A MATHEMATICAL MODEL OF WATER ENTRY.

Technical note,

By

A. M. Mackey

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

by

A M Mackey
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A MATHMATICAL MODEL OF WATER ENTRY, (U/U)

P RÉCIS

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.

C O N C L U S I O N S

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.
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 ($\phi$), pitch ($\theta$), and yaw ($\psi$), 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 or 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 $\Psi$ 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:

$$e_0 = \cos \frac{\Psi}{2}$$
$$e_1 = \alpha_s \sin \frac{\Psi}{2}$$
$$e_2 = \beta_s \sin \frac{\Psi}{2}$$
$$e_3 = \gamma_s \sin \frac{\Psi}{2}$$

(1)

It may be seen that:

$$\sum e_i^2 = 1$$

(2)

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

$$e_0 = \cos \frac{\Phi}{2} \cos \frac{\Theta}{2} \cos \frac{\Psi}{2} + \sin \frac{\Phi}{2} \sin \frac{\Theta}{2} \sin \frac{\Psi}{2}$$
$$e_1 = \sin \frac{\Phi}{2} \cos \frac{\Theta}{2} \cos \frac{\Psi}{2} - \cos \frac{\Phi}{2} \sin \frac{\Theta}{2} \sin \frac{\Psi}{2}$$
$$e_2 = \cos \frac{\Phi}{2} \sin \frac{\Theta}{2} \cos \frac{\Psi}{2} + \sin \frac{\Phi}{2} \cos \frac{\Theta}{2} \sin \frac{\Psi}{2}$$
$$e_3 = \cos \frac{\Phi}{2} \cos \frac{\Theta}{2} \sin \frac{\Psi}{2} - \sin \frac{\Phi}{2} \sin \frac{\Theta}{2} \cos \frac{\Psi}{2}$$

(3)

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

$$T = \begin{bmatrix}
e_0 e_1 - e_2 e_3 & 2 e_0 e_2 - 2 e_0 e_3 & 2 e_0 e_2 + 2 e_0 e_3 \\
e_0 e_2 + 2 e_0 e_3 & e_0^2 - e_1^2 + e_2^2 - e_3^2 & 2 e_0 e_1 - 2 e_0 e_3 \\
e_0 e_3 - 2 e_0 e_2 & 2 e_0 e_1 + 2 e_0 e_3 & e_0^2 - e_1^2 - e_2^2 + e_3^2\
\end{bmatrix}$$

(4)

14. The terminology:

$$\mathbf{T} = \begin{bmatrix}x_1 & y_1 & z_1 \\
x_2 & y_2 & z_2 \\
x_3 & y_3 & z_3 \end{bmatrix}$$

(5)
5. 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 \((\dot{p}, \dot{q}, \dot{r})\) 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:

\[
\begin{align*}
\dot{m} \left( \dot{u} - vr + wq + y_g(pq - \dot{r}) + z_g(pr + \dot{q}) - gX_3 \right) &= F_x \\
\dot{m} \left( \dot{v} - wp + ur - y_g(p^2 + p^2) + z_g(qr - \dot{p}) - gY_3 \right) &= F_y \\
\dot{m} \left( \dot{w} - uq + vp + y_g(qr + \dot{p}) - z_g(p^2 + q^2) - gZ_3 \right) &= F_z \\
I_x \ddot{p} + m \left( y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur) + g(z_gY_3 - y_gZ_3) \right) &= L_x \\
I_y \ddot{q} + (I_x - I_y) \, rp + m \, z_g \left( \dot{u} - vr + wq - gX_3 \right) &= L_y \\
I_z \ddot{r} + (I_y - I_x) \, pq + m \, y_g \left( vr - \dot{u} - wq + gX_3 \right) &= L_z
\end{align*}
\]

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:

\[
\begin{align*}
\text{segment 'x' co-ordinate} &= x = \frac{x_n + x_{n+1}}{2} \\
\text{segment radius} &= R = \frac{R_n + R_{n+1}}{2} \\
\text{segment width} &= dx = x_n - x_{n+1} \\
\text{segment angle} &= \alpha = \tan^{-1} \frac{(R_{n+1} - R_n)}{dx}
\end{align*}
\]

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 \(\hat{n}_s\), then in the body co-ordinate system this is:

\[
\hat{n} = \hat{n}_s \left[ T \right]
\]
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 \(\beta_1, \beta_2\) of:

\[
(0, R \cos \beta, R \sin \beta), \quad \mathbf{m} = d
\]  

(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:

\[
\left| \frac{d}{R(n_y^2 + n_z^2)^{1/2}} \right| < 1
\]

(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, \(\sigma\), is less than 0.3 and that the local angle of incidence, \(i\), of the body surface to the flow is:

\[
\sin(i) = 0.152 \sin(i_m) + 0.608 \sin^3(i_m) - 0.34 \exp(-R \cos \alpha \frac{da}{dx}) - 0.36 \sigma + 0.28 \sin^2(i_b)
\]

(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, \(i_\beta\), of a point at angular position \(\beta\) on a segment is:

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

(12)

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

\[
u_s \sin \alpha - (v_s^2 + w_s^2)^{1/2} \cos \alpha > \sin(i) \left( u_s^2 + v_s^2 + w_s^2 \right)^{1/2}
\]

(13)

then there is no cavitation and if:

\[
u_s \sin \alpha + (v_s^2 + w_s^2)^{1/2} \cos \alpha < \sin(i) \left( u_s^2 + v_s^2 + w_s^2 \right)^{1/2}
\]

(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:-
semi major axis = \( a = 0.4 \sin(i) R_{ef} (1 + R \cos \alpha \frac{da}{dx})/\sigma \) \hspace{1cm} (15)

semi minor axis = \( b = R_{ef} + 0.13a \) \hspace{1cm} (16)

where the effective segment radius \( R_{ef} \) is

\[
R_{ef} = R(u_s^2 + v_s^2 + w_s^2)^{\frac{1}{2}} / (u_s - (v_s^2 + w_s^2)^{\frac{1}{2}} \tan \alpha) \hspace{1cm} (17)
\]

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 \( \rho \), displaced by each wetted sector is:

\[
dm = \rho R^2 dx (\beta_2 - \beta_1 - \sin (\beta_2 - \beta_1))/2 \hspace{1cm} (18)
\]

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

\[
dF = dm g (X_3, Y_3, Z_3) \hspace{1cm} (19)
\]

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, \( V_\beta \), at angular position \( \beta \) 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:

\[
V_\beta = ((u,v,w) + ((p,q,r) \times (x,R\cos\beta,R\sin\beta))) \cdot (\sin\alpha, \cos\beta \cos\alpha, \sin\beta \cos\alpha) \hspace{1cm} (20)
\]

