF(TEM3.GT.TEM2)RETURN
      BET1C=TEM3+BET1D
      IF(TEM4.GT.TEM2)GOTO230
225  BET2C=TEM4+BET1D
      GOTO300
230  BET2C=TEM2+BET1D
      GOTO300
240  BET1C=BET1D
      IF(TEM4.GT.TEM2)GOTO230
      IF(TEM3.GT.TEM2)GOTO225
      BET2C=TEM4+BET1D
      ISEG=1
      BET3C=TEM3+BET1D
      BET4C=TEM2+BET1D
C      CALCULATE FORCES AND ADDED MASSES
300  BET1C=SCALE(BET1C)
      BET2C=SCALE(BET2C)
      IF(BET2C.LT.BET1C)BET2C=BET2C+6.283185
      SINB1=SIN(BET1C)
      SINB2=SIN(BET2C)
      COSB1=COS(BET1C)
      COSB2=COS(BET2C)
      IF(ISW1.EQ.1.AND.ISW2.EQ.0)GOTO500
C      AI TO FI INTEGRALS USED FOR FORCES AND MASSES

```

```

AI=BET2C-BET1C
BI=SINB2-SINB1
CI=COSE1-COSE2
TEM3=(SIN(BET2C+BET2C)-SIN(BET1C+BET1C))/4.0
TEM4=AI/2.0
TEM7=SIN(TEM4)
IF(AI.GT.3.142)TEM7=1.0
DI=TEM4+TEM3
EI=(SINB2*SINB2-SINB1*SINB1)/2.0
FI=TEM4-TEM3
TEM1=RAD*DAX
TEM2=1030.0*TEM1
TEM3=ABS(COSA)
TEM4=SINA/TEM3
TEM5=COSA/TEM3
TEM6=RAD*SINA-XAX*COSA
TEM7=TEM2*HT*TEM7
TEM8=TEM7*TEM4
TEM9=TEM8*SINA
TEM10=TEM8*COSA
TEM11=TEM8*TEM6
TEM12=TEM7*TEM5
TEM13=TEM12*COSA
TEM14=TEM12*TEM6
TEM15=TEM7*TEM6*TEM6/TEM3
C   ADDED MASSES
A(1,1)=A(1,1)+TEM9*AI
A(1,2)=A(1,2)+TEM10*BI
A(1,3)=A(1,3)+TEM10*CI
A(1,5)=A(1,5)+TEM11*CI
A(1,6)=A(1,6)-TEM11*BI
A(2,2)=A(2,2)+TEM13*DI
A(2,3)=A(2,3)+TEM13*EI
A(2,5)=A(2,5)+TEM14*EI
A(2,6)=A(2,6)-TEM14*DI
A(3,3)=A(3,3)+TEM13*FI
A(3,5)=A(3,5)+TEM14*FI
A(5,5)=A(5,5)+TEM15*FI
A(5,6)=A(5,6)-TEM15*EI
A(6,6)=A(6,6)+TEM15*DI
TEM8=(BET1C+BET2C)*0.5
TEM7=COS(TEM8)
TEM8=SIN(TEM8)
TEM7=BOFU+0.25*(BOFU*(COSE1+COSE2+TEM7+TEM7)+BOFW*
1(SINB1+SINB2+TEM8+TEM8))
TEM8=CDRAG*TEM2*ABS(TEM7)
TEM9=TEM8*TEM5
TEM10=BOFU*AI+BOFU*BI+BOFW*CI
TEM11=BOFU*BI+BOFU*DI+BOFW*EI
TEM12=BOFU*CI+BOFU*EI+BOFW*FI
IF(ISW2.EQ.0)GOTO350
C   NON LINEAR FORCE
DAFX=TEM8*TEM4*(TEM10+TEM10-TEM7*AI)
DAFY=TEM9*(TEM11+TEM11-TEM7*BI)
DAFZ=TEM9*(TEM12+TEM12-TEM7*CI)

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      IF (ISW1.EQ.1) GOTO 400
C      BUOYANCY FORCE
      TEM11=0.5*TEM2*RAD*(AI-SIN(AI))
      DAFX=DAFX-R(4)*TEM11
      DAFY=DAFY-R(5)*TEM11
      DAFZ=DAFZ-R(6)*TEM11
      GOTO 400
C      LINEAR FORCE
350    TEM7=CLIFT*TEM2*SQRT(BODU*BODU+BODV*BODV+BODW*BODW)
      TEM8=TEM7*TEM5
      DAFX=TEM7*TEM4*TEM10
      DAFY=TEM8*TEM11
      DAFZ=TEM8*TEM12
400    A(1,7)=A(1,7)-DAFX
      A(2,7)=A(2,7)-DAFY
      A(3,7)=A(3,7)-DAFZ
      TEM14=TEM6/COSA
      A(5,7)=A(5,7)-DAFZ*TEM14
      A(6,7)=A(6,7)+DAFY*TEM14
      GOTO 900
C      CRUCIFORM TAIL
500    TEM6=1030.0*DAX
      TEM10=TEM6*CLIFT*SQRT(BODU*BODU+BODV*BODV+BODW*BODW)
      TEM1=RAD*RAD*0.5
      TEM2=T-0.5-FLOAT(IFIX(T))
      TEM3=TEM1*0.01
      TEM4=0.3/RAD
      TEM5=0.4/RAD
      Y1=-RAD
      Y2=RAD
      Z1=-RAD
      Z2=RAD
      IF (SINB1*SINB2.GE.0.0) GOTO 520
      TEM5=RAD*(SINB1*COSB2-COSB1*SINB2)/(SINB1-SINB2)
      IF (SINB1.GT.0.0) GOTO 510
      Y1=TEM5
      GOTO 540
510    Y2=TEM5
      GOTO 540
520    IF ((SINB1+SINB2).GT.0.0) GOTO 530
      IF ((BET2C-BET1C).GT.3.14159) GOTO 540
      GOTO 700
530    IF (COSB1.GT.COSB2) GOTO 700
540    AI=Y2-Y1
      BI=AI*(Y2+Y1)/2.0
      CI=(Y2*Y2*Y2-Y1*Y1*Y1)/3.0
      TEM7=TEM6*HT*AI/(RAD+RAD)
      TEM8=TEM7*XAX
C      ADDED MASSES AND FORCES 'HORIZONTAL FIN'
      A(3,3)=A(3,3)+TEM7*AI
      A(3,4)=A(3,4)+TEM7*BI
      A(3,5)=A(3,5)-TEM8*AI
      A(4,4)=A(4,4)+TEM7*CI
      A(4,5)=A(4,5)-TEM8*BI
      A(5,5)=A(5,5)+TEM8*XAX*AI

