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PARACHUTE DYNAMICS AND STABILITY ANALYSIS OF THE QUEEN MATCH RECOVERY SYSTEM

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ABSTRACT

System deceleration dynamics and stability are fundamental performance parameters in establishing the design of a space recovery system. This paper presents the findings of a one month study of analytical and computational work in predicting the parachute dynamics and system stability of the Queen Match Recovery System. The study's primary objective being to formulate a mathematical model for the descent dynamics of a parachute/satellite system and to use that model as the basis for a computer simulation, stability analysis, and parametric optimization of the Queen Match Recovery System.

NOMENCLATURE

$\vec{C}_i$	=	Velocity vector of body i, i = 1, 2, 3
C_{Mi}	=	Aerodynamic moment coefficient of body i
C_{Ni}	=	Aerodynamic normal force coefficient of body i
C_{Ti}	=	Aerodynamic tangential force coefficient of body i
D_o	=	Parachute nominal diameter
$\vec{F}_i$	=	Aerodynamic forces of body i
g	=	Gravitational acceleration
$\vec{h}_i$	=	Angular momentum of body i
I_A	=	Principal apparent moments of inertia matrix of the parachute
I_i	=	Principle moments of inertia, body i
$\vec{M}_i$	=	Moment matrix of body i
m_i	=	Mass of body i
M_{1A}	=	Apparent mass tensor of parachute
P_i	=	Angular velocity about x-axis; body i
Q_i	=	Angular velocity about Y-axis; body i
R_i	=	Angular velocity about Z-axis; body i
S_{oi}	=	Nominal area of body i
U_i	=	Linear velocity along X-axis, body i
V_i	=	Linear velocity along Y-axis, body i
W_i	=	Linear velocity along Z-axis, body i
$\vec{v}_i$	=	Velocity of body i with respect to the air
β_i	=	Side-slip angle of body i
ϕ, θ, γ_i	=	Euler angles, body i
$\vec{\Omega}_i$	=	Angular velocity vector, body i
ρ	=	Air density

Subscripts

1	=	Parachute
2	=	Riser
3	=	Vehicle (SPV)

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INTRODUCTION

Queen Match was an SDI sensor experiment that was launched by sounding rockets. Upon completion of its mission, the Queen Match Sensor Payload Vehicle (SPV) would re-enter the earth's lower atmosphere initially decelerated by body drag (a paper to be presented by Mr. Don Tong of the Boeing Aerospace Company). Subsequently, a two stage parachute system was deployed for final system deceleration and recovery. After a number of previous successful recoveries, an SPV was lost in the summer of 1988. Upon the loss of the SPV, a thorough investigation and analysis of the recovery process by the Boeing Aerospace Company (BAC) was conducted. From this analysis, the possibilities of a tumbling or base down SPV which wrapped up the drogue, an excessively short drogue riser which would reduce the drogue effective drag, aerodynamic heating within the parachute compartment, or failure of the drogue to deploy were all considered. The culmination of this investigation resulted in a competitive solicitation for a new parachute recovery system that would overcome the potential failure modes identified in Boeing's investigation. Pioneer Aerospace Corporation was awarded the contract and began development of the new recovery system in January 1989. The target date for the next Queen Match was six months after contract award which allowed only five months from design conception to qualification tests and final hardware delivery. Due to the concerns of the previous recovery system, and because the contract schedule did not permit time to conduct extensive full scale development tests, much emphasis was placed on component development testing and system analysis. Of most importance in the analysis was the flight behavior of the parachute and the SPV during deployment and inflation. This paper presents the findings of a one month study of analytical and computational work in predicting the parachute dynamics and system stability of the Queen Match Recovery System. A paper depicting the direct design aspects and testing of the Queen Match Recovery System based upon the aforementioned analysis is given by Mr. Paul Woodruff and Mr. William Everett of the Pioneer Aerospace Corporation.

RECOVERY SYSTEM ANALYSIS

Technical Approach

The technical approach is structured to access the descent dynamics and stability characteristics of a general parachute-riser-vehicle combination. The advantage to a general case study is the ability to study a wider range of possible configurations with a minimum number of simplifying assumptions. Two primary tasks describe the approach taken in the analysis of the problem.

* The parachute-riser-vehicle configuration was arranged according to specifications and information provided by the contractor and particular requirements of the descent conditions. A mathematical model incorporating an elastic riser, three bodies each with six degrees of freedom was developed. A complete software package was written to perform the non-linear simulation.

* Using the nonlinear software package, simulations of the nonlinear dynamics of the parachute-riser-vehicle were made for a variety of initial conditions. Particular attention was paid to equilibrium trajectories and dynamic stability of the recovery system.

In short, the technical objective of this study was to as accurately as possible, analyze the descent dynamics, predict stability characteristics, identify performance parameters and thereby aide in the design of the Queen Match SPV Recovery System.

General Recovery Sequence

The Queen Match SPV recovery process begins with the re-entry of the SPV from earth orbit. The SPV then continues on a ballistic trajectory modified by its own aerodynamics descending approximately to 15,000 feet. At 15,000 feet, the drogue parachute (9.7-foot-diameter conical ribbon) mortar deploys and inflates to a reefed mode, moderately stabilizing and decelerating the SPV. At approximately 6 seconds after mortar deployment, the drogue disreefs to its full-open drag area of 38 ft^2, and further stabilizes and decelerates the SPV.

Another 10.5 seconds after drogue disreef, the aft cover is released from the SPV and pulled free by the drogue. A small bag attached to the aft cover then deploys a 4.5-foot-diameter Ribless Guide Surface Parachute which acts as a pilot parachute for the main canopy. The pilot chute inflates, extracts the main pack and deploys the 71.8-foot Triconical Recovery Parachute. The Triconical Recovery Parachute is reefed for 4 seconds whereupon it inflates to full-open. Full-open main canopy occurs at approximately 7000 feet.

The analysis of the descent dynamics in this paper is focused upon the interaction of the drogue parachute and the SPV. The analysis begins at mortar deployment of the drogue and ends at aft cover release.

The recovery system components, the drogue parachute, the main parachute and the SPV were chosen in accordance with the requirements established by the contractor. The mass and inertial properties of the SPV have changed during the course of this study. However, the inertial properties and mass used are representative and provide an adequate model of the final configuration.

