AD-783 517

AIRCREW AUTOMATED ESCAPE SYSTEM SIMULATION MODEL

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February 1974

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

AD-783517

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: TR-3098
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): AIRCREW AUTOMATED ESCAPE SYSTEM SIMULATION MODEL
5. TYPE OF REPORT & PERIOD COVERED
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Christopher Gracey
8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Weapons Laboratory, Dahlgren, Va. 22448
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS
12. REPORT DATE: February 1974
13. NUMBER OF PAGES: 90
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A math model is presented for simulating the performance of the SEU-3/A Ejection Seat Escape System which employs propulsion, parachute, and stabilization subsystems. Seat/man, man alone, and seat alone configurations are treated as rigid bodies in six degrees-of-freedom. "Canopy first" recovery parachute deployment by rocket and/or drogue parachute is modelled as well as "lines first" drogue deployment. Parachute opening equations are treated in detail, and riser/suspension line forces are assumed to be elastic. In addition, an aircraft model is formulated.

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S/N 0102-014-6601

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

NWL Technical Report No. TR-3098
February 1974

AIRCREW AUTOMATED ESCAPE SYSTEM SIMULATION MODEL

Christopher Gracey

Warfare Analysis Department

ii

FOREWORD

This report describes current progress toward achieving the long-range goal of developing a Navy capability to simulate the performance of any aircrew escape system in any aircraft. The work was authorized by the Engineering Department, Naval Weapons Laboratory. The report was reviewed by Dr. Thomas A. Clare, Head, Aeromechanics Branch and Russell D. Cuddy, Head, Aeroballistics Division. Acknowledgement is given to Mr. F. L. Stevens for assisting in the formulation, Mr. D. J. Lemoine for programming the model, and Mr. S. R. Hardy for improving the simulation through numerous computer runs and analyses.

Released by:

RALPH A. NIEMANN
Head, Warfare Analysis Department

CONTENTS

I. INTRODUCTION

In February 1972, the Naval Aerospace Recovery Facility, El Centro, contracted Vought Aeronautics Company to simulate the performance of the SIIIS-3 Escape System. The SIIIS-3, now designated the SEU-3/A, Escape System has been developed by Stencel Aero Engineering Corporation to replace the Martin Baker seat in the AV-8A (Harrier) aircraft. NAVAIR requested the Aeroballistics Division of the Naval Weapons Laboratory (NWL) to technically monitor Vought's contract. In addition, NWL was assigned the long range task of developing a Navy in-house capability to simulate any escape system in any aircraft. This report describes part of the work completed to date toward achieving this goal.

The Aeroballistics Division has the responsibility, among others, for Fleet air- and surface-launched weapons flight dynamics support. This work includes the formulation of math models to describe weapon performance, programming these models efficiently, preparing test programs to determine weapon parameters, adjusting these parameters to match test performance, and preparing fleet information. The experience gained in these areas can be applied to escape systems as well.

Originally, NWL considered obtaining Vought's computer program from the Air Force, who purchased it together with a computer study[1] in 1970. However, for several reasons, it was deemed more efficient to formulate and program a separate escape system performance simulation. Both the math model developed herein and Vought's model described in Reference 1 (Part 1, Volume 2, Appendices I-IV) treat the basic framework for the escape system simulation in a similar manner. For example, both models contain: (a) an aircraft simulation; (b) aircraft/seat interactions through rail/slider block linkage; (c) six-degree-of-freedom seat/man, man alone, and seat alone simulations; (d) catapult, sustainer rocket, stabilization, and aerodynamic forces and moments; as well as (e) parachute models. The two simulations differ, however, in the manner with which the details of each major segment are modelled. The philosophy employed in the Navy simulation is to model each segment with enough detail to provide flexibility in studying the effects of hardware modifications, crewman physiological effects, etc. without sacrificing overall model efficiency. In addition, extensive use was made of the current literature related to escape system modelling to obtain accurate state-of-the-art techniques.

Before proceeding with a description of NWL's current progress, a brief list of the major requirements of an escape system simulation is given below to place present achievements in perspective with future goals. The performance simulation should provide assistance to management, engineers, and Navy personnel in the following areas:

1. Establishing escape system performance requirements for a given aircraft.

2. Evaluating contractor proposals for escape systems.

3. Evaluating the effect of hardware design modifications on overall system performance.

4. Monitoring escape system test programs.

5. Preparing fleet information.

In fulfilling these requirements, NWL has concentrated primarily on the test monitoring function. After completing formulation and coding of the escape system model, simulations have been conducted of actual tests of the SEU-3/A Escape System in order to determine the adequacy of the math model. Program modifications and parameter adjustments were made to achieve agreement between simulated and test performance data. A separate report(7) presents the results of these simulations. After acceptable agreement between test and simulated performance data has been obtained for all system tests, the model can be used to simulate escape system performance for a wide range of aircraft conditions that were not covered in the testing program.

A CDC 6700 computer program, entitled ICARUS(6), has been coded to describe the formulation presented herein for the SEU-3/A Escape System. Therefore, a brief description of the operation of the SEU-3/A Escape System as it pertains to the performance simulation will be given. It is to be noted, however, that ICARUS is intended to be used to simulate other ejection seats, extraction systems, or capsule systems. For this reason, the math model was programmed in modular form so that certain segments could be reprogrammed to incorporate peculiarities of each individual escape system.