The magnitude of the pressure force, \( dF \), on the elemental area, \( R d\beta \ dx/\cos \alpha \), is:

\[
dF = \frac{1}{2} \rho V_\beta^2 C_D R d\beta \ dx/\cos \alpha \hspace{1cm} (21)
\]

where \( C_D \) is the force coefficient.
27. If a constant velocity, $V_{\beta}$, is chosen to be of the same order as $V_{\beta}$, then to a first approximation:

$$V_{\beta}^2 = V_{\beta}^{2} - 2V_{\beta} - V_{\beta}^{0}$$

(22)

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

$$dF_x = \frac{1}{2} \rho C_D V_{\beta}^{2} R \tan \alpha \int_{\beta_1}^{\beta_2} (2V_{\beta} - V_{\beta}^{0}) \, d\beta$$

$$dF_y = \frac{1}{2} \rho C_D V_{\beta}^{2} R \int_{\beta_1}^{\beta_2} (2V_{\beta} - V_{\beta}^{0}) \cos \beta \, d\beta$$

(23)

$$dF_z = \frac{1}{2} \rho C_D V_{\beta}^{2} R \int_{\beta_1}^{\beta_2} (2V_{\beta} - V_{\beta}^{0}) \sin \beta \, d\beta$$

The moment, $d\ell$, of $dF$ about the origin is:

$$d\ell = (x, R \cos \beta, R \sin \beta) \times dF$$

(24)

in: $d\ell = (h \tan \alpha - x) (0, dF_x, -dF_y)$

(25)

The external forces and moments applied to the body by quasi steady state pressures are obtained by summing $dF$ and $d\ell$ 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:

$$\begin{bmatrix} M_x \\ M_y \\ M_z \\ H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} X_u X_v X_w X_p X_q X_f \\ Y_u Y_v Y_w Y_p Y_q Y_f \\ Z_u Z_v Z_w Z_p Z_q Z_f \\ K_u K_v K_w K_p K_q K_f \\ M_u M_v M_w M_p M_q M_f \end{bmatrix} \begin{bmatrix} u \\ v \\ w \\ p \\ q \end{bmatrix}$$

(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:

\[
\mathbf{F} = \frac{d\mathbf{M}}{dt} + ((p, q, r) \times \mathbf{M}) \tag{27}
\]

and

\[
\mathbf{L} = \frac{d\mathbf{H}}{dt} + ((u, v, w) \times \mathbf{M}) + ((p, q, r) \times \mathbf{H}) \tag{28}
\]

29. In order to evaluate the added mass matrix it is assumed that associated with every element of area, \(Rd\beta dx/\cos \alpha\), is a volume of fluid, \(Rhd\beta dx/\cos \alpha\), 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 \(\beta\) on a segment is therefore:

\[
d\mathbf{M} = V_\beta \rho Rh d\beta dx/\cos \alpha \tag{29}
\]

where \(V_\beta\) 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:

\[
d\mathbf{M}_x = \rho Rh dx \tan \alpha \int_{\beta_1}^{\beta_2} V_\beta d\beta
\]

\[
d\mathbf{M}_y = \rho Rh dx \int_{\beta_1}^{\beta_2} V_\beta \cos \beta d\beta \tag{30}
\]

\[
d\mathbf{M}_z = \rho Rh dx \int_{\beta_1}^{\beta_2} V_\beta \sin \beta d\beta
\]

Angular momentum about the body origin is:

\[
d\mathbf{H} = (x, R \cos \beta, R \sin \beta) \times d\mathbf{M} \tag{31}
\]

ie

\[
d\mathbf{H} = (R \tan \alpha - x) (0, \mathbf{dM}_z, -\mathbf{dM}_y) \tag{32}
\]

30. The coefficients of \(u, v, w, p, q, r\) 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

\[
\frac{d\mathbf{M}}{dt} \quad \frac{d\mathbf{H}}{dt}
\]

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:

\[
\begin{bmatrix}
\frac{du}{dt} \\
\frac{dv}{dt} \\
\frac{dw}{dt} \\
\frac{dp}{dt} \\
\frac{dq}{dt} \\
\frac{dr}{dt}
\end{bmatrix} = \begin{bmatrix} A \\ B \\ C \end{bmatrix} dt + \begin{bmatrix} D \\ E \\ F \end{bmatrix}
\]

(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.

33. 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:

\[
\begin{bmatrix}
x \\
\frac{1}{2}p \\
q \\
r
\end{bmatrix} = \begin{bmatrix} 0 & -q & -r \\
p & 0 & -r \\
-q & r & 0 \\
r & q & -p \\
\end{bmatrix} e
\]

(34)

and

\[
\begin{bmatrix}
x_o \\
y_o \\
z_o
\end{bmatrix} = \begin{bmatrix} T \\
u \\
v \\
n \\
\end{bmatrix}
\]

(35)

Discussion of the numerical simulation

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

3h. 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:-
\[ h = \frac{2}{\pi} \left( R^2 - R_h^2 \right)^{\frac{1}{2}} \]  

(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:

\[ h = \frac{R}{2} \]  

(37)

for a sphere of radius \( R \) and that

\[ h = R \]  

(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, \( \phi \), may be represented by (Ref 6):

\[ \phi = ac \exp (-wz_o) \cos w(x_o - ct) \]  

(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, \( \theta \), 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 \( 20^\circ \) 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.

ACKNOWLEDGEMENTS

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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Reference


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:-

<table>
<thead>
<tr>
<th>NAME OF VARIABLE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>BODY PARACHUTE</td>
<td></td>
</tr>
<tr>
<td>VBOD(1)</td>
<td>VPAR(1) U</td>
</tr>
<tr>
<td>VBOD(2)</td>
<td>VPAR(2) V</td>
</tr>
<tr>
<td>VBOD(3)</td>
<td>VPAR(3) W</td>
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<td>VBOD(4)</td>
<td>VPAR(4) P</td>
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<td>VBOD(5)</td>
<td>VPAR(5) Q</td>
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<td>VBOD(6)</td>
<td>VPAR(6) R</td>
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<td>VBOD(7)</td>
<td>VPAR(7) E0</td>
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<td>VBOD(8)</td>
<td>VPAR(8) E1</td>
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<td>VBOD(9)</td>
<td>VPAR(9) E2</td>
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<tr>
<td>VBOD(10)</td>
<td>VPAR(10) E3</td>
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<tr>
<td>VBOD(11)</td>
<td>VPAR(11) X</td>
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<td>VBOD(12)</td>
<td>VPAR(12) Y</td>
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<tr>
<td>VBOD(13)</td>
<td>VPAR(13) Z</td>
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<tr>
<td>XBOD XPAR</td>
<td>TRANSFORMATION MATRIX</td>
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<tr>
<td>YBOD XPAR</td>
<td></td>
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<tr>
<td>ZBOD XPAR</td>
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<tr>
<td>ADMBOD ADMPAR</td>
<td>(THE FIRST 6 COLUMNS IS THE MASS MATRIX)</td>
</tr>
<tr>
<td>BDMBOD BDMPAR</td>
<td>(THE 7TH COLUMN IS THE EXTERNAL FORCES)</td>
</tr>
<tr>
<td>PWBOD(1)</td>
<td>PWFAR(1) X/U2</td>
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<td>PWBOD(2)</td>
<td>PWFAR(2) Y/V</td>
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<td>PWBOD(3)</td>
<td>PWFAR(3) Y/R</td>
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<td>PWBOD(4)</td>
<td>PWFAR(4) M/W</td>
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<td>PWBOD(5)</td>
<td>PWFAR(5) M/Q</td>
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<td>PWBOD(6)</td>
<td>PWFAR(6) X/UDOT</td>
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<td>PWBOD(7)</td>
<td>PWFAR(7) Y/VDOT</td>
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<td>PWBOD(8)</td>
<td>PWFAR(8) Y/RDOT</td>
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<tr>
<td>PWBOD(9)</td>
<td>PWFAR(9) N/RDOT</td>
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<td>PWFAR(10) Y/V2</td>
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<td>PWBOD(11)</td>
<td>PWFAR(11) Y/RV</td>
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<td>PWFAR(12) M/W2</td>
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<td>PWBOD(13)</td>
<td>PWFAR(13) M/QW</td>
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<td>PWBOD(14)</td>
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<td>PWFAR(15) M/W</td>
</tr>
<tr>
<td>PWBOD(16)</td>
<td>PWFAR(16) M/Q</td>
</tr>
</tbody>
</table>