Simplifying Assumptions

Several simplifying assumptions are employed which reduce the computational magnitude without compromising the general nature of the problem. Others are made to improve the math model to the extent that the state of the art allows. The simplifying assumptions are as follows:

* Upon full open the parachute is assumed to be axisymmetric and has a fixed shape.

* The riser connecting the parachute and SPV is elastic and transmits only axial forces to the attach points on the SPV and parachute axes of symmetry. Furthermore, the riser is constrained not to rotate about its body-fixed Z axis.

* The SPV is a rigid, axisymmetric body.

* The aerodynamic center of pressure of the parachute coincides with the parachute center of mass.

Recovery Subsystem Sequence Of Operations

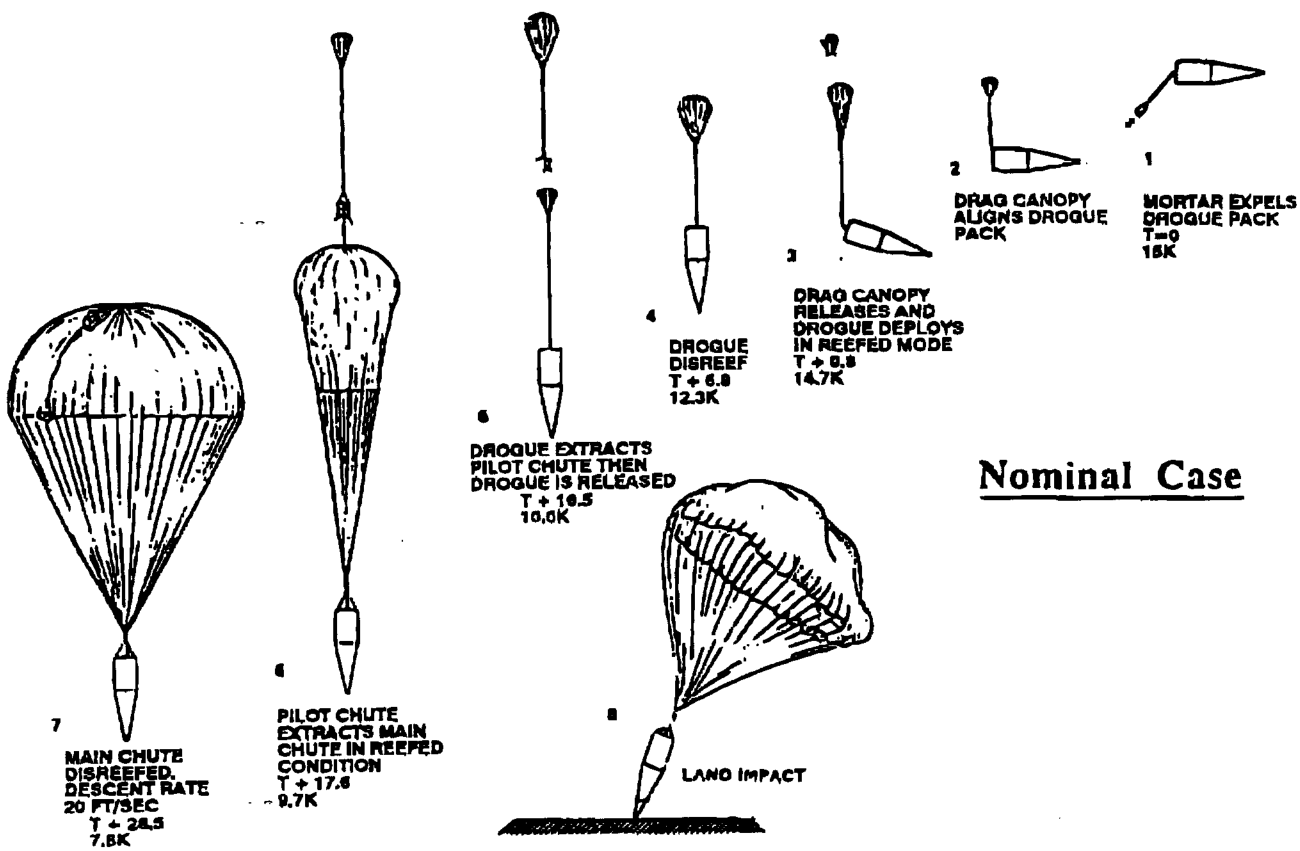


Figure 1

* The aerodynamic center of the SPV is constrained to remain on the SPV's axes of symmetry and does not necessarily coincide with the center of mass.

* The hydrodynamic effects of the parachute are considered and are represented by tensors of apparent mass and apparent moments of inertia.

* The hydrodynamic effects of the SPV are not considered.

* The separation distance between the SPV and the parachute is considered sufficient to neglect forebody wake effects.

* A flat earth is used for trajectory calculations.

DEVELOPMENT OF A NONLINEAR DYNAMICAL MODEL OF THE PARACHUTE/RISER/SPV SYSTEM

The parachute/riser/SPV system is modeled as three-bodies each with six-degrees-of-freedom. Since the parachute and SPV are connected by the riser, and given the constraints of the riser, the parachute-riser-SPV system reduces to a 15-degree-of-freedom problem.

The Differential Equations of Motion

The reference frames of the three-body-system are shown in Figure 2. Four right handed orthogonal reference frames are needed to specify the motions of the parachute (system 1), the riser (system 2), and the SPV (system 3). The fourth orthogonal reference frame is that of the earth whose origin O_E is fixed on an assumed flat earth, and where Z_E is direct downward, X_E is horizontal, and Y_E is cross range to the right.

In the body-fixed moving frames of systems 1, 2, and 3 the origins of the parachute and the SPV are at their respective centers of mass, O_1 and O_3. The riser origin is at the parachute/riser confluence point. Z_i axes are aligned with the axes of symmetry with Z_1 directed toward the parachute/riser confluence point, Z_2 directed toward the SPV attach point, and Z_3 directed toward the nose of the SPV. The X_i and Y_i axes are determined by the initial deployment conditions.