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DAFZ=TEM10*(BODW*AI+PROT*BI)
A(3,7)=A(3,7)-DAFZ
A(4,7)=A(4,7)-TEM10*(BODW*BI+PROT*CI)
IF(ABS(BI).LT.TEM3)A(4,7)=A(4,7)+
1(SIGN(TEM4,TEM2)-PROT)*ABS(DAFZ)*TEM1
A(5,7)=A(5,7)+XAX*DAFZ
700 IF(COSB1*COSB2.GE.0.0)GOTO720
TEM5=RAD*(SINB2*COSB1-COSB2*SINB1)/(COSB1-COSB2)
IF(COSB2.GT.0.0)GOTO710
Z1=TEM5
GOTO740
710 Z2=TEM5
GOTO740
720 IF((COSB1+COSB2).GT.0.0)GOTO730
IF((BET2C-BET1C).GT.3.14159)GOTO740
GOTO900
730 IF(SINB2.GT.SINB1)GOTO900
740 AI=Z2-Z1
BI=A1*(Z2+Z1)/2.0
CI=(Z2*Z2*Z2-Z1*Z1*Z1)/3.0
TEM7=TEM6*HT*AI/(RAD+RAD)
TEM8=TEM7*XAX
C   ADDED MASSES AND FORCES 'VERTICAL FIN'
A(2,2)=A(2,2)+TEM7*AI
A(2,4)=A(2,4)-TEM7*BI
A(2,6)=A(2,6)+TEM8*AI
A(4,4)=A(4,4)+TEM7*CI
A(4,6)=A(4,6)-TEM8*BI
A(6,6)=A(6,6)+TEM8*XAX*AI
DAFY=TEM10*(BODV*AI-PROT*BI)
A(2,7)=A(2,7)-DAFY
A(4,7)=A(4,7)+TEM10*(BODV*BI-PROT*CI)
IF(ABS(BI).LT.TEM3)A(4,7)=A(4,7)+
1(SIGN(TEM5,TEM2)-PROT)*ABS(DAFY)*TEM1
A(6,7)=A(6,7)-XAX*DAFY
900 IF(ISEG.EQ.0)RETURN
BET1C=BET3C
BET2C=BET4C
ISEG=0
GOTO300
END
SUBROUTINE ENERT(A,B,R,U,D,X,Y,Z,PM,FY,PZ,PIX,FIY,DT)
C   FORCES DUE TO GRAVITATIONAL AND INERTIAL SOURCES BUT
C   EXCLUDING TERMS CONTAINING DU/DT,DV/DT,.....,DR/DT
DIMENSION V(13),X(3),Y(3),Z(3),D(6),S(6),R(6),A(6,7),B(6,6)
F2=V(4)*V(4)
PQ=V(4)*V(5)
PR=V(4)*V(6)
Q2=V(5)*V(5)
R2=V(6)*V(6)
QR=V(5)*V(6)
UQ=V(1)*V(5)
UR=V(6)*V(1)
VF=V(4)*V(2)
VR=V(2)*V(6)