II. SEU-3/A ESCAPE SYSTEM OPERATION

Figure 1 is a schematic(2) of the SEU-3/A Ejection Seat showing the primary seat components. Following an aircraft failure mode requiring emergency egress, the sequence of events which occur after firing handle initiation is the following:

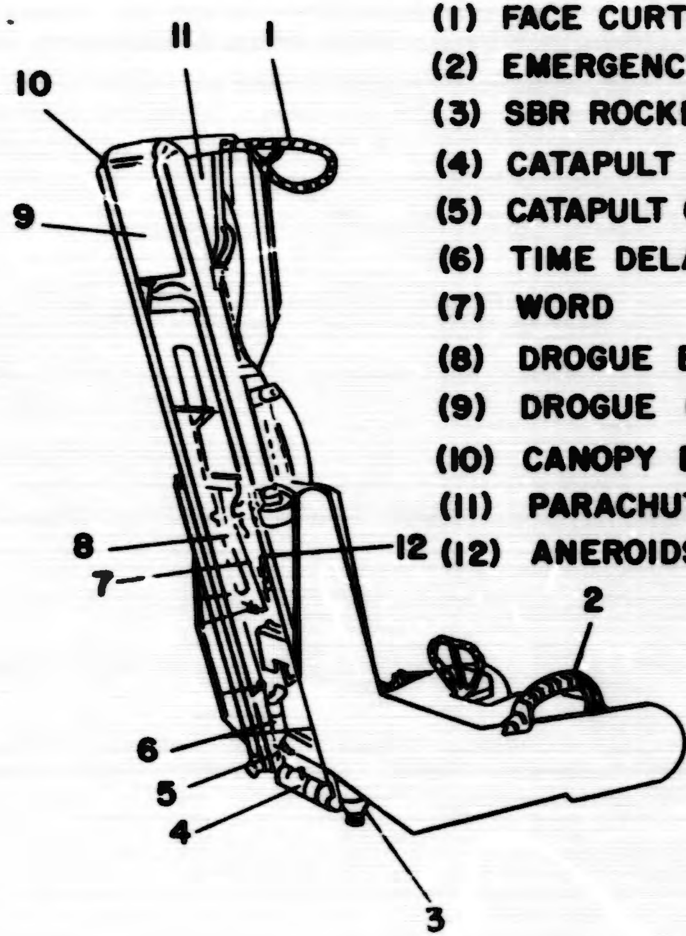
(1) Catapult cartridge initiation
(2) Canopy breaking
(3) Catapult unlock and first seat motion
(4) Drogue projection
(5)[1] Seat sequencing initiation and SBR ignition
(6) Catapult separation
(7)[1] WORD release
(8) Parachute pack opening
(9)[1] WORD ignition
(10)[1] DART start
(11)[1] SBR burnout
(12)[1] DART end
(13)[1] WORD burnout
(14) Line stretch and spreader gun firing
(15) Seat/man separation
(16) First full inflation

At catapult unlock (3), the pressure buildup in the catapult tubes, located inside the seat rails, provides thrust producing first seat motion. The two seat rails then move through six slider blocks attached to the aircraft. As the seat headbox enters the airstream, the drogue parachute container is projected from the seat (4). Prior to the separation of the catapult tubes from the seat rails, the seat sequencing is initiated and the Seat Back Rockets (SBR) ignite (5). The SBR is a sustainer rocket system consisting of two rocket motors, one located on each side of the seat. The rocket motors move with the seat bucket as it is adjusted to accommodate the pilot, thus reducing center of gravity to rocket thrust misalignment. The SBR's, of course, provide additional thrust to the seat, moving it away from the aircraft.

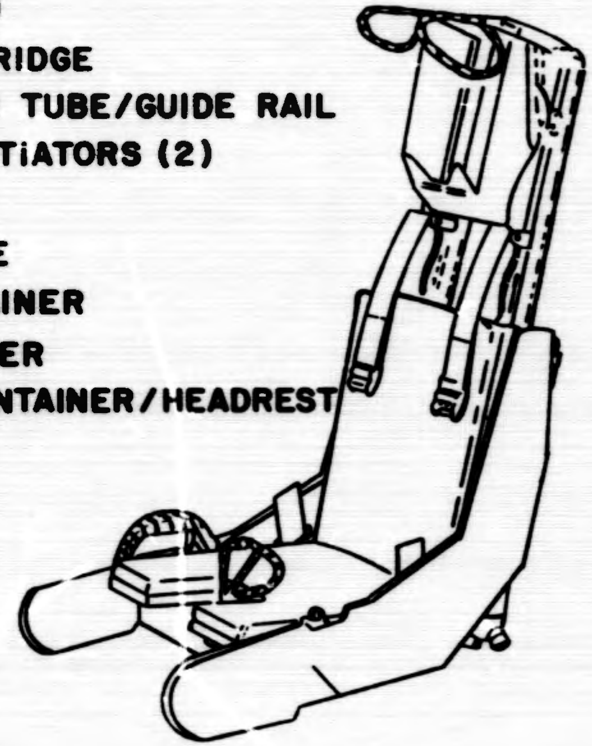
As the seat continues its trajectory away from the aircraft, deployment of the recovery parachute and stabilization of the seat during deployment are necessary. Deployment of the recovery parachute is accomplished by the Wind Oriented Rocket Deployment (WORD) system. The WORD rocket, or WORD, is a small rocket

[1]Appendix A, contains a description of the acronyms associated with the SEU-3/A Escape System.