The Euler angles Φ_i, Θ_i, γ_i describe the orientation of the body-fixed reference frames with respect to the earth fixed inertial frame. The ordered rotations are γ_i about Z_i followed by Θ_i about Y_i and ϕ_i about X_i as illustrated in Figure 3.

The direction cosine matrix $[B^j]$ in terms of the Euler angles and the sequence γ, Θ, Φ, is as follows:

$$[B^j] = \begin{bmatrix} \cos\Theta_j\cos\gamma_j & \cos\Theta_j\sin\gamma_j & -\sin\Theta_j \\ \sin\Theta_j\cos\gamma_j\sin\phi_j - \cos\phi_j\sin\gamma_j & \sin\phi_j\sin\Theta_j\sin\gamma_j + \cos\phi_j\cos\gamma_j & \sin\phi_j\cos\Theta_j \\ \cos\phi_j\sin\Theta_j\cos\gamma_j + \sin\phi_j\sin\gamma_j & \cos\phi_j\sin\Theta_j\sin\gamma_j - \sin\phi_j\cos\gamma_j & \cos\phi_j\cos\Theta_j \end{bmatrix} \quad (1\text{-A})$$

Conversely,

$$[B^j]^T = \begin{bmatrix} \cos\Theta_j\cos\gamma_j & \sin\Theta_j\cos\gamma_j\sin\phi_j - \cos\phi_j\sin\gamma_j & \cos\phi_j\sin\Theta_j\cos\gamma_j + \sin\phi_j\sin\gamma_j \\ \cos\Theta_j\sin\gamma_j & \sin\phi_j\sin\Theta_j\sin\gamma_j + \cos\phi_j\cos\gamma_j & \cos\phi_j\sin\Theta_j\sin\gamma_j - \sin\phi_j\cos\gamma_j \\ -\sin\Theta_j & \sin\phi_j\cos\Theta_j & \cos\phi_j\cos\Theta_j \end{bmatrix} \quad (1\text{-B})$$

The elements of the cosine matrix are written B^j_{ik} where i is the row number and k is the column number.

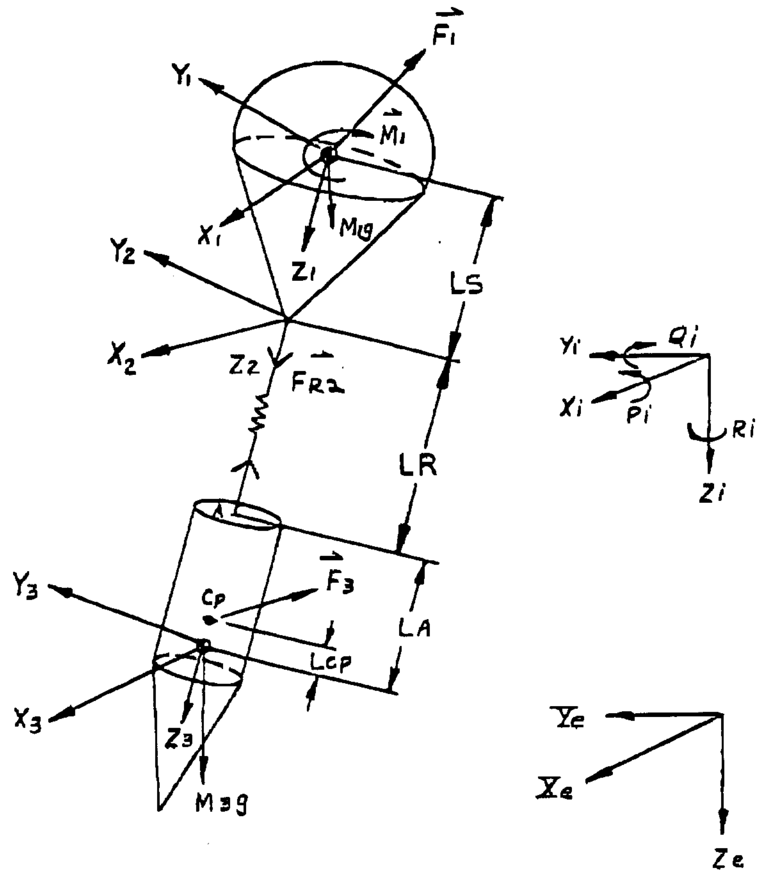
The Euler angle rates are given by:

$$\dot{\gamma}_j = (Q_j\sin\phi_j + R_j\cos\phi_j)\sec\Theta_j \quad (2\text{-A})$$

$$\dot{\Theta}_j = Q_j\cos\phi_j - R_j\sin\phi_j \quad (2\text{-B})$$

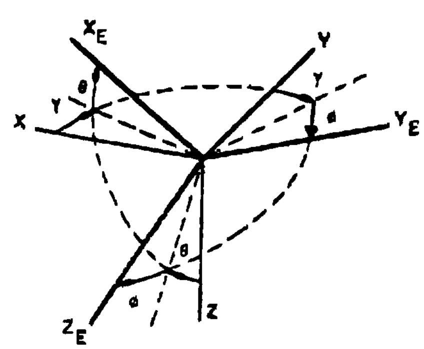
$$\dot{\phi}_j = P_j + (Q_j\sin\phi_j + R_j\cos\phi_j)\tan\Theta_j \quad (2\text{-C})$$

The indices j = 1, 2, 3 correspond to the parachute, riser, and SPV, respectively.



FBD QUEEN MATCH
INFLATION AND
CANOPY DESCENT

Figure 2



Euler Angle Rotations

Figure 3

The Dynamics Of Motion: Force And Moment Equations

Parachute Equations of Motion

The equations of motion for the parachute are divided into force and moment equations about the center of mass.

The force equations, written in vector notation, are:

$$\vec{F}_1 + m_1 [B^1] \vec{g} + [B^1][B^2]^T \vec{F}_{r2} = m_1 (\dot{\vec{C}}_1 + \vec{\Omega}_1 \times \vec{C}_1) + [M_{1a}] (\dot{\vec{C}}_1 + \vec{\Omega}_1 \times \vec{C}_1) \quad (3)$$

where F_{r2} is the riser force,

$$\vec{F}_{r2} = \begin{bmatrix} 0 \\ 0 \\ F_{r2} \end{bmatrix}$$

m_1 is the parachute mass and

$$M_{1a} = \begin{bmatrix} M_{1AX} & 0 & 0 \\ 0 & M_{1AY} & 0 \\ 0 & 0 & M_{1AZ} \end{bmatrix} \quad (4)$$

is the apparent mass tensor resulting from the air mass accelerations produced by the parachute motion.