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WF=V(3)*V(4)
WQ=V(3)*V(5)
YM=FM*FY
ZM=FM*FZ
X3=X(3)*9.81
Y3=Y(3)*9.81
Z3=Z(3)*9.81
C    MOTION FORCES
A(1,7)=A(1,7)-FM*(WQ-VR+FY*FQ+FZ*FR-X3)
A(2,7)=A(2,7)-FM*(UR-WP-FY*(R2+P2)+FZ*QR-Y3)
A(3,7)=A(3,7)-FM*(VP-UQ+FY*QR-FZ*(P2+Q2)-Z3)
A(4,7)=A(4,7)-ZM*(WP-UR+Y3)-YM*(VP-UQ-Z3)
A(5,7)=A(5,7)-(PIX-PIY)*FR-ZM*(WQ-VR-X3)
A(6,7)=A(6,7)-(PIY-PIX)*FQ-YM*(VR-WQ+X3)
C    ADDED MASS EQUALITIES
A(2,1)=A(1,2)
A(3,1)=A(1,3)
A(3,2)=A(2,3)
A(3,6)=-A(2,5)
A(4,2)=A(2,4)
A(4,3)=A(3,4)
A(5,1)=A(1,5)
A(5,2)=A(2,5)
A(5,3)=A(3,5)
A(5,4)=A(4,5)
A(6,1)=A(1,6)
A(6,2)=A(2,6)
A(6,3)=A(3,6)
A(6,4)=A(4,6)
A(6,5)=A(5,6)
S(1)=R(4)+X3
S(2)=R(5)+Y3
S(3)=R(6)+Z3
DO3I=4,6
S(I)=0.0
3    R(I)=V(I)
    TEM1=A(1,1)+A(2,2)+A(3,3)
    TEM2=B(1,1)+B(2,2)+B(3,3)
    IF(TEM1.GE.TEM2)GOTO4
C    SHEDDING MASS
DO100I=1,6
DO100J=1,6
100  A(I,J)=B(I,J)+0.2*(A(I,J)-B(I,J))
4    DO5I=1,6
5    I(I)=0.0
    DO10I=1,6
C    ADDED MASS FORCES
A(1,7)=A(1,7)-R(I)*(A(3,I)*R(5)-A(2,I)*R(6))+A(1,I)*S(I)
A(2,7)=A(2,7)-R(I)*(A(1,I)*R(6)-A(3,I)*R(4))+A(2,I)*S(I)
A(3,7)=A(3,7)-R(I)*(A(2,I)*R(4)-A(1,I)*R(5))+A(3,I)*S(I)
A(4,7)=A(4,7)-R(I)*(A(3,I)*R(2)-A(2,I)*R(3)+A(6,I)*R(5)
1-A(5,I)*R(6))+A(4,I)*S(I)
A(5,7)=A(5,7)-R(I)*(A(1,I)*R(3)-A(3,I)*R(1)+A(4,I)*R(6)
1-A(6,I)*R(4))+A(5,I)*S(I)
A(6,7)=A(6,7)-R(I)*(A(2,I)*R(1)-A(1,I)*R(2)+A(5,I)*R(4)

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1-A(4,I)*R(5))+A(6,I)*S(I)
DO10J=1,6
IF(TEM1.LT.TEM2)GOTO10
C    RATE OF CHANGE OF MASS
D(J)=D(J)-R(I)*(A(J,I)-B(J,I))
C    OLD ADDED MASSES
10  B(J,I)=A(J,I)
C    TOTAL MASS MATRIX
A(1,1)=A(1,1)+PM
A(1,5)=A(1,5)+ZM
A(1,6)=A(1,6)-YM
A(2,2)=A(2,2)+PM
A(2,4)=A(2,4)-ZM
A(3,3)=A(3,3)+PM
A(3,4)=A(3,4)+YM
A(4,2)=A(4,2)-ZM
A(4,3)=A(4,3)+YM
A(4,4)=A(4,4)+PIX
A(5,5)=A(5,5)+PIY
A(5,1)=A(5,1)+ZM
A(6,1)=A(6,1)-YM
A(6,6)=A(6,6)+PIY
C    ADJUST TIME INCREMENT TO SUIT NATURE OF MOTION
TEM1=ABS(D(1)/A(1,1))+ABS(D(2)/A(2,2))+ABS(D(3)/A(3,3))
1+50.0*(ABS(D(4)/A(4,4))+ABS(D(5)/A(5,5))+ABS(D(6)/A(6,6)))
C    SET DT=0 FOR IMPULSIVE VELOCITY CHANGE
IF(TEM1.GT.1.0)DT=0.0
TEM1=ABS(A(1,7)/A(1,1))+ABS(A(2,7)/A(2,2))+ABS(A(3,7)/A(3,3))
1+50.0*(ABS(A(4,7)/A(4,4))+ABS(A(5,7)/A(5,5))+ABS(A(6,7)/A(6,6)))
TEM1=0.05/SQRT(TEM1)
C    REDUCE DT IF ACCELERATION IS LARGE
IF(DT.GT.TEM1)DT=TEM1
RETURN
END
SUBROUTINE DERIV(A,U,D,X,Y,Z,DT)
C    SOLVE AND INTEGRATE THE EQUATIONS OF MOTION
DIMENSION A(6,7),V(13),D(6),X(3),Y(3),Z(3),DV(6)
DO5I=1,6
C    EVALUATE HALF TOTAL EXTERNAL FORCE IMPULSE
5  A(I,7)=0.5*(A(I,7)*DT+D(I))
C    SOLVE EQUATIONS OF MOTION BY FORCING THE LOWER L.H. OF
C    THE MASS MATRIX TO ZERO AND THE DIAGONAL TO UNITY
DO20J=1,5
TEM=A(J,J)
DO10K=J,7
10  A(J,K)=A(J,K)/TEM
I=J+1
DO20L=I,6
DO20K=I,7
20  A(L,K)=A(L,K)-A(L,J)*A(J,K)
DV(6)=A(6,7)/A(6,6)
DV(5)=A(5,7)-A(5,6)*DV(6)
DV(4)=A(4,7)-A(4,6)*DV(6)-A(4,5)*DV(5)
DV(3)=A(3,7)-A(3,6)*DV(6)-A(3,5)*DV(5)-A(3,4)*DV(4)
DV(2)=A(2,7)-A(2,6)*DV(6)-A(2,5)*DV(5)-A(2,4)*DV(4)-A(2,3)*DV(3)