FIGURE I. <u>SEU</u>-<u>3/A</u> <u>ESCAPE</u> <u>SYSTEM</u> <u>COMPONENTS</u>



(1) FACE CURTAIN EJECTION HANDLE
(2) EMERGENCY RELEASE HANDLE
(3) SBR ROCKET (2)
(4) CATAPULT CARTRIDGE
(5) CATAPULT OUTER TUBE/GUIDE RAIL
(6) TIME DELAY INITIATORS (2)
(7) WORD
(8) DROGUE BRIDLE
(9) DROGUE CONTAINER
(10) CANOPY BREAKER
(11) PARACHUTE CONTAINER/HEADREST
(12) ANEROIDS (2)



attached to the back of the seat. The WORD release mechanism (7) is operated according to the seat sequencing (5) which is a function of seat airspeed and altitude. Seat sequencing and its effect on recovery chute deployment will be discussed in the next paragraph. During SBR burn time and recovery chute deployment, the seat is subject to adverse attitudes. To stabilize the seat during this phase of the ejection sequence a Directional Automatic Realignment of Trajectory (DART) system is employed. The DART system consists of a brake attached to the seat through which two lines attached to the aircraft play out as the seat moves away from the aircraft. The moment on the seat produced by the DART brake force is designed to correct any adverse seat attitude. As the seat moves farther from the aircraft, the DART lines break (10), permitting the seat to continue its trajectory away from the aircraft.

Seat sequencing is determined by the seat airspeed and altitude, as mentioned previously. Seat sequencing, in turn, controls the recovery chute deployment mode, described schematically in Figure 2. In the low speed (below 225 kts.), low altitude (below 14,000 ft.) mode of operation, the WORD release mechanism functions on a short time delay. As the WORD falls away from the seat under its own inertia, a firing pin is pulled igniting the WORD rocket. If the seat altitude is below 14,000 feet, the recovery chute container opens. The recovery chute will subsequently be deployed from its container under the tension developed in the line connecting it to the WORD rocket. Figure 3 illustrates the low airspeed, low altitude event sequencing for the SEU-3/A Escape System.

If the seat altitude is above 14,000 feet, the recovery chute container will not open. In this case the WORD lanyard is attached to the seat head box. As tension develops in the drogue-WORD and WORD lanyards, the drogue chute is pulled out of its container. The drogue chute subsequently opens and exerts a force on the seat/man combination rotating it to a "feet-to-wind" attitude until the seat descends below 14,000 feet. At this point the recovery chute container opens permitting deployment of the recovery chute under the force exerted by the drogue chute.

If the seat velocity at SBR ignition is greater than 225 knots, the intermediate time delay functions rather than the short time delay. When the intermediate time delay functions, the 7000-foot aneroid is armed. Because of the longer time delay and greater seat speed than in the low speed mode, the drogue chute will deploy prior to WORD ignition. In this case, the drogue is attached to the seat via the WORD rocket. If the seat altitude is less than 7,000 feet, the recovery chute container will open and the WORD rocket will release. Under the force exerted on it by the drogue chute, the WORD is pulled away from the seat extracting a firing pin which ignites the WORD rocket. Under the action of the drogue chute and WORD rocket, the recovery chute is deployed into the airstream.