Furthermore

$$\vec{F}_1 = \begin{bmatrix} F_{1x} \\ F_{1y} \\ F_{1z} \end{bmatrix} \qquad \vec{g} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\vec{C}_1 = \begin{bmatrix} U_1 \\ V_1 \\ W_1 \end{bmatrix} \qquad \vec{\Omega}_1 = \begin{bmatrix} P_1 \\ Q_1 \\ R_1 \end{bmatrix}$$

$$\dot{\vec{C}}_1 = \begin{bmatrix} \dot{U}_1 \\ \dot{V}_1 \\ \dot{W}_1 \end{bmatrix}$$

The aerodynamic forces are given by:

$$F_{1x} = C_{N1} (q_1 S_{01}) \cos B_1 \quad (5)$$

$$F_{1y} = C_{N1} (q_1 S_{01}) \sin B_1 \quad (6)$$

$$F_{1z} = - C_{T1} q_1 S_{01} \quad (7)$$

where

$$q_1 = 1/2\rho |\vec{v}_1|^2 \text{ (dynamic pressure)} \quad (8)$$

$$B_1 = \tan^{-1} \left[\frac{V_1}{U_1} \right] \text{ (side-slip angle)} \quad (9)$$

The moment equations about the parachute body-fixed axis at the parachute center of mass can be written as

$$\vec{M} = \dot{\vec{h}}_1 + \vec{\Omega}_1 \times \vec{h}_1 \quad (10)$$

where

$$\vec{h}_1 = [I_1] \vec{\Omega}_1$$

$$= \begin{bmatrix} I_{xx1} & 0 & 0 & P_1 \\ 0 & I_{yy1} & 0 & Q_1 \\ 0 & 0 & I_{zz1} & R_1 \end{bmatrix} \quad (11)$$

or,

$$\vec{h}_1 = \begin{bmatrix} P_1 I_{xx1} \\ Q_1 I_{yy1} \\ R_1 I_{zz1} \end{bmatrix} \quad (12)$$

The apparent moments of inertia resulting from the air mass accelerations are:

$$[I_A] = \begin{bmatrix} I_{xx1A} & 0 & 0 \\ 0 & I_{yy1A} & 0 \\ 0 & 0 & I_{zz1A} \end{bmatrix}$$

Using the parallel axis theorem, a combined moment of inertia matrix can be written as:

$$[I_1^*] = \begin{bmatrix} I^*_{xx1} & 0 & 0 \\ 0 & I^*_{yy1} & 0 \\ 0 & 0 & I^*_{zz1} \end{bmatrix}$$

Hence the moment equation may be written as:

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} P_1 I^*_{xx1} \\ Q_1 I^*_{yy1} \\ R I^*_{zz1} \end{bmatrix} + \begin{bmatrix} P_1 \\ Q_1 \\ R_1 \end{bmatrix} \times \begin{bmatrix} P_1 I^*_{xx1} \\ Q_1 I^*_{yy1} \\ R I^*_{zz1} \end{bmatrix} \qquad (13)$$

The moment forces of the parachute are as follows. Note, it is assumed for the parachute that the center of mass (C.M.) and aerodynamic center are coincident.

$$\vec{M} = \vec{M_1} + \vec{L_S} \times ([B^1][B^2]^T \vec{F}_{R2}) \qquad (14)$$

where $\vec{M_1}$ = Parachute aerodynamic moments

$\vec{L_s}$ = Distance from C.M. to parachute/riser confluence point

and

$$\vec{M_1} = \begin{bmatrix} -C_{M1}(q_1 S_{o1}) \sin\beta_1 L_{M1} \\ C_{M1}(q_1 S_{o1}) \cos\beta_1 L_{M1} \\ 0 \end{bmatrix} \qquad (15)$$

where C_{M1} = Aerodynamic moment coefficient

L_{M1} = Reference length

Also

$$\vec{L_S} = \begin{bmatrix} 0 \\ 0 \\ L_S \end{bmatrix}$$

The moment reference length, L_{M1}, is generally one nominal diameter ahead of the skirt plane of the parachute.

To write the aerodynamic moments about the body fixed axis located at the parachute center of mass, L_{M1}, must be defined as follows.

Since the normal force of the parachute is experimentally measured at the vent of the canopy, the height of the canopy plus the moment reference length is given by:

$$1.325\ D_o = 0.325\ D_o + D_o \qquad (16)$$

(Note: the distance from the vent to parachute C.M. is 0.325 Do.)

The moment then is:

$$N(1.325\ D_o) = C_M q S_o D_o \qquad (17)$$

where

N = Normal force acting on vent of parachute

Conducting the necessary matrix operations and solving for $\dot{U}_1$, $\dot{V}_1$, and $\dot{W}_1$, respectively yields:

$$\dot{U}_1 = [F_{1X} + m_1 B^1{}_{13} g + B_{s1} F_{R2}]/(m_1 + M_{1AX}) + V_1 R_1 - W_1 Q_1 \quad (18)$$

$$\dot{V}_1 = [F_{1Y} + m_1 B^1{}_{23} g + B_{s2} F_{R2}]/(m_1 + M_{1AY}) + W_1 P_1 - U_1 R_1 \quad (19)$$

$$\dot{W}_1 = [F_{1Z} + m_1 B^1{}_{33} g + B_{s3} F_{R2}]/(m_1 + M_{1AZ}) + V_1 Q_1 - V_1 P_1 \quad (20)$$

where

$$\begin{bmatrix} B_{S1} \\ B_{S2} \\ B_{S3} \end{bmatrix}$$

are the elements of the third column of the matrix operation $[B^1][B^2]^T$

similarly,

$$\dot{P}_1 = [1/I^*_{xx1}][-C_{M1}(q_1 S_{01})\sin\beta_1(0.325\ D_o/1.325) - L_s B_{s2} F_{r2} - (I^*_{zz1} - I^*_{yy1})\ Q_1\ R_1] \quad (21)$$

$$\dot{Q}_1 = [1/I^*_{yy1}][C_{M1}(q_1 S_{01})\cos\beta_1(0.325\ D_o/1.325) + L_s B_{s1} F_{r2} - (I^*_{xx1} - I^*_{zz1})\ R_1\ P_1] \quad (22)$$

$$\dot{R}_1 = [1/I^*_{zz1}][(I^*_{xx1} - I^*_{yy1})\ P_1\ Q_1] \quad (23)$$

SPV Equations of Motion

The equations of motion for the SPV are written in the same manner as the parachute, with the exception that the apparent mass and apparent moment of inertia effects are not considered.