PABOD PAPAR IN AIR EQUIVALENT TO PWBOD,PWFAR
PAPBR FULLY DEPLOYED VALUES OF PAPAR
PWPBR FULLY DEPLOYED VALUES OF PWFAR
C
C RBOD       RPAR       RELATIVE MOTION FIELD
C
C XAXBOD     XAXPAR     X CO-ORD     
C RADBOD     RADPAR     RADIUS      
C DAXBOD     DAXPAR     DX         EXTERNAL SHAPE
C
C SINBOD     SINPAR     SIN(SLOPE)  
C COSBOD     COSPAR     COS(SLOPE)  
C HTTBD       HTPAR     EQUIVALENT HEIGHT OF ADDED MASS 
C
C ISW1BO     ISW2BO     COUNTS BROKEN SHROUD LINES
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READ(1,20)SEA
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)
DO30 I=1,16
C BODY FORCE DERIVATIVES
30 READ(2,21)PFABO(I), PWBOE(I)
C (TAIL IN CAVITY LIFT COEFFICIENT)*0.5
READ(2,20)CLBOD
C (BODY IN CAVITY DRAG COEFFICIENT)*0.5
READ(2,20)CBOD
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)FYBOD
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
POIDT=TMAX/POINUM
IFIRST=1
ISECON=1
DO75 I=1,6
DO75 J=1,6
BDMPAR(I,J)=0.0
BDMBOD(I,J)=0.0
58 NBOD=0
C BODY GEOMETRY TEM2=X CO-ORD, TEM4=RADIUS,
C TEMB=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,II,J1
FORMAT(3F13.5,5I2)
IF(TEM4.LT.-0.1)GOTO200
IF(Ii.NE.I.OR.J1.NE.J)GOTO67
TEM5=TEM1-TEM2
TEM6=TEM4-TEM3
TEM7=SGRT(TEM5*TEM5+TEM6*TEM6)
IF((TEM5/TEM7).GT.0.002)GOTO65
TEM5=0.002*ABS(TEM6)
TEM7=SGRT(TEM5*TEM5+TEM6*TEM6)

65 NBOD=NBOD+1
XAXBOD(NBOD)=(TEM1+TEM2)/2.0
RADBOD(NBOD)=(TEM3+TEM4)/2.0
HTTBOD(NBOD)=(TEM6+TEM9)/2.0
DAXBOD(NBOD)=TEM5
SINBOD(NBOD)=TEM6/TEM7
COSBOD(NBOD)=TEM5/TEM7
ISWIBO(NBOD)=I1
ISW2BO(NBOD)=J1
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)
D600501=4,10

6050 VPAR(1)=VBOD(1)
VPAR(2)=VBOD(11)+BODTL*VBOD(1)
VPAR(12)=VBOD(12)+BODTL*VBOD(2)
VPAR(13)=VBOD(13)+BODTL*VBOD(3)
C SY:WEPP,DAT CONTAINS THE DESCRIPTION OF THE PARACHUTE
CALL ASSIGN(4,'SY:WEPP,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,TLFP DESCRIBE SHROUD LINE STRESS/STRAIN
C CHARACTERISTIC SEE 7000
READ(4,20)TLFA
READ(4,20)TLFB
READ(4,20)TLFC
READ(4,20)TLFP
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
END
C RATE OF DEPLOYMENT PARAMETER
READ(4,20)SDLPAR
DO2030I=1,16
C PARACHUTE FORCE DERIVATIVES
2030 READ(4,21)FAPBR(I),FWAPBR(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)MPAR
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)G0T02060
TEM5=TEM1-TEM2
TEM6=TEM4-TEM3
TEM7=SQR(T(TEM5*TEM5+TEM6*TEM6))
IF((TEM5/TEM7),GT,0.002)G0T02005
TEM5=0.002*ABS(TEM6)
TEM7=SQR(T(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
COSPAPAR(NPAR)=TEM5/TEM7
TEM1=TEM2
TEM3=TEM4
G0T02000
2060 SHIIANG=6.283185/FLOAT(NSHD)
D02065I=1,NSHD
2065 ISHD(I)=0
SCLFar=SCLMin
DT=0.0
GOT06005
C  
FROM 200 TO 1500 IS FORCES ON BODY
C  TEST FOR PRESENCE OF NOSE CAP
200  IF(IPIMP.EQ.0)GOT0202
   IF(TRAIV*VEL2.LT.PIMP)GOT0202
   IPIMP=0
   GOT058
202  DO205I=1,6
   DO205J=1,7
   ADMFAR(I,J)=0.0
205  ADMBOD(I,J)=0.0
   CALL XYZ(VBOD(1),XBOD(1),YBOD(1),ZBOD(1),VBOD(11),VBOD(12),VBOD(13))
C  DEPTH OF EXTREMITIES OF BODY
   DEP=SURECG-XAXEIOD(I)*SURECG
   TEM2=SURECG-XAXBOD(1)*SURECG
   DEPM=(DEP+TEM2)/2.0
   TEM7=BODRAD*SQT(TEM1)
   TEM3=DEP-TEM7
   TEM4=TEM2-TEM7
   TEM5=DEP+TEM7+BODRAD
   TEM2=TEM2+TEM7+BODRAD
C  FIRST ESTIMATE OF TIME INCREMENT
   DT=BODRAD/SORT(VBOD(I)+VBOD(2)+VBOD(3)+VBOD(4)+VBOD(5)+VBOD(6))
   IF(DT.GT.0.02)DT=0.02
   IF(DEPME.GT.0.0)GOT0308
C  RELATIVE MOTION FIELD IN AIR
   RBOD(1)=VBOD(I)-WINDX*XBO(I)-WINDY*YBOD(2)
   RBOD(2)=VBOD(2)-WINDX*YBOD(1)-WINDY*XBOD(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.TRELM)ADMBOD(5,7)=ADMBOD(5,7)+TORLAN
   IF(TEM1.GT.0.0)GOT0210
C  BODY IS FULLY IN AIR
   PCAV=101000.0
   TRAV=0.0
   IIM=0
   GOT0400
208  IIM=1
C  RELATIVE MOTION FIELD IN WATER
210  RBOD(1)=VBOD(1)-WATER(1)*XBOD(1)-WATER(2)*YBOD(2)-WATER(3)*ZBOD(3)
   RBOD(2)=VBOD(2)-WATER(1)*YBOD(1)-WATER(2)*XBOD(2)-WATER(3)*ZBOD(3)
   RBOD(3)=VBOD(3)-WATER(1)*ZBOD(1)-WATER(2)*XBOD(2)-WATER(3)*YBOD(3)
   RBOD(4)=WATER(4)*XBOD(1)+WATER(5)*YBOD(2)+WATER(6)-9.81*XBO(I)
   RBOD(5)=WATER(4)*YBOD(1)+WATER(5)*XBOD(2)+(WATER(6)-9,81)*YBOD(2)
   RBOD(6)=WATER(4)*ZBOD(1)+WATER(5)*XBOD(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)
   PAMB=10100,0*WDEF
IF (PCAV.EQ.0.0) GOTO 216
PCAV=PAMB-TRAV*300.0/BODRAD
IF (PCAV.LT.0.0) PCAV=0.0
PAMB=PAMB-PCAV