FIGURE 2. **RECOVERY PARACHUTE DEPLOYMENT MODES**

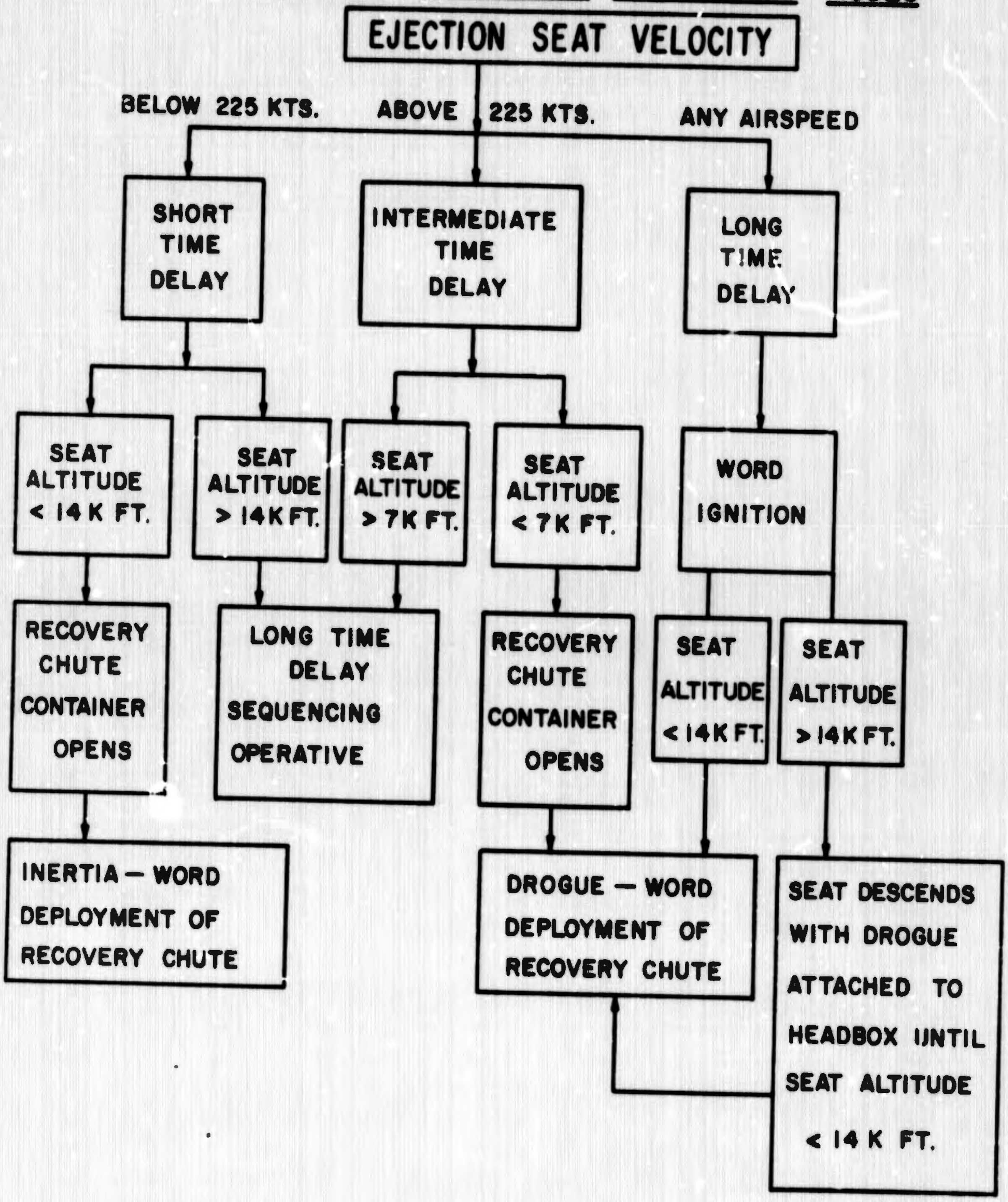
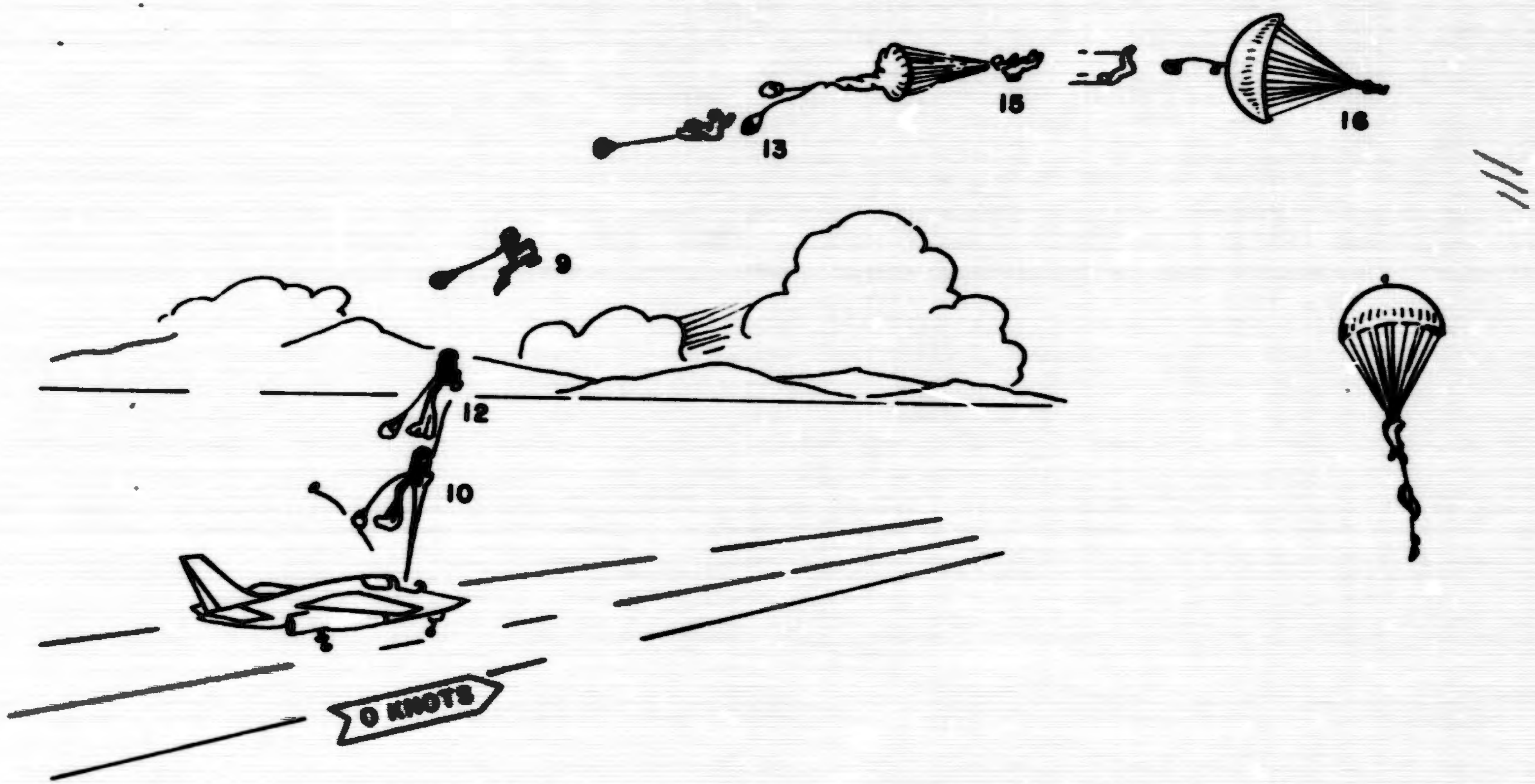


FIGURE 3. SEU-3/A ZERO/ZERO PERFORMANCE



See page 3 for
event definitions

If the seat altitude in the high speed mode is greater than 7,000 feet, WORD rocket ignition is delayed even longer. When the long time delay functions, the WORD rocket ignites under the action of the drogue chute. If the seat altitude is below 14,000 feet, the recovery chute container will open. Subsequently, the WORD and drogue chute will deploy the recovery chute. If, however, the seat altitude is above 14,000 feet, the recovery chute container will not open. The WORD lanyard attaches to the seat head box until the seat descends to an altitude below 14,000 feet. At this altitude the recovery chute container opens, and the recovery chute deploys under the action of the drogue chute.