The force equations of the SPV, written in vector notation, are:

$$\vec{F}_3 + m_3\,[B^3]\,\vec{g} - [B^3][B^2]^T\,\vec{F}_{R2} = m_3\,(\dot{\vec{C}}_3 + \vec{\Omega}_3 \times \vec{C}_3) \quad (24)$$

where

$$\vec{C}_3 = \begin{bmatrix} U_3 \\ V_3 \\ W_3 \end{bmatrix}$$

$$\dot{\vec{C}}_3 = \begin{bmatrix} \dot{U}_3 \\ \dot{V}_3 \\ \dot{W}_3 \end{bmatrix} \qquad \vec{\Omega}_3 = \begin{bmatrix} P_3 \\ Q_3 \\ R_3 \end{bmatrix}$$

The aerodynamic forces are given by:

$$F_{3x} = C_{N3}(q_3 S_{03})\cos\beta_3 \quad (25)$$

$$F_{3y} = C_{N3}(q_3 S_{03})\sin\beta_3 \quad (26)$$

$$F_{3z} = -\,C_{T3}(q_3 S_{03}) \quad (27)$$

where

$$q_3 = 1/2\sigma|\vec{v}_3|^2 \text{(dynamic pressure)} \quad (28)$$

$$\beta_3 = \tan^{-1}\left[\frac{V_3}{U_3}\right] \text{(side-slip angle)} \quad (29)$$

The moment forces of the SPV, written in vector notation, are as follows:

$$\vec{M} = \vec{LCP} \times \vec{F}_3 + \vec{LA} \times (-[B^3][B^2]^T \vec{F}_{R2}) \quad (30)$$

where

LCP = Distance from aerodynamic center to C.M.
LA = Distance from riser attach point to C.M.

Also

$$\vec{LCP} = \begin{bmatrix} 0 \\ 0 \\ LCP \end{bmatrix} \qquad \vec{LA} = \begin{bmatrix} 0 \\ 0 \\ -LA \end{bmatrix}$$

Note: The SPV aerodynamic center is its center of pressure and varies with Mach number and SPV angle of attack.

Again, conducting the necessary matrix operations and solving for $\dot{U}_3$, $\dot{V}_3$, and $\dot{W}_3$, respectively yields:

$$\dot{U}_3 = [F_{3x} + m_3B^3{}_{13}g - B_{s4}F_{R2}]/m_3 + V_3R_3 - W_3Q_3 \quad (31)$$

$$\dot{V}_3 = [F_{3y} + m_3B^3{}_{23}g - B_{s5}F_{R2}]/m_3 + W_3P_3 - U_3R_3 \quad (32)$$

$$\dot{W}_3 = [F_{3z} + m_3B^3{}_{33}g - B_{s6}F_{R2}]/m_3 + U_3Q_3 - V_3P_3 \quad (33)$$

where $\begin{bmatrix} B_{s4} \\ B_{s5} \\ B_{s6} \end{bmatrix}$ are elements of the third column of the matrix operation $[B^3]\,[B^2]^T$

Similarly

$$\dot{P}_3=[-F_{3y}LCP-B_{s5}F_{R2}LA-(I_{zz3}-I_{yy3})Q_3R_3]/I_{xx3} \quad (34)$$

$$\dot{Q}_3=[F_{3x}LCP+B_{s4}F_{R2}LA-(I_{xx3}-I_{zz3})R_3P_3]/I_{yy3} \quad (35)$$

$$\dot{R}_3=[(I_{xx3}-I_{yy3})P_3Q_3]/I_{zz3} \quad (36)$$

The Kinematics of Motion

The Riser Constraint

The riser, assumed to be elastic, provides a convenient method of interconnecting the equations of motion of the parachute and the SPV. Consider the linear velocities at each end of the riser.

At the parachute/riser confluence point:

$$[B^2]^T \begin{bmatrix} U_2 \\ V_2 \\ W_2 \end{bmatrix} = [B^1]^T \begin{bmatrix} U_1 + Q_1L_s \\ V_1 - P_1L_s \\ W_1 \end{bmatrix} \quad (37)$$

And at the riser attach point on the SPV:

$$[B^2]^T \begin{bmatrix} U_2 + Q_2LR \\ V_2 - P_2LR \\ W_2 + \dot{L}R \end{bmatrix} = [B^3]^T \begin{bmatrix} U_3 - Q_3LA \\ V_3 - P_3LA \\ W_3 \end{bmatrix} \quad (38)$$

where

LR = Riser length

LA = Distance from SPV C.M. to riser attach point

Solving for U_2, V_2, W_2, respectively yields:

$$\begin{bmatrix} U_2 \\ V_2 \\ W_2 \end{bmatrix} = [B^2][B^1]^T \begin{bmatrix} U_1 + Q_1L_s \\ V_1 - P_1L_s \\ W_1 \end{bmatrix} \quad (39)$$

Now, let $\vec{V}_{R1}$ be the earth-fixed velocity of the parachute/riser confluence point, then:

$$\vec{V}_{R1} = \begin{bmatrix} \dot{X}_{R1} \\ \dot{Y}_{R1} \\ \dot{Z}_{R1} \end{bmatrix} = [B^1]^T \begin{bmatrix} U_1 + Q_1L_s \\ V_1 - P_1L_s \\ W_1 \end{bmatrix} \quad (40)$$

Substituting equation (40) into equation (39) and solving for U_2, V_2, W_2, yields:

$$\begin{bmatrix} U_2 \\ V_2 \\ W_2 \end{bmatrix} = [B^2] \begin{bmatrix} \dot{X}_{R1} \\ \dot{Y}_{R1} \\ \dot{Z}_{R1} \end{bmatrix} \quad (41)$$