216 CAV=PAMB/(515.0*VEL2)
IF (TEM3.LT.0.0 OR TEM4.LT.0.0) GOTO 240
C BODY IS FULLY IMMERSED IN WATER
IF (CAV.LT.0.3) GOTO 250
C THERE IS NO CAVALTY
CALL HYDRO (ADMBOI, PWBOD, VBOD, RBOI)
TRAV=9999.0
PCAV=0.0
GOTO 400
C BODY IS PARTIALLY WET
240 DT=DT/5.0
250 ICROS=1
ICS=0
IUP=0
SINMAX=SQR(V2W2/VEL2)
IF (DEPME.GT.0.0) CALL HYDRO (ADMBOI, PWBOD, VBOD, RBOI)
IF (TIM.EQ.0.0 OR PCAV.EQ.0.0) GOTO 256
C TRAV=DISTANCE TRAVELLED AFTER IMPACT
TEM8=VBOD(11)-TORX
TEM9=VBOD(12)-TORY
TEM10=VBOD(13)-TORZ
TRAV=SQR(TEM8*TEM8+TEM9*TEM9+TEM10*TEM10)
C CALCULATE UNDERPRESSURE
256 DUNPE=101000.0*(1.0-(0.2-0.07*XZ4OE1(3))*TRAV/BODRAD)
C CALCULATE FORCES AND ADDED MASSES FOR EACH BODY SEGMENT
DO 1500 J=1,NBOD
ITES=0
XAX=XAXBOD(J)
RAD=RADBOD(J)
DAX=DAXBOD(J)
SINA=SINBOD(J)
COSA=COSBOD(J)
ISWI=ISWIBO(J)
ISW2=ISW2BO(J)
FROT=VBOD(4)
BODU=RBOI(1)
BODV=RBOI(2)+XAX*VBOD(6)
BODW=RBOI(3)-XAX*VBOD(5)
IF (IUP.EQ.0.0 OR XAX.GT.CGOUF) GOTO 1110
C UPWARD VELOCITY ON REAR OF CAVALTY
TEM1=(CGOUF-XAX)/CAVUP
IF (TEM1.GT.1.0) TEM1=1.0
BODV=BODV+TEM1*UPVEL
BODW=BODW+TEM1*UPWEL
1110 BODF=BODV*SINA
BWF=BODV*COSA-RAD*VBOD(6)*SINA
BFW=BODV*COSA-RAD*VBOD(5)*SINA
CALL DEPTH
IF (IDRY.EQ.1) GOTO 1500
IF (TIM.EQ.1) GOTO 1120
C SET UP IMPACT POSITION
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) GOTO 1170
IF (ISW2.EQ.0) GOTO 1150
C TEST SEGMENT FOR CAVITATION
C BETIC TO BET2C WILL BE THE WETTED SECTOR OF THE SEGMENT
1130 TEM7=U2V2*BODV+BODW*U2V2
U2V2W2=TEM7+BODU*BODW
IF (PCAV.GT.0.0) GOTO 1132
PAMB=10100.0*WDEF-XAX*RBOI(4)/9.81
1132 CAUSEG=PAMB/(515.0*U2V2W2)
IF (CAUSEG.GT.1.0) GOTO 1150
IF (CAUSEG.LT.0.001) CAUSEG=0.001
TEM6=SQR(TEM7)
TEM27=SQR(TEM7)
TEM1=COSA*TEM27
TEM4=U2V2*TEM1/TEM6
IF (SINMAX.LT.TEM4) SINMAX=TEM4
J1=J-1
IF (J.EQ.1) J1=1
C CALCULATE INCIDENCE CONDITION FOR CAVITATION
TEM28=RAE*(SINBOI(J1)*COSA-COSBOI(J1)*SINA)
TEM28=TEM28*-(COSBOI(J1)+COSA)/(DAXBOD(J1)+DAX)
TEM2=0.25*TRAV/RAD
IF (TEM2.GT.0.76) TEM2=0.76
TEM2=TEM2*(0.24+0.8*SINMAX*SINMAX)
CONINC=TEM2*SINMAX-0.34*EXP(-TEM2)-0.08*CAUSEG+0.28*TEM7/U2V2W2
TEM2=CONINC*TEM6
IF ((BOFU+TEM1).GT.TEM2) GOTO 1140
C SEGMENT IS ALL DRY
C CALCULATE GEOMETRY OF AXIAL CAVITY IF PRESENT
TEM2=TEM27/TEM6
TEM3=ABS(BODU)/TEM6
TEM4=ABS(TEM2*SINA/COSA)
IF (TEM4.LE.0.0) GOTO 1400
TEM1=RAE/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.CA VB) CAVB=TEM9
ICS=0
IF (((CAVA+CAVA).LT.TRAV) GOTO 1135
CAVA=0.84*TRAV
CAVB=0.10*TRAV
ICS=1
1135 IF (CAVA.LE.0.0) GOTO 1400
C FIT CAVITY TO NOSE
TEM4=TEM1/CAVB
CXOR=CAVA*SQR(1.0-TEM4*TEM4)
TEM4=TEM4*CAVA*CAVA/CAVB
TEM5=CXOR/SQR(CXOR+TEM4*TEM4)
TEM4 = TEM2 * COSA + ABS(TEM3 * SINA)
IF(TEM5 .LE. TEM4) GOTO 1400
CAVY = BODY / TEM6
CAVZ = BODW / TEM6
CGOR = CXOR - XAX
XAXOR = XAX
SQVYZ = SQRT(CAVY * CAVY + CAVZ * CAVZ)
ATVZVy = ATAN2(CAVZ, CAVY)
SCRAS = 0
IF(XAX .LT. 0.0) OR (ICS .EQ. 0) GOTO 1400
C
UPWARD VELOCITY ON REAR OF CAVITY
CGOUP = CGOR
CAUVF = CAVA
IF=1
UPEL = TEM6 * (0.005 * RBOD(5) + SIGN(0.025, RBOD(5)))
UPWE = TEM6 * (0.005 * RBOD(6) + SIGN(0.025, RBOD(6)))
IF(ABS(XBOD(3)).LT.0.96) GOTO 1400
UPVEL = TEM6 * SIGN(0.025, VBOD(6))
UPWEL = TEM6 * SIGN(0.025, VBOD(5))
GOTO 1400
140
IF((BOFU-TEM1).GE.TEM2) GOTO 1150
C
SEGMENT IS PARTIALLY WET BY CAVITATION CONDITION
TEM2 = (TEM2 - BOFU) / TEM1
TEM1 = ATAN2(BODY, BODW)
TEM3 = SQRT(1.0 - TEM2 * TEM2)
TEM4 = ATAN2(TEM2, TEM3)
BET1C = TEM4 - TEM1
BET2C = 3.1416 - TEM4 - TEM1
GOTO 1200