After deployment of the recovery chute in each of the modes discussed above, the firing lanyard from the seat to the recovery chute plays out. When tension develops in the line, a pin is pulled firing the spreader gun. The spreader gun is attached to the skirt of the canopy and it ballistically forces the canopy mouth to enlarge. As the risers and suspension lines develop tension from the differential momentum between the inflating canopy and the seat/man, the seat and man separate. The seat moves away from the man as the man/parachute system decelerates further under the action of the inflating canopy.

Reference 2 contains a complete description of the SEU-3/A Escape System and its operation.

III. FORMULATION

The formulation is divided into the following sections:

(1) Aircraft equations of motion
(2) Seat/man equations of motion
(3) Seat/man forces and moments
  (a) Aircraft
  (b) Catapult
  (c) Sustainer rocket
  (d) Slider block
  (e) Aerodynamic
  (f) Stabilization
(4) Drogue container equations of motion
(5) Drogue parachute equations of motion
(6) Deployment rocket equations of motion
(7) Recovery parachute equations of motion
(8) Man alone equations of motion
(9) Seat alone equations of motion

The aircraft equations of motion are limited to three degrees-of-freedom. If complete six degree-of-freedom calculations are necessary in the future, they can be easily incorporated. The seat/man, man alone, and seat alone six degree-of-freedom equations of motion are identical in form; however, each is presented separately for completeness. Likewise, the drogue and recovery chute particle equations of motion with lift are redundant, except for the deployment modelling. The drogue chute is deployed "lines first" while the recovery chute is deployed "canopy first". Both the WORD rocket and drogue container are simulated as particles in three degrees-of-freedom; the WORD equations contain thrust. The interaction between the various bodies through suspension lines, risers, and lanyards are simulated as elastic forces,[(9),(10),(13-16),(20),(23)], proportional to the displacement of one body relative to the other. These forces as well as the other forces and moments on the seat/man configuration are treated in detail.

Appendix B contains a list of symbols and notations employed in the formulation divided into sections as follows:

(1) Coordinate Systems
(2) Modified Euler Angles
(3) Airplane Coordinate System Position Vectors
(4) Catapult Coordinate System Position Vectors
(5) Seat/Man Coordinate System Position Vectors

(6) Man Alone Coordinate System and Seat Alone Coordinate System Position Vectors
(7) Earth Fixed Coordinate System Position Vectors
(8) Direction Cosine Matrices
(9) Direction Cosine Angles/Unit Vectors
(10) Velocity Components
(11) Quaternions
(12) Airplane, Seat/Man, Man Alone, and Seat Alone Parameters
(13) Parachute Parameters
(14) DART System Parameters
(15) WORD System Parameters
(16) Drogue Container Parameters
(17) Slider Block Parameters
(18) Event Times
(19) Forces and Moments
(20) Dynamic Pressure, Aerodynamic Angles
(21) Tables

Vector notation is used in the formulation wherever possible for brevity, but occasionally components are used for clarity. The subscripts employed in the notation, while rather lengthy, are helpful in recalling the definitions of parameters. In most cases, the same notation is used in the computer program coding. The following is a list of the most frequently used subscripts and their definitions:

Subscripts:
C – catapult
S – seat/man
A – aircraft
MA – man alone
SA – seat alone
RC – recovery chute
DC – drogue container/drogue chute

Position vectors are denoted by the symbol, $\vec{r}$. For example, the vector $\vec{r}_{AC}$ denotes the position vector from the aircraft C.G. to the catapult, and the vector $\vec{r}_S$ denotes the position vector of the seat/man C.G. with respect to the earth. The notation is not intended, in general, to indicate in which coordinate system a vector is presented, however, but the definitions of these vectors will clarify this point. Direction cosine matrices are denoted by either A or D. For example, A_{AE} is the direction cosine matrix which transforms the components of a vector presented in the earth fixed coordinate system to components presented in the aircraft coordinate system. The conventions used in the remainder of the notation should become apparent through familiarization with the definitions.

For the most part the notation and conventions used in the formulation are consistent with those employed in References 3 and 11.

A. Aircraft Equations of Motion

The aircraft equations of motion are written in a wind axis system[11] (WAS) to provide aircraft trajectories in the horizontal or vertical plane. The control variables are load factors, roll rate, and angle-of-attack while the derivated variables are velocity, flight path angle, and velocity azimuth angle.

$$m_A \left(\dot{\vec{V}}_A + \vec{\omega}_W \times \vec{V}_A\right) = -g\vec{n} - \vec{g}$$

or in component form

$$\dot{V}_A = -g(n_x + a_{WE12}) \tag{1}$$

$$r_w V_A = -g(n_y + a_{WE22}) \tag{2}$$

$$-q_w V_A = -g(n_z + a_{WE32}) \tag{3}$$

The direction cosine matrix, A_{WE} which transforms a vector from the EFCS to the WAS is given by:

$$A_{WE} = \begin{bmatrix} a_{WE11} & a_{WE12} & a_{WE13} \\ a_{WE21} & a_{WE22} & a_{WE23} \\ a_{WE31} & a_{WE32} & a_{WE33} \end{bmatrix} = \begin{bmatrix} C\chi C\gamma & S\gamma & C\gamma S\chi \\ -S\mu S\chi - C\mu C\chi S\gamma & C\mu C\gamma & S\mu C\chi - C\mu S\chi S\gamma \\ -C\mu S\chi + S\mu C\chi S\gamma & -S\mu C\gamma & C\mu C\chi + S\mu S\chi S\gamma \end{bmatrix}$$

where

χ = negative rotation about the y_E axis to x', $y' = y_E$, z'
γ = positive rotation about the z' axis to x'', y'', $z'' = z'$
μ = positive rotation about the x'' axis to x_W, y_W, z_W
C = cosine
S = sine