Similarly,

$$\begin{bmatrix} U_2 + Q_2 LR \\ V_2 - P_2 LR \\ W_2 + \dot{L}R \end{bmatrix} = [B^2][B^3]^T \begin{bmatrix} U_3 - Q_3 LA \\ V_3 - P_3 LA \\ W_3 \end{bmatrix} \quad (42)$$

Now let $\vec{V}_A$, be the earth-fixed velocity of the riser attach point on the SPV, then:

$$\vec{V}_A = \begin{bmatrix} \dot{X}_A \\ \dot{Y}_A \\ \dot{Z}_A \end{bmatrix} = [B^3]^T \begin{bmatrix} U_3 - Q_3 LA \\ V_3 - P_3 LA \\ W_3 \end{bmatrix} \quad (43)$$

Conducting the necessary matrix operations and solving for P_2, Q_2, LR, respectively yields:

$$P_2 = [B^2_{21} (\dot{X}_{R1} - \dot{X}_A) + B^2_{22} (\dot{Y}_{R1} - \dot{Y}_A) + B^2_{23} (\dot{Z}_{R1} - \dot{Z}_A)]/LR \quad (44)$$

$$Q_2 = [B^2_{11} (\dot{X}_A - \dot{X}_{R1}) + B^2_{12} (\dot{Y}_A - \dot{Y}_{R1}) + B^2_{13} (\dot{Z}_A - \dot{Z}_{R1})]/LR \quad (45)$$

$$\dot{L}R = B^2_{31} (\dot{X}_A - \dot{X}_{R1}) + B^2_{32} (\dot{Y}_A - \dot{Y}_{R1}) + B^2_{33} (\dot{Z}_A - \dot{Z}_{R1}) \quad (46)$$

Note: The constraints on the riser, do not allow the riser to rotate about it's body-fixed Z-axis (i.e. $R_2 = 0$). This assumption ($R_2 = 0$) was allowed since swivels were to be used in the riser system.

The riser force, $\vec{F}_{R2}$, is simply

$$\vec{F}_{R2} = \begin{bmatrix} 0 \\ 0 \\ F_{R2} \end{bmatrix} \quad (47)$$

where

$$F_{R2} = K_F (LR - LR_o) \quad (48)$$

and

K_F = Spring constant

LR_o = Unstretched riser length.

The true riser length, LR, is determined by integrating equation (46).

By use of the cosine matrix, the earth-fixed velocities of the SPV, V_m, are:

$$\vec{V}_m = \begin{bmatrix} \dot{X}_m \\ \dot{Y}_m \\ \dot{Z}_m \end{bmatrix} = [B^3]^T \begin{bmatrix} U_3 \\ V_3 \\ W_3 \end{bmatrix} \quad (49)$$

The earth-fixed position of the SPV can be determined by integrating equation (49).

ANALYSIS OF THE QUEEN MATCH RECOVERY SYSTEM

To determine the performance envelope and hence, the design constraints of the Queen Match SPV Recovery System a wide variety of initial conditions were imposed upon the computer model for analysis. These initial conditions ranged from an aft base down drogue mortar deployment to drogue mortar deployment in a flat spin. With the exception of the flat spin, all initial displacements were in the X_3 Z_3 plane. Figure 4 illustrates the general case of each initial condition analyzed.

Though not depicted in this paper, the computer model incorporated the following:

DROGUE ANALYSIS CASE DEFINITION

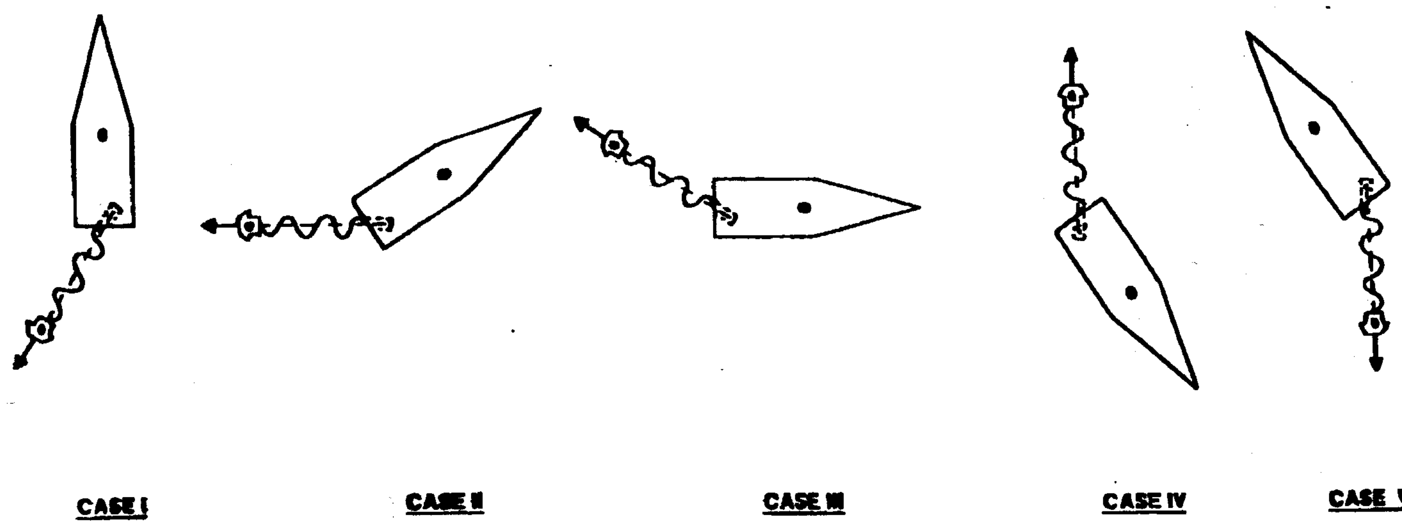


Figure 4

* Mortar reaction load

* Parachute inflation dynamics

* Ripstitch and break-tie energy attenuation

* Snatch force dynamics

* Riser/SPV contact dynamics

Computer Model Results

Sample results of the computer model are given in Figures 5-10. In general, the results of the computer model are as follows:

* All cases show the recovery system to be stable.