C
SEGMENT IS COMPLETELY WET BY CAVITATION CONDITION
1150
BET1C = 0.0
BET2C = 6.2831
ITES = 1
GOTO 1200
C
TEST FOR INTERSECTION WITH CAVITY
1170
TEM1 = CGOR + XAX
TEM8 = CAVA
IF(TEM1 .GT. 0.0 .OR. ITES .EQ. 0) GOTO 1175
TEM8 = CAVC
1175
TEM1 = TEM1 / TEM8
TEM1 = TEM1 * TEM1
IF((TEM1 .GE. 1.0) ) GOTO 1180
CAVR = CAVB * SQRT(1.0 - TEM1)
CAV = ABS(XAXOR - XAX) * SQVYZ
TEM1 = CAVR + RAD
IF((CAV .GE. TEM1)) GOTO 1180
TEM1 = CAVR - RAD
IF((CAV .LE. TEM1)) GOTO 1400
TEM1 = -TEM1
IF((CAV .LE. TEM1)) GOTO 1180
TEM1 = (CAV * CAVD + RAD * RAD - CAVR * CAVR) / (2.0 * CAVD * RAD)
TEM2 = SQRT(1.0 - TEM1 * TEM1)
TEM3 = ATAN2(TEM2, TEM1)
BET1C = ATVZVY + TEM3
BET2C = ATVZVY - TEM3
GOTO 1200
1180 IF(ISW2.EQ.0)GOTO 1150
ICROS=1
SINMAX=SQRT(YEL2/V2W2)
GOTO 1130
1200 CALL FORCES(ADMBOD,RBOD,HTTBOD(J),CLBOD,CLBOD)
IF(ICROS.EQ.1.AND.ICS.EQ.0)GOTO 1500
1400 IF(IDEP.EQ.0.OR.DUNPE,LT,0.0.OR.ISW2,EQ.0)GOTO 1500
C UNDERPRESSURE FORCE
TEM4=DUNPE*DAX*RA
TEM1=TEM4*(COS(BET1)-COS(BET2))
TEM2=TEM4*(SIN(BET2)-SIN(BET1))
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
CONTINUE
400 IF(ISECON.EQ.1)GOTO 4500
C UP TO 4500 IS FORCES ON PARACHUTE
CALL XYZ(VP,PAR,XPAR,YPAR,ZPAR)
CALL SEA(WATER,XPAR,YPAR,ZPAR,VPAR(11),VPAR(12),VPAR(13))
C DEPTH OF EXTREMITIES OF PARACHUTE
DEP=SURECG-XAXPAR(1)*DURECG
TEM2=SURECG-XAXPAR(1)*DURECG
TEM7=FARRAD*SATEM1
TEM1=DEP+TEM7
TEM3=DEP-TEM7
TEM14=TEm2-TEM7
DEPME=(TEM1+TEM14)/2.0
IF(DEPMES.GT.0.0)GOTO 3210
C RELATIVE MOTION FIELD IN AIR
RPAR(1)=VPAR(1)-WINDX*XPAR(1)-WINDY*XPAR(2)
RPAR(2)=VPAR(2)-WINDX*XPAR(1)-WINDY*XPAR(2)
RPAR(3)=VPAR(3)-WINDX*XPAR(1)-WINDY*XPAR(2)
RPAR(4)=-9.81*XPAR(3)
RPAR(5)=-9.81*YPAR(3)
RPAR(6)=-9.81*ZPAR(3)
CALL HYDRO(ADMPAR,FAPAR,VPAR,RPAR)
IF(TEM1,LT,0.0)GOTO 3400
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)*XPAR(1)-WATER(2)*XPAR(2)-WATER(3)*XPAR(3)
RPAR(3)=VPAR(3)-WATER(1)*XPAR(1)-WATER(2)*XPAR(2)-WATER(3)*XPAR(3)
RPAR(4)=WATER(4)*XPAR(1)+WATER(5)*XPAR(2)+(WATER(6)-9.81)*XPAR(3)
RPAR(5)=WATER(4)*XPAR(1)+WATER(5)*XPAR(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)GOTO 3240
C PARACHUTE COULD BE PART WET
C SET UP TEST FOR INTERSECTION WITH CAVITY FROM BODY
IF(ICROS.EQ.0)GOTO 3220
IF(CAV,LT,0.01)CAV=0.001
CAVA=2.0*BODRAD/CAV
CAVB=BODRAD*0.13*CAVA
TEM1=TORX-VBOD(11)  
TEM2=TORY-VBOD(12)  
TEM3=TORZ-VBOD(13)  
TEM15=TEM1*XPAR(1)+TEM2*XPAR(2)+TEM3*XPAR(3)  
IF(TEM15.EQ.0.0)GOT03230  
TEM4=VBOD(11)-VPAR(11)  
TEM5=VBOD(12)-VPAR(12)  
TEM6=VBOD(13)-VPAR(13)  
TEM16=TEM4*XPAR(1)+TEM5*XPAR(2)+TEM6*XPAR(3)  
TEM17=-TEM16/TEM1  
IF(TEM17.LE.0.0)GOT03230  
TEM4=YDOD(11)-YPAR(11)  
TEM5=vBAR(12)-YPAR(12)  
TEM6=VEC(13)-YPAR(13)  
TEM16=TEM4*XPAR(1)+TEM5*XPAR(2)+TEM6*XPAR(3)  
TEM17=-TEM16/TEM1  
IF(TEM17.LE.0.0)GOT03230  
TEM18=SQRT(TEM11*TEM1+TEM2*TEM2+TEM3*TEM3)  
TEM1=TEM4+TEM1*TEM17  
TEM2=TEM5+TEM2*TEM17  
TEM3=TEM6+TEM3*TEM17  
CAVY=TEM11*YPAR(1)+TEM21*YPAR(2)+TEM31*YPAR(3)  
CAVZ=TEM11*ZPAR(1)+TEM21*ZPAR(2)+TEM31*ZPAR(3)  
CAVD=SQRT(CAVY*CAVY+CAVZ*CAVZ)  
TEM1=1.0/TEM1  
IF(TEM11.LE.0.0)GOT03230  
TEM1=TEM1*TEM1  
IF(TEM11.GE.1.0)GOT03230  
CAVR=CAVB*SQRT(1.0-TEM11)  
TEM1=CAVR+PARRAD  
IF(CAVR.GE.0.0)GOT03230  
TEM1=CAVR-PARRAD  
IF(CAV11.LE.0.0)GOT03230  
ATUZ=ATAN2(CAVZ,CAVY)  
ICAV=1  
GOT03250  
3225 IF(DEPME.GT.0.0)CALL HYDRO(ADMPAR,VPAR,VPAR,RPAR)  
GOT03400  
3230 ICAV=0  
IF(TEM13.LT.0.0.OR.TEM14.LT.0.0)GOT03250  
C PARACHUTE IS FULLY WET  
3240 CALL HYDRO(ADMPAR,PWPAR,VPAR,RPAR)  
GOT03400  
3250 IF(DEPME.GT.0.0)CALL HYDRO(ADMPAR,VPAR,VPAR,RPAR)  
C CALCULATE FORCES AND ADDED MASSES ON EACH SEGMENT  
DO4500J=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)  
BOFW=RPAR(2)*COSA+VPAR(6)*TEM1  
CALL DEPTH  
IF(IDR1.EQ.0)GOT04500  
IF(1CAV.EQ.0)GOT04350
TEM1 = CAVR + RAD
IF (CAVD, GE, TEM1) GOTO 4350
TEM1 = CAVR - RAD
IF (CAVD, LE, TEM1) GOTO 4500
TEM1 = -TEM1
IF (CAVD, LE, TEM1) GOTO 4350
TEM1 = (CAVD * CAVD * RAD * RAD - CAVR * CAVR) / (2.0 * CAVD * RAD)
TEM2 = SQRT (1.0 - TEM1 * TEM1)
TEM3 = ATAN2 (TEM2, TEM1)
BET1C = ATVZVY + TEM3
BET2C = ATVZVY - TEM3
GOTO 4400