The relationship between $\vec{\omega}_w$ and $(\dot{\chi},\dot{\gamma},\dot{\mu})^T$ is given by

$$\begin{bmatrix} p_w \\ q_w \\ r_w \end{bmatrix} = \begin{bmatrix} -S\gamma & 0 & 1 \\ -C\mu C\gamma & S\mu & 0 \\ S\mu C\gamma & C\mu & 0 \end{bmatrix} \begin{bmatrix} \dot{\chi} \\ \dot{\gamma} \\ \dot{\mu} \end{bmatrix}$$

Substituting these relationships in Equations (2) and (3), we obtain

$$\dot{\chi} = \frac{-g}{V_A \cos\gamma} \left[n_y \sin\mu + n_z \cos\mu \right] \tag{4}$$

$$\dot{\gamma} = \frac{-g}{V_A} \left[n_y \cos\mu - n_z \sin\mu + \cos\gamma \right] \tag{5}$$

Equations (1), (4), and (5) are integrated together with the following trajectory equations to determine the spatial time history of the aircraft:

$$\begin{bmatrix} \dot{x}_A \\ \dot{y}_A \\ \dot{z}_A \end{bmatrix} = A_{WE}^T \begin{bmatrix} V_A \\ 0 \\ 0 \end{bmatrix} = V_A \begin{bmatrix} \cos\chi \cos\gamma \\ \sin\gamma \\ \sin\chi \cos\gamma \end{bmatrix}$$

In order to determine the initial conditions for the seat/man configuration it is first necessary to transform the aircraft velocity and angular rates from the WAS to the Airplane Coordinate System (APCS). Note that this transformation assumes constant aircraft angle-of-attack.

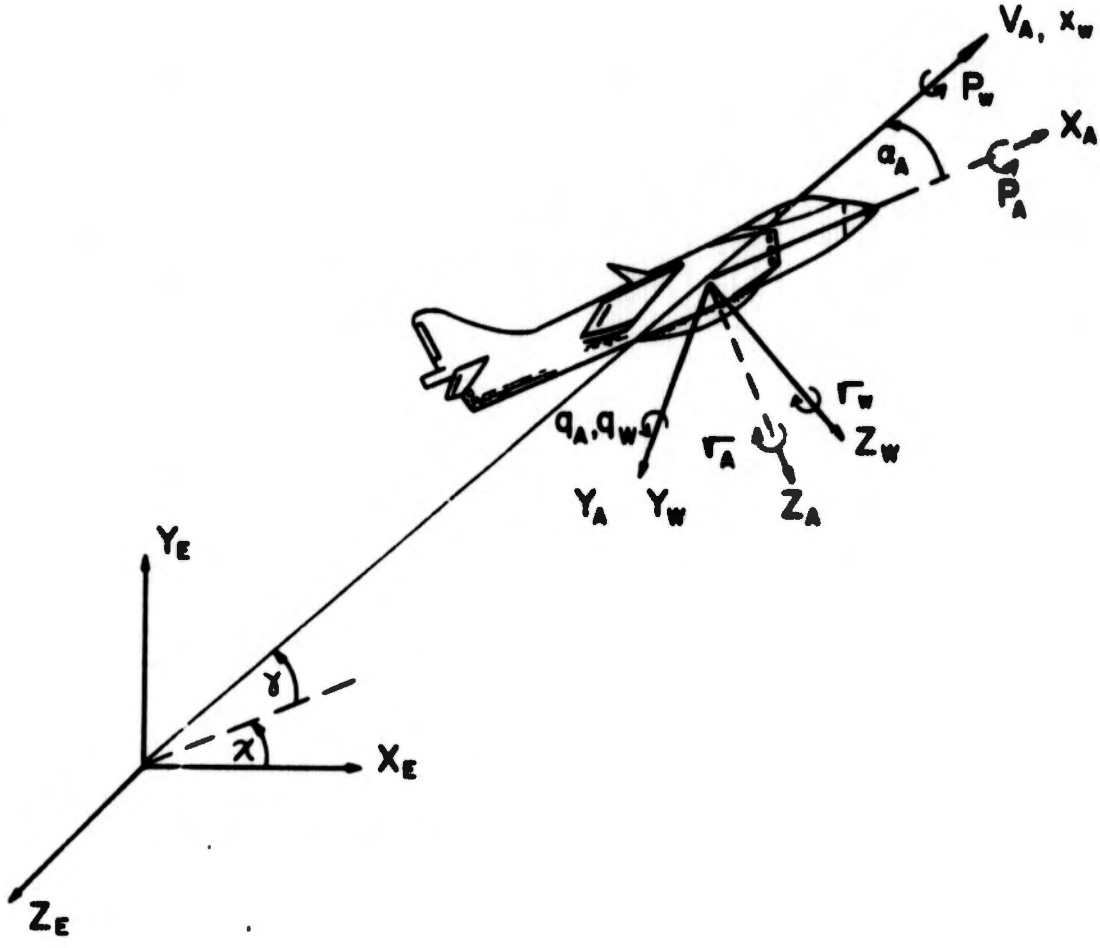
$$A_{AE} = \begin{bmatrix} a_{AE11} & a_{AE12} & a_{AE13} \\ a_{AE21} & a_{AE22} & a_{AE23} \\ a_{AE31} & a_{AE32} & a_{AE33} \end{bmatrix} = \begin{bmatrix} \cos\alpha_A & 0 & -\sin\alpha_A \\ 0 & 1 & 0 \\ \sin\alpha_A & 0 & \cos\alpha_A \end{bmatrix} A_{WE}$$

where,

α_A = a negative rotation about the y_w axis to the APCS.