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      DV(1)=A(1,7)-A(1,6)*DV(6)-A(1,5)*DV(5)-A(1,4)*DV(4)-A(1,3)*DV(3)-
1A(1,2)*DV(2)
      D05850I=1,6
C      INCREMENT VELOCITIES BY HALF TOTAL INCREMENT
5850  V(I)=V(I)+DV(I)
      DT2=DT*0.5
C      INCREMENT QUATERNIONS
      V(7)=V(7)-(V(8)*V(4)+V(9)*V(5)+V(10)*V(6))*DT2
      V(8)=V(8)+(V(7)*V(4)-V(10)*V(5)+V(9)*V(6))*DT2
      V(9)=V(9)+(V(10)*V(4)+V(7)*V(5)-V(8)*V(6))*DT2
      V(10)=V(10)-(V(9)*V(4)-V(8)*V(5)-V(7)*V(6))*DT2
      V(11)=V(11)+(X(1)*V(1)+Y(1)*V(2)+Z(1)*V(3))*DT
      V(12)=V(12)+(X(2)*V(1)+Y(2)*V(2)+Z(2)*V(3))*DT
      V(13)=V(13)+(X(3)*V(1)+Y(3)*V(2)+Z(3)*V(3))*DT
      D05860I=1,6
C      INCREMENT VELOCITIES BY REMAINING HALF INCREMENT
5860  V(I)=V(I)+DV(I)
      TEM=(3.0-V(7)*V(7)-V(8)*V(8)-V(9)*V(9)-V(10)*V(10))/2.0
      D05870I=7,10
C      NORMALISE QUATERNIONS
5870  V(I)=V(I)*TEM
      RETURN
      END
      FUNCTION SCALE(X)
C      MAKE ANGLE X IN RANGE 0 TO 2*PI
10    IF(X.GE.0.0)GOTO20
      X=X+6.283185
      GOTO10
20    IF(X.LT.6.283185)GOTO30
      X=X-6.283185
      GOTO20
30    SCALE=X
      RETURN
      END
      SUBROUTINE EULER(S,T,F,X,Y,Z)
C      EXTRACT ROLL(F),PITCH(T),AZIMUTH(S) IN DEGREES FROM THE
C      TRANSFORMATION MATRIX
      DIMENSION X(3),Y(3),Z(3)
      T1=X(3)*X(3)
      T2=0.0
      IF(T1.LT.1.0)T2=SQRT(1.0-T1)
      T=-57.3*ATAN2(X(3),T2)
      F=57.3*ATAN2(Y(3),Z(3))
      S=57.3*ATAN2(X(2),X(1))
      RETURN
      END

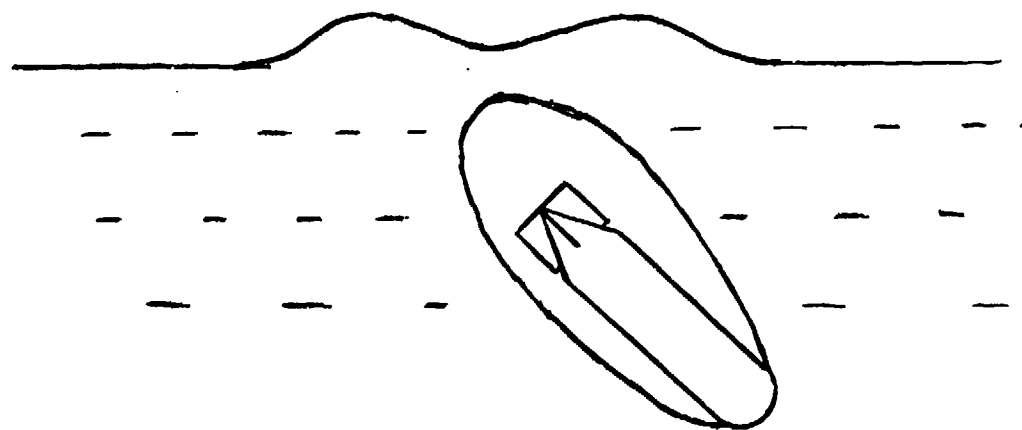
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a) FLOW FORMATION