CALL WET BY CAVITY INTERSECTION
4350 BET1C = 0.0
BET2C = 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
TYP = 0.0
TPZ = 0.0
TEM12 = -SHDANG
DO7500I = 1, NSHD
TEM12 = TEM12 + SHDANG
IF (ISHDI(I), EQ, 1) GOTO 7450
C EXTENSION OF LINE
TEM1 = TLX - PARTL
TEM6 = PARRAD * COS(TEM12)
TEM2 = TLY - TEM6
TEM7 = FARRAD*SIN(TEM12)
TEM3 = TLZ - TEM7
TEM4 = SQR(TEM1*TEM1 + TEM2*TEM2 + TEM3*TEM3)
TEM5 = TEM4 - TLFL
IF(TEM5 .LE. 0.0) GOTO 7500

C RATE OF EXTENSION OF LINE
TEM8 = BODU - (VPAR(1) + VPAR(5)*TEM7 - VPAR(6)*TEM6)
TEM9 = BODW - (VPAR(2) + PARTL - VPAR(4)*TEM7)
TEM10 = BODW - (VPAR(3) + VPAR(4)*TEM6 - VPAR(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*TLFP
IF(TEM4 .GT. TEM9) TEM4 = TEM9
IF(TEM4 .LT. -TEM9) TEM4 = -TEM9
TEM8 = TEM8 + TEM4
IF(TEM8 .GT. TLFB) ISHD(I) = 1
TFX = TFX + TEM8*TEM1
TFY = TFY + TEM8*TEM2
TPZ = TPZ + TEM8*TEM3
GOTO 7500

7450 ITEM = 0
C AT LEAST ONE SHROUD LINE IS BROKEN
DO 7455 J = 1, NSHD
7455 ITEM = ITEM + ISHD(J)
IF(ITEM .EQ. NSHD) GOTO 7550
CONTINUE

C TEAR STRIP BEHAVIOUR
TEM1 = SQR(TFX*TFX + TPY*TPY + TPZ*TPZ)
IF(TEM1 .LT. TLFT) GOTO 7600
IF(TLFL .GT. TLFTL) GOTO 7530
C TEAR STRIP YIELDS
TLFL = 1.001*TLFL
GOTO 7000

7530 IF(TEM1 .LT. TLFF) GOTO 7600
C PARACHUTE HAS BROKEN FREE FROM BODY
7550 TREL = 10000.0
ISECON = 1
GOTO 5500

C TORSIONAL TORQUE
7600 TEM2 = TWA
IF(TEM2 .GT. 3.0) TEM2 = 3.0
IF(TEM2 .LT. -3.0) TEM2 = -3.0
TEM1 = TEM1*TEMTWIST*SCLPAR*SCLPAR
C ADD SHROUD LINE FORCES TO PARACHUTE AND BODY
ADMPAR(1, 7) = ADMPAR(1, 7) + TFX
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
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) - TME*S1
ADMBOD(5, 7) = ADMBOD(5, 7) - TBZ*BODTL - TME*S2
ADMBOD(6, 7) = ADMBOD(6, 7) + TBY*BODTL - TME*S3

CALL ENERT(ADMBOD, BDMBOD, RBOD, YBOD, DBOD, XBO, YBOD, ZBOD, PMBOD, 1PYBOD, PBZBOD, PBXBO, PB1YBOD, DT)
CALL ENERT(ADMPAR, BPMAR, RPAR, DPAR, XPAR, YPAR, ZPAR, PMPAR, 10.0, 0.0, PXPAR, PYPAR, DT)
CALL DERIV(ADMPAR, BPMAR, RPAR, DPAR, XPAR, YPAR, ZPAR, DT)
C PARACHUTE DEPLOYMENT
SCLPAR = SCLPAR + SLDPAR*(RPAR(1) - ABS(RPAR(2)) - ABS(RPAR(3)))*DT
TWA = TWA + (VBO(4) - VPAR(4))*DT
IF(SCLPAR .GT. SCLMAX) SCLPAR = SCLMAX
IF(SCLPAR .LT. SCLMIN) SCLPAR = SCLMIN
IF(SCLOLD .EQ. SCLMAX) AND (SCLPAR .EQ. SCLMAX) GOTO 5700