* In most cases, rotation of the SPV about its Z fixed body axis (roll), further stabilizes and reduces peak forces on the recovery system.

* In some cases, the peak reefed opening forces appear abnormally higher than the peak full open forces. It is thought that this is caused by a modeling limitation in that the drogue canopy inflates at the same rate for both a riser load/no load condition. Currently, this is a limitation of the state of the art; however, it provides a conservative measure of what the peak force may be.

An interesting finding was that in one case the SPV rotated to a 360 degree stable condition initially at 180 degrees, while the riser stabilized to zero degrees. In reality, the riser and SPV are both stable in these positions. However, this case revealed that a full rotation of the SPV had occurred indicating that riser/SPV contact was made. Analysis of the riser/SPV contact further revealed that upon contact with the SPV the riser rode along the perimeter of the SPV aft cover in the direction of the parachute until the SPV was righted. This finding resulted in a protective riser sleeve in the recovery system design.

Other results from the computer analysis of the Queen Match Recovery System had a bearing on the design of the following:

* Reefing systems

* Ripstitch and break-tie energy attenuators.

* Mortar system

* Structural Attachments on SPV

In addition, the model showed the SPV recovery system to be marginally stable during the reefed drogue chute state where a slowed full rotation (tumble) could occur until disreef of the drogue where the recovery system would be more stabilized. This phenomena actually occurred during flight test validating the results of the model. Further, upon release of the drogue and deployment of the main canopy, the model showed that the SPV would rotate past 45 degrees but no more than 70 degrees. This phenomona was also validated in flight tests.

In one case, it was desired to simulate an aft-base re-entry of the SPV. A simulation of the aft-base re-entry would require an aft center of gravity configuration. However, analysis from the model showed that the drogue chute would not generate sufficient force to maintain the proper vehicle attitude to ensure deployment of the main canopy in an SPV aft center of gravity configuration. Based upon the results of the model and previous validation of the model by flight tests, the aft center of gravity test configuration was cancelled.

CONCLUSIONS

The conclusions of the nonlinear computer simulation of the Queen Match Recovery System are as follows:

* All cases showed the recovery system to be stable.

* In most cases, rotation of the SPV about its Z fixed body axis (roll), further stabilizes and reduces peak forces on the recovery system.

* In some cases, the peak reefed opening forces appeared abnormally higher than the peak full open forces. It was thought that this was caused by a modeling limitation in that the drogue canopy inflates at the same rate for both a riser load/no load condition. Currently, this is a limitation of the state of the art; however, it does

provide a conservative measure of what the peak force may be.

In short, the Queen Match Recovery System met the contract requirements with the exception of one case. This one case exception was mainly due to an increase in the SPV mass and initial dynamic pressures during the course of this study. However, this one exception fell well within the design integrity of recovery system.

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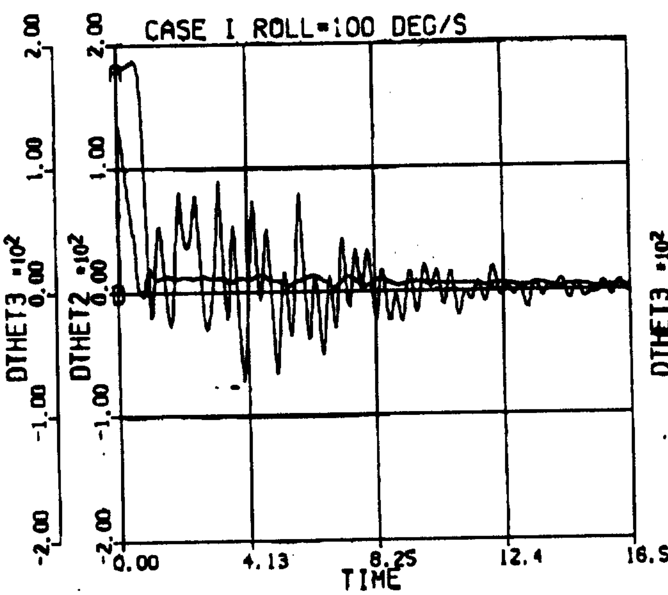
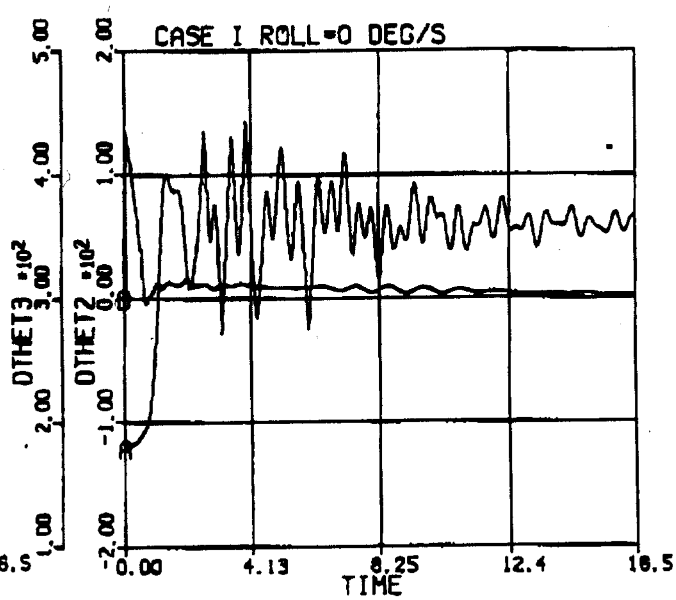