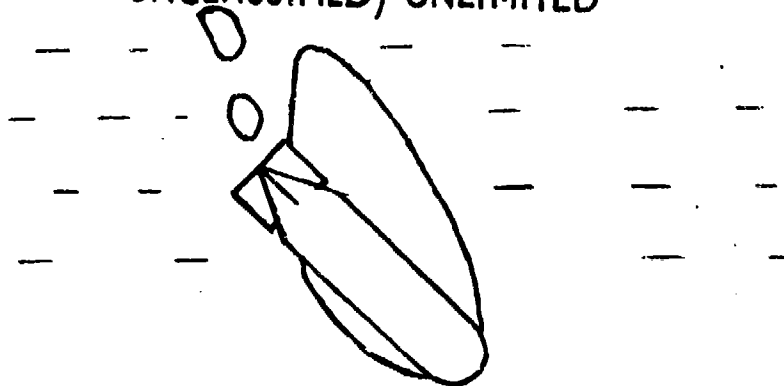


b) OPEN CAVITY

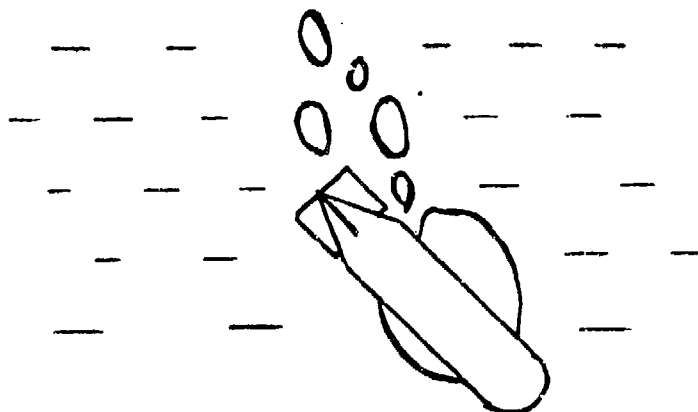


c) CLOSED CAVITY

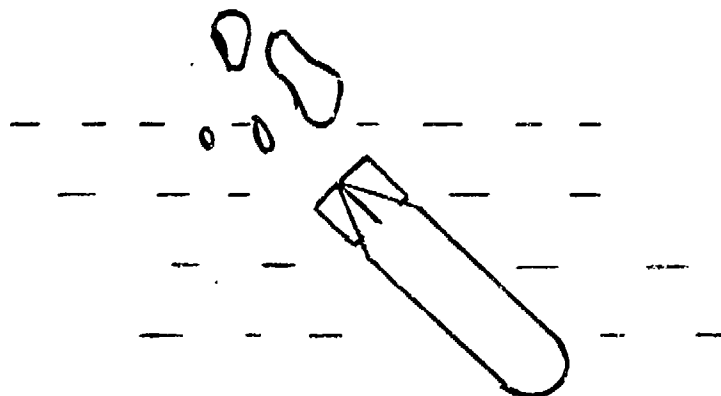
FIG.1. THE PHASES OF WATER ENTRY



d) TAIL SLAP



e) CAVITY COLLAPSE



f) FULLY WET

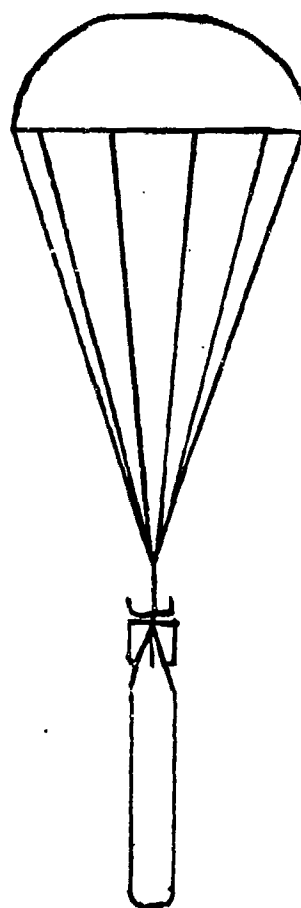
FIG. 1. THE PHASES OF WATER ENTRY



RELATIVE DENSITY = 1.0
SCALE = 1/20

FIG. 2. A TYPICAL LIGHT WEIGHT TORPEDO

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SCALE 1/50

FIG. 3. A TYPICAL AIR DELIVERY PARACHUTE SYSTEM

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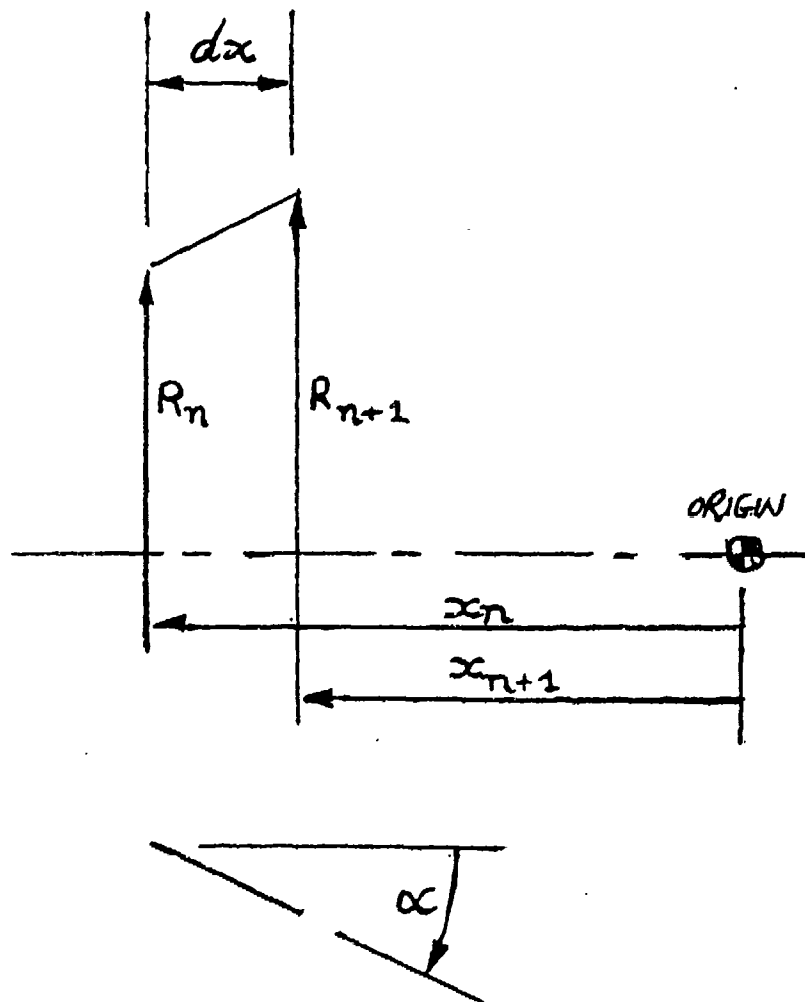