6005 TEM2 = SCLPAR*SCLPAR
DO 6100 I = 1, 16
FAFAAR(I) = PAPER(I) * TEM2
6100 PWFAAR(I) = PWFAAR(I) * TEM2
SCLOLD = SCLPAR
PARRAD = SCLPAR*PBRRAD
GOTO 5700
C BODY ALONE
5500 CALL ENERT(ADMBOD, BDMBOD, RBOD, YBOD, DBOD, XBO, YBOD, ZBOD, PMBOD, 1PYBOD, PBZBOD, PBXBO, PB1YBOD, DT)
IF(IFIRST .EQ. 0) GOTO 5505
C FIRST PASS THROUGH PROGRAMME TO SET UP BDMBOD ETC.
IFIRST = 0
GOTO 5505
5505 CALL DERIV(ADMBOD, VBOD, DBOD, XBO, YBOD, ZBOD, DT)
C INCREMENT TIME
5700 T = T + DT
C CHECK PARACHUTE STATUS
IF(T .GT. TREL1 AND .ISECON .EQ. 1) GOTO 6000
IF(T .GT. TREL2) SCLMAX = SCL2
IF(T .LT. POIT) GOTO 200
C OUTPUT A RECORD
C THE WRITE STATEMENTS AND NEED TO CALL EULER SHOULD BE VARIED AS REQUIRED
5705 POIT = T + POIT
CALL EULER(TEM1, TEM2, TEM3, XBO, YBOD, ZBOD)
IF(.ISECON .EQ. 1) GOTO 5900
CALL EULER(TEM4, TEM5, TEM6, XPAR, XPAR, 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)
GOTO 5900
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)
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
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(9)-V(7)*V(10))
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(9)+V(8)*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

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,SEA,SEAW,SEAC,COMX,COMY,WDEF,SURMY,SURMZ,
1STOTEM1,ATSYSZ,SUERCG,DURECG,BET1D,BET2D,COR,XAXOR,CAVA,CAVB,
2SQVYVZ,ATVZVY,BET1C,BET2C,BOFU,BOFW,PCAV,XAX,RAD,DIAX,SINA,
3COSA,ISW1,ISW2,ITES,ICROS,IDEF,DRY,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
30.

\[ SOTEM1 = \sqrt{\text{TEM1}} \]
\[ ATSYSZ = \tan^{-1}(\text{SURMY} \times \text{SURMZ}) \]
\[ SURECG = ZN \times (\text{SEAA} \times S - ZF'OS) \]
\[ DURECG = XN \times X(1) + YN \times X(2) + ZN \times X(3) \]
RETURN
END

SUBROUTINE HYDRO(A, P, V, R)
C
FULLY IMMERSED FORCES AND ADDED MASSES
DIMENSION F(16), A(6,7), V(13), R(6)
U = \text{ABS}(R(1))
U2 = R(1) \times U
UP = V(4) \times U
UQ = U \times V(5)
UR = U \times V(6)
UV = U \times R(2)
UW = U \times R(3)
WVAB = \sqrt{R(2) \times R(2) + R(3) \times R(3)}
V2 = R(2) \times WVAB
W2 = R(3) \times WVAB
QA2 = V(5) \times WVAB
RA2 = V(6) \times WVAB
FORCES
A(1,7) = P(1) \times U2 + F(14) \times R(4)
A(2,7) = P(3) \times U2 + F(14) \times R(4)
A(3,7) = -P(3) \times U2 + F(14) \times R(5)
A(4,7) = -P(15) \times R(6) + P(4) \times W2 + P(12) \times W2 + P(13) \times QA2
A(5,7) = P(15) \times R(5) - P(4) \times UQ + P(12) \times UR - P(12) \times R(5)
A(6,7) = F(16) \times UP
A(6,6) = P(9)
RETURN
END

SUBROUTINE DEPTH
C
CALCULATES THE INTERSECTION OF A SEGMENT WITH THE SEA SURFACE
C
BET1 TO BET2 IS THE INTERSECTION SECTOR
COMMON/BLOCK1/T, SEAA, SEAW, SEAC, COMX, COMY, WDEF, SURMY, SURMZ,
1SOTEM1, ATSYSZ, SURECG, DURECG, BET1D, BET2D, CGOR, XAXOR, CAVA, CAVB,
2SQVVZ, ATVZVY, BET1C, BET2C, BOFU, BOFY, PCAV, XAX, RAD, DAX, SINA,
3COSA, ISW1, ISW2, ITES, ICROS, IDEP, IDRY, BODU, BODV, BODW, PROT
IDEP = 0
IDRY = 0
SURE = SURECG - XAX \times DURECG
SURE = SURE / SQRT(1 - SURE \times SURE)
IF(SURE.LE.RAD)200
IDEP = 1
RETURN
120
IF(SURE.LT.-RAD)200
SURE = SURE / RAD
TEM1 = SQR(1.0 - SURE \times SURE)
TEM2 = ATAN2(SUREP 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(AFRPHT,CLIFT,CDRA)
C FORCES AND ADDED MASSES FOR EACH WET SECTOR
DIMENSION A(697), PR(6)
COMMON/BLOCK1/T, SEAA, SEAW, SEAC, COMX, COMY, WDEF, SURMY, SURMZ,
1STEM1, ATEYSZ, SURECG, DURECG, BET1D, BET2D, CGOR, XAXOR, CAVA, CAVB,
2SVYVZ, AVUVY, BET1C, BET2C, BOFU, BOFY, BOFV, PCAV, XAX, RAD, DAX, SINA,
3COSA, ISW1, ISW2, ITES, ICROS, IDEP, IDRY, BODU, BODV, BODW, PROT
C SORT OUT ACTUAL WETTED SECTOR FROM DEPTH AND CAVITATION DATA
ISEG = 0
IF(IDEF.EQ.1) GOTO 300
IF(ITES.EQ.0) GOTO 205
BET1C = BET1D
BET2C = BET2D
GOTO 300
205 TEM2 = SCALE(BET2D - BET1D)
TEM3 = SCALE(BET1C - BET1D)
TEM4 = SCALE(BET2C - BET1D)
220 IF(TEM4.LT.0.0) GOTO 240
IF(TEM3.GT.0.0) GOTO 220
BET1C = TEM3 + BET1D
IF(TEM4.GT.0.0) GOTO 230
225 BET2C = TEM4 + BET1D
GOTO 300
230 BET2C = TEM2 + BET1D
GOTO 300
240 BET1C = BET1D
IF(TEM4.GT.0.0) GOTO 225
IF(TEM3.GT.0.0) GOTO 220
BET2C = TEM4 + BET1D
ISEG = 1
BET3C = TEM3 + BET1D
BET4C = TEM2 + BET1D
C CALCULATE FORCES AND ADDED MASSES
300 BET1C = SCALE(TEM1)
BET2C = SCALE(BET2C)
IF(BET2C.LT.0.0) BET2C = BET2C + 0.283105
SINB1 = SIN(BET1C)
SINB2 = SIN(BET2C)
COSB1 = COS(BET1C)
COSB2 = COS(BET2C)
IF(ISW1.EQ.1 .AND. ISW2.EQ.0) GOTO 500
C AI TO FI INTEGRALS USED FOR FORCES AND MASSES
AI = BET2C - BET1C
BI = SINB2 - SINB1
CI = COSB1 - COSB2