Figure 5



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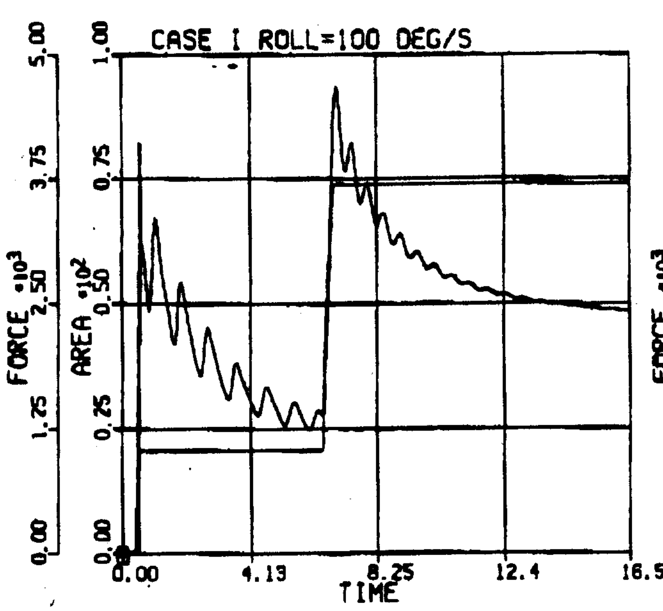

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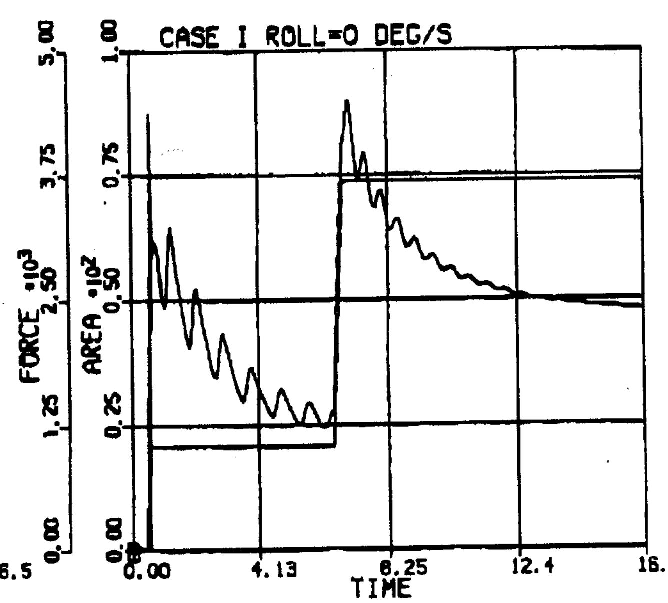

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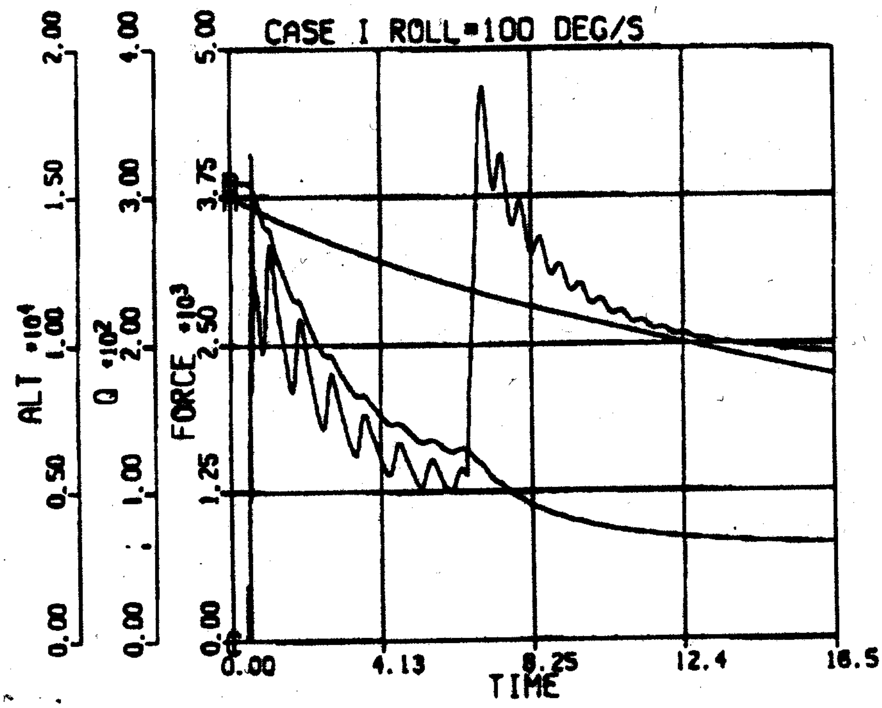

Figure 9

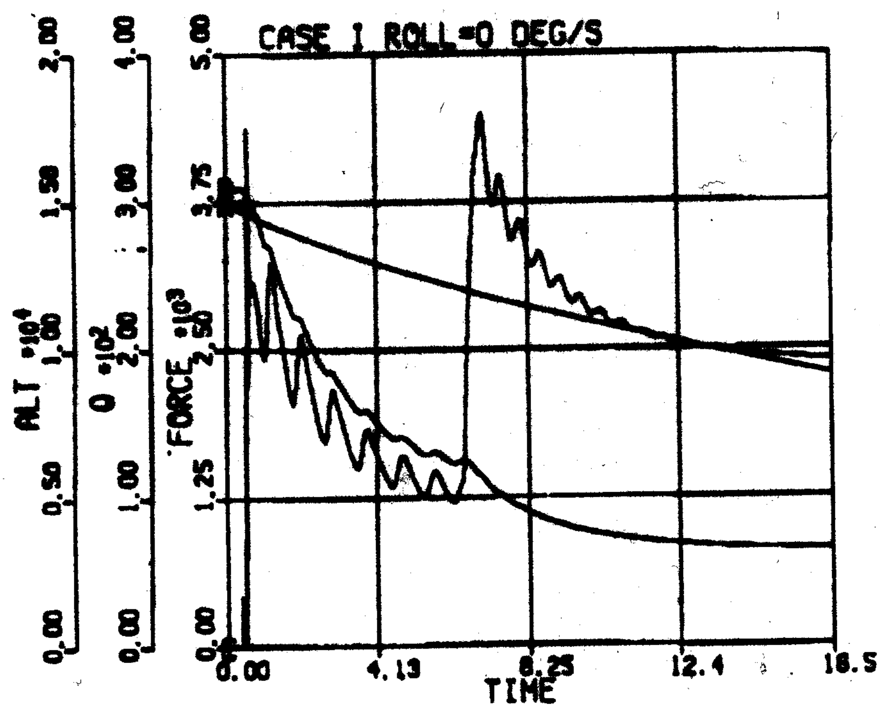

Figure 10