FIG. 4. A BODY SEGMENT

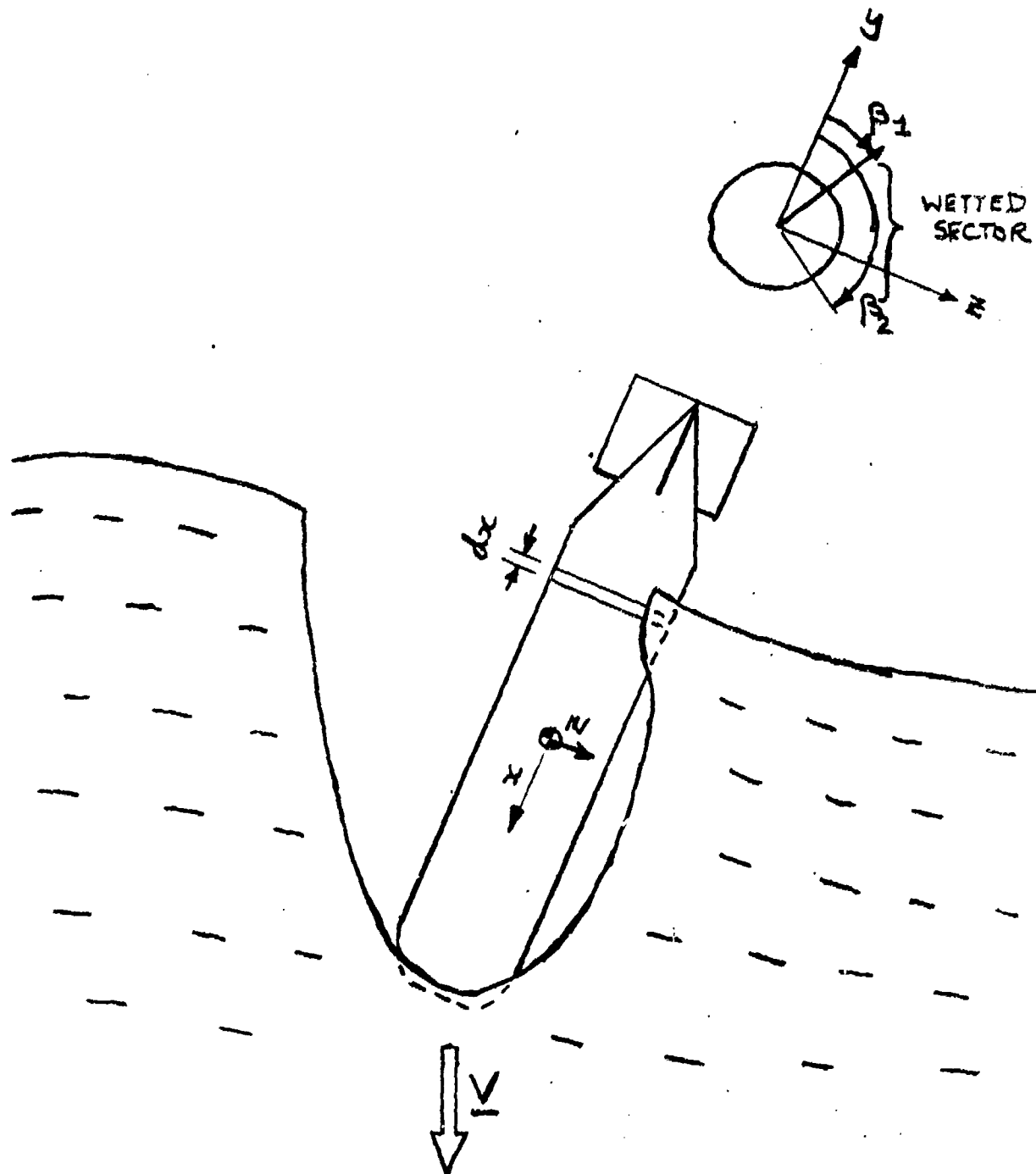


FIG. 5. THE GEOMETRY OF WATER ENTRY

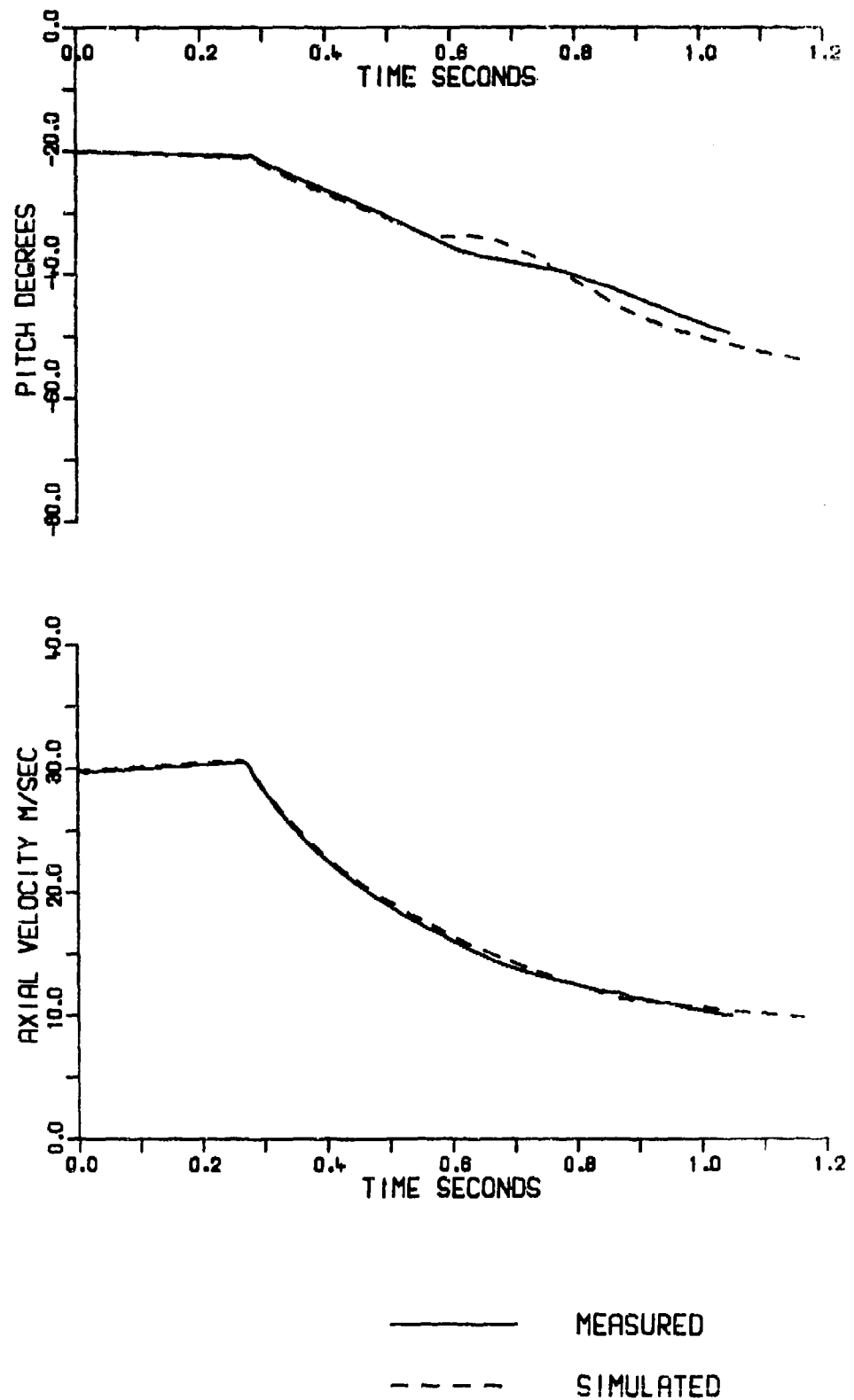