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 = (SIN(BET2C * 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*SIN - 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 * (BOFW * (COSB1 + COSB2 + TEM7 + TEM7) + BOFW * 
1 (SINB1 + SINB2 + TEM8 + TEM8))
TEM8 = CDRA6 * TEM2 * ABS(TEM7)
TEM9 = TEM8 * TEM5

TEM10 = BOFU * AI + BOFW * EI + BOFW * CI
TEM11 = BOFU * BI + BOFW * DI + BOFW * EI
TEM12 = BOFU * CI + BOFW * EI + BOFW * FI

IF (ISW2.EQ.0) GOTO 350

NON LINEAR FORCE

DAFX = TEM8 * TEM4 * (TEM10 + TEM10 - TEM7 * AI)
DAFY = TEM9 * (TEM11 + TEM11 - TEM7 * BI)
DAFZ = TEM9 * (TEM12 + TEM12 - TEM7 * CI)
IF(ISW1.EQ.1)GOTO400

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
GOTO400

C     LINEAR FORCE
350    TEM2=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
GOTO900

C     CRUCIFORM TAIL
500    TEM6=1030.0*XAX
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)GOTO520
TEM5=RAD*(SINB1*COSB2-COSB1*SINB2)/(SINB1-SINB2)
IF(SINB1.GT.0.0)GOTO510
Y1=TEM5
GOTO540
510    Y2=TEM5
GOTO540
520    IF((SINB1+SINB2).GT.0.0)GOTO530
IF((BET2C-BET1C).GT.3.14159)GOTO540
GOTO700
530    IF(COSB1.GT.COSB2)GOTO700
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
DAFZ=TEM1O*(BODW*AI+PROT*BI)
A(3,7)=A(3,7)-DAFZ
A(4,7)=A(4,7)-TEM1O*(BODW*BI+PROT*CI)
IF(ABS(4BI)*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(COS1*BOSB2 .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-BET4C) .GT. 3.14159)GOTO740
GOTO900
730 IF(SINB2,GT. SINB1)GOTO900
740 AI=Z2-Z1
BI=AI*(Z2*Z2)/2.0
CI=(Z2*Z2*Z2-Z1*Z1)/3.0
TEM7=TEM6*HT*AI/(RAD+RAD)
TEM9=TEM7*XAX
C ADDED MASSES AND FORCES 'VERTICAL FIN'
A(2,7)=A(2,7)+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)+TEM9*XAX*AI
DAFY=TEM10*(BODW*AI+PROT*BI)
A(2,7)=A(2,7)-DAFY
A(4,7)=A(4,7)+TEM10*(BODW*BI+PROT*CI)
IF(ABS(4BI)*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,V,D,X,Y,Z,PM,RY,PZ,PIV,PIY,DT)
C FORCES DUE TO GRAVITATIONAL AND INERTIAL SOURCES BUT
C EXCLUDING TERMS CONTAINING DU/DT,DU/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)
QR=V(1)*V(5)
UR=V(6)*V(1)
VP=V(4)*V(2)
VR=V(2)*V(6)
WF = V(3) * U(4)  
WG = V(3) * U(5)  
YM = FM * PY  
ZM = FM * PZ  
X3 = X(3) * 9.81  
Y3 = Y(3) * 9.81  
Z3 = Z(3) * 9.81

**MOTION FORCES**

A(1,7) = A(1,7) - PM * (WG - VR + PY * P2 + PZ * PR - X3)  
A(2,7) = A(2,7) - PM * (UR - WP - PY * (R2 + P2) + PZ * QR - Y3)  
A(3,7) = A(3,7) - PM * (VP - UQ + PY * QR - PZ * (F2 + 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 * (WG - VR - X3)  
A(6,7) = A(6,7) - (PIY - PIX) * PQ - YM * (VR - QW + X3)

**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)

**SHEDDING MASS**

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) GOTO 04

**ADDED MASS FORCES**

A(1,7) = A(1,7) - R(I) * (A(3, I) * R(5) - A(2, I) * R(6)) + A(I, 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)  
1-A(5, I) * R(6) + A(4, I) * S(I)  
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)
1-A(4,1)*R(5))+A(6,1)*S(I)
DO10J=1,6
IF(TEM1.LT.TEM2)GOTO10
C RATE OF CHANGE OF MASS
D(J)=D(J)-R(I)*(A(J,1)-B(J,1))
C OLD ADDED MASSES
10 B(J,1)=A(J,1)
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(DT.GT.TEM1)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,V,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)
DO1=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,1)
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)
\[
DV(1) = A(1, 7) - A(1, 6) * DV(6) - A(1, 5) * DV(5) - A(1, 4) * DV(4) - A(1, 3) * DV(3) - 1A(1, 2) * DV(2)
\]

5850  \( V(I) = V(I) + DV(I) \)

5860  \( V(I) = V(I) + DV(I) \)

5870  \( V(I) = V(I) * \text{TEM} \)

FUNCTION SCALE(X)

MAKE ANGLE X IN RANGE 0 TO 2*PI

10  IF (X.GE.0.0) GOTO 20

X = X + 6.283185
GOTO 10

20  IF (X.LT.6.283185) GOTO 30

X = X - 6.283185
GOTO 20

30  SCALE = X

RETURN

ENDP

SUBROUTINE EULER(S,P,T,P,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

ENDP
FIG. 1. THE PHASES OF WATER ENTRY

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
FIG. 2. A TYPICAL LIGHT WEIGHT TORPEDO

RELATIVE DENSITY = 1.0
SCALE = 1/20
FIG. 3. A TYPICAL AIR DELIVERY PARACHUTE SYSTEM

SCALE 1/50
FIG. 4. A BODY SEGMENT
FIG. 5. THE GEOMETRY OF WATER ENTRY
FIG. 6. THE VARIATION OF PITCH ANGLE AND AXIAL VELOCITY WITH TIME
FIG. 7. THE VARIATION OF PITCH ANGLE AND AXIAL VELOCITY WITH TIME
FIG. 8  THE VARIATION OF PITCH ANGLE AND AXIAL VELOCITY WITH TIME
UNCLASSIFIED/UNLIMITED
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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A Mathematical Model of Water Entry

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