Figure 4 is an illustration of the parameters used in the aircraft equations of motion. The aircraft velocity and angular rate components in the APCS are given by:

FIGURE 4. PARAMETERS USED IN THE AIRCRAFT EQUATIONS OF MOTION



$$\begin{bmatrix} u_A \\ v_A \\ w_A \end{bmatrix} = \begin{bmatrix} V_A \cos\alpha_A \\ 0 \\ V_A \sin\alpha_A \end{bmatrix}$$

$$\begin{bmatrix} p_A \\ q_A \\ r_A \end{bmatrix} = \begin{bmatrix} -C\alpha_A S\gamma - S\mu C\gamma S\alpha_A & -C\mu S\alpha_A & C\alpha_A \\ -C\mu C\gamma & S\mu & 0 \\ -S\alpha_A S\gamma + S\mu C\gamma C\alpha_A & C\mu C\alpha_A & S\alpha_A \end{bmatrix} \begin{bmatrix} \dot{\chi} \\ \dot{\gamma} \\ \dot{\mu} \end{bmatrix}$$

The Catapult Coordinate System (CCS), an intermediate coordinate system fixed to the aircraft, is established for convenience in defining points on the seat and formulating seat/aircraft interactions. The direction cosine matrix, D_{CA}, which transforms a vector from the APCS to the CCS, is defined as follows:

$$D_{CA} = \begin{bmatrix} d_{CA11} & d_{CA12} & d_{CA13} \\ d_{CA21} & d_{CA22} & d_{CA23} \\ d_{CA31} & d_{CA32} & d_{CA33} \end{bmatrix} = \begin{bmatrix} C\psi_C C\theta_C & S\theta_C & C\theta_C S\psi_C \\ -S\phi_C S\psi_C - C\phi_C C\psi_C S\theta_C & C\phi_C C\theta_C & S\phi_C C\psi_C - C\phi_C S\psi_C S\theta_C \\ -C\phi_C S\psi_C + S\phi_C C\psi_C S\theta_C & -S\phi_C C\theta_C & C\phi_C C\psi_C + S\phi_C S\psi_C S\theta_C \end{bmatrix}$$

where,

ψ_c = a negative rotation about y_A axis to $x', y' = y_A, z'$
θ_c = a positive rotation about z' axis to $x'', y'', z'' = z'$
ϕ_c = a positive rotation about x'' axis to x_C, y_C, z_C

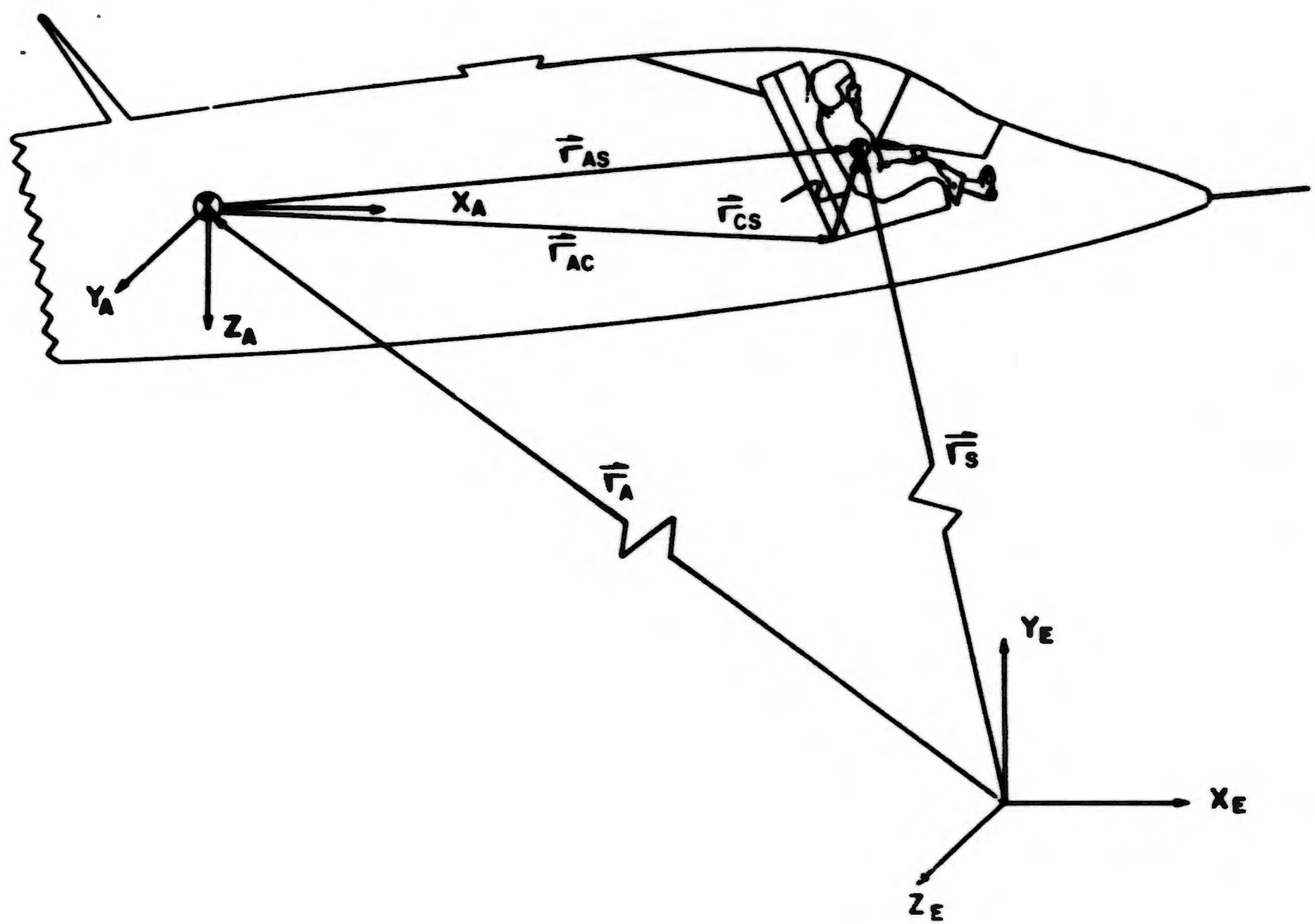
The vector from the aircraft to the seat/man C.G., presented in the APCS, is given by