FIG. 6. THE VARIATION OF PITCH ANGLE AND
AXIAL VELOCITY WITH TIME
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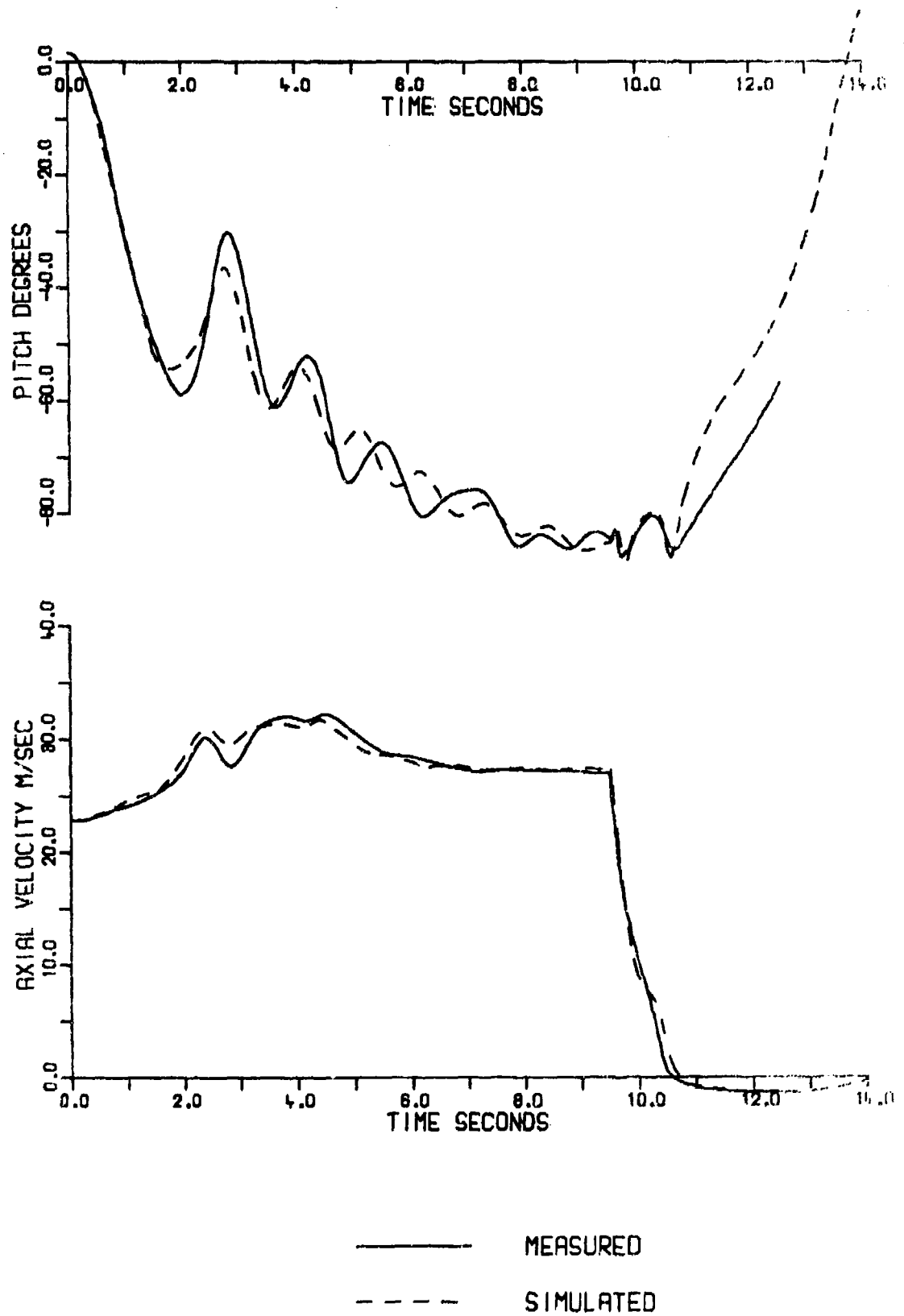


FIG. 7. THE VARIATION OF PITCH ANGLE AND
AXIAL VELOCITY WITH TIME

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FIG. 8

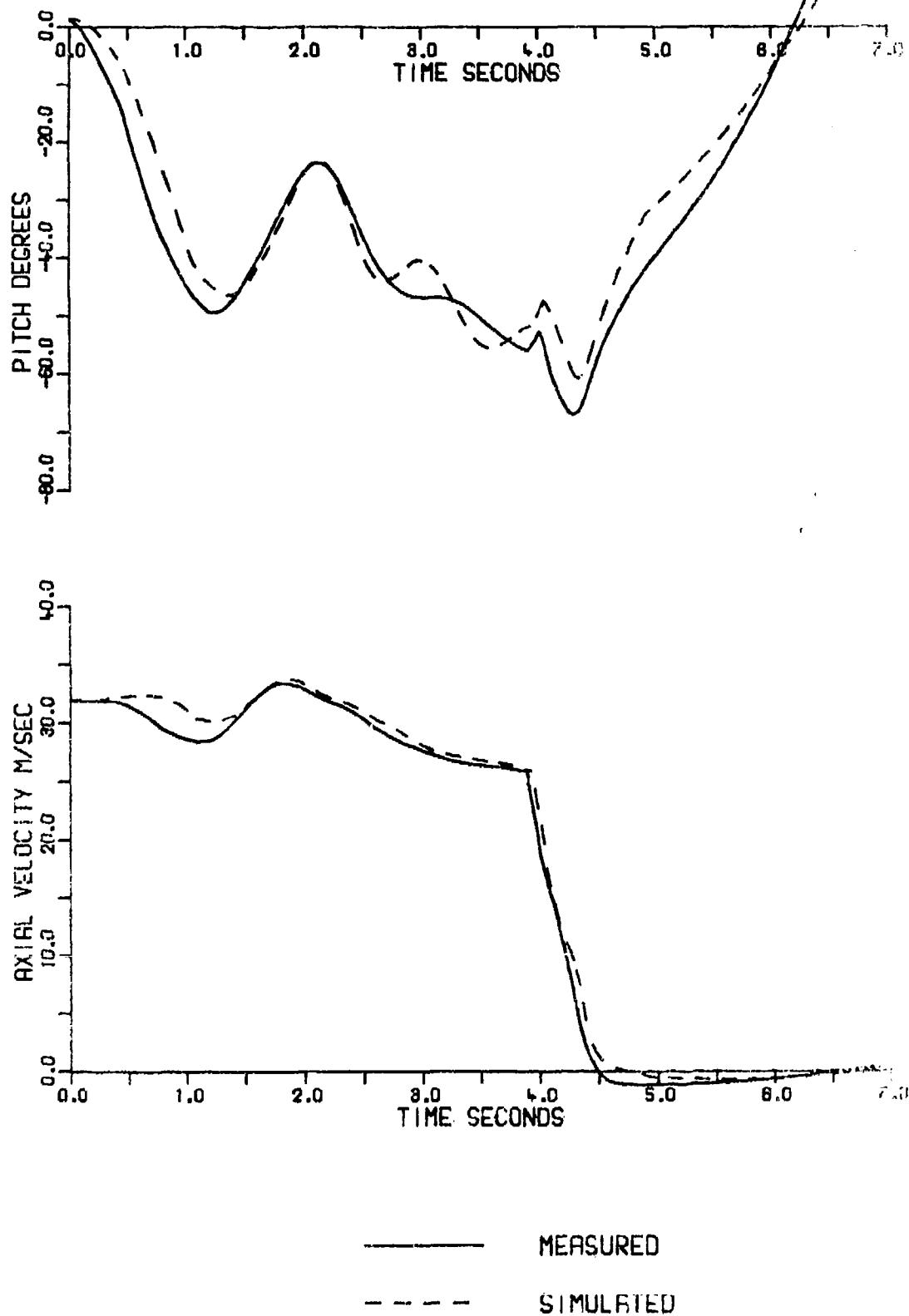


FIG.8 THE VARIATION OF PITCH ANGLE AND AXIAL VELOCITY WITH TIME

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<u>UNCLASSIFIED//UNLIMITED</u> AUWE Technical Note 636/79 A M Mackey October, 1979 681.3.06: 532.582.8: 623.565.6 A Mathematical Model of Water Entry A computer simulation of the water entry of an axisymmetric body with or without a cruciform tail and with or without a parachute delivery system is described. The predictions of the simulation are shown to agree with experimental observations of water entry motion. The FORTRAN program which implements this model is listed.	<u>UNCLASSIFIED//UNLIMITED</u> AUWE Technical Note 636/79 A M Mackey October, 1979 681.3.06: 532.582.8: 623.565.6 A Mathematical Model of Water Entry A computer simulation of the water entry of an axisymmetric body with or without a cruciform tail and with or without a parachute delivery system is described. The predictions of the simulation are shown to agree with experimental observations of water entry motion. The FORTRAN program which implements this model is listed.
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