$$\vec{r}_{AS} = \vec{r}_{AC} + D^T_{CA}\vec{r}_{CS} \text{ . (See Figure 5)}$$

The vector from the origin of the CCS to the aircraft C.G., presented in the CCS, is given by

$$\vec{r}_{CA} = -D_{CA}\vec{r}_{AC} \text{ .}$$

FIGURE 5. **SEAT / MAN POSITION RELATIVE TO AIRCRAFT**



The direction cosine matrix, D_{SC}, which transforms a vector from the CCS to the Seat/Man Coordinate System (SMCS) is given by

$$D_{SC} = \begin{bmatrix} d_{SC11} & d_{SC12} & d_{SC13} \\ d_{SC21} & d_{SC22} & d_{SC23} \\ d_{SC31} & d_{SC32} & d_{SC33} \end{bmatrix} = \begin{bmatrix} C\psi_{SC}C\theta_{SC} & S\theta_{SC} & C\theta_{SC}S\psi_{SC} \\ -S\phi_{SC}S\psi_{SC} - C\phi_{SC}C\psi_{SC}S\theta_{SC} & C\phi_{SC}C\theta_{SC} & S\phi_{SC}C\psi_{SC} - C\phi_{SC}S\psi_{SC}S\theta_{SC} \\ -C\phi_{SC}S\psi_{SC} + S\phi_{SC}C\psi_{SC}S\theta_{SC} & -S\phi_{SC}C\theta_{SC} & C\phi_{SC}C\psi_{SC} + S\phi_{SC}S\psi_{SC}S\theta_{SC} \end{bmatrix}$$

where

ψ_{SC} = a negative rotation about y_C axis to $x', y'=y_A, z'$
θ_{SC} = a positive rotation about z' axis to $x'', y'', z''=z'$
ϕ_{SC} = a positive rotation about x'' axis to x_C, y_C, z_C

The direction cosine matrix, D_{AS}, which transforms a vector from SMCS to the APCS is given by

$$D_{AS} = \begin{bmatrix} d_{AS11} & d_{AS12} & d_{AS13} \\ d_{AS21} & d_{AS22} & d_{AS23} \\ d_{AS31} & d_{AS32} & d_{AS33} \end{bmatrix} = D_{CA}^T D_{SC}^T$$

The direction cosine matrix, A_{SE}, which transforms a vector from the FFCS to the SMCS is given by

$$A_{SE} = \begin{bmatrix} a_{SE11} & a_{SE12} & a_{SE13} \\ a_{SE21} & a_{SE22} & a_{SE23} \\ a_{SE31} & a_{SE32} & a_{SE33} \end{bmatrix} = D_{AS}^T A_{AE}$$

The seat/man Euler angles are determined initially as follows:

$$\theta_S = \arcsin(a_{SE12}), \; -\pi/2 < \theta_S < \pi/2$$

$$\phi_S = \arctan(-a_{SE32}/a_{SE22}), \; 0 < \phi_S < 2\pi$$

$$\psi_S = \arctan(a_{SE13}/a_{SE11}), \; 0 < \psi_S < 2\pi$$

A unit quaternion, $\vec{\lambda}_S$, is used to update A_{SE} when integration of the seat/man equations of motion begins. The initial values of the components of $\vec{\lambda}_S$ are given by

$$\lambda_{0S} = C\phi_S/2\ C\theta_S/2\ C\psi_S/2 + S\phi_S/2\ S\theta_S/2\ S\psi_S/2$$

$$\lambda_{1S} = -C\phi_S/2\ S\theta_S/2\ S\psi_S/2 + S\phi_S/2\ C\theta_S/2\ C\psi_S/2$$

$$\lambda_{2S} = -C\phi_S/2\ C\theta_S/2\ S\psi_S/2 + S\phi_S/2\ S\theta_S/2\ C\psi_S/2$$

$$\lambda_{3S} = C\phi_S/2\ S\theta_S/2\ C\psi_S/2 + S\phi_S/2\ C\theta_S/2\ S\psi_S/2$$

The following points on the seat are transformed from the CCS to the SMCS. Figure 6 illustrates the vector addition involved in these transformations.

Vector from the seat/man C.G. to the drogue container in the SMCS:

$$\vec{r}_{SDC} = D_{SC}(\vec{r}_{CDC} - \vec{r}_{CS}).$$

Vector from the seat/man C.G. to the recovery chute in the SMCS:

$$\vec{r}_{SRC} = D_{SC}(\vec{r}_{CRC} - \vec{r}_{CS}).$$

Vector from the seat/man C.G. to the WORD rocket attach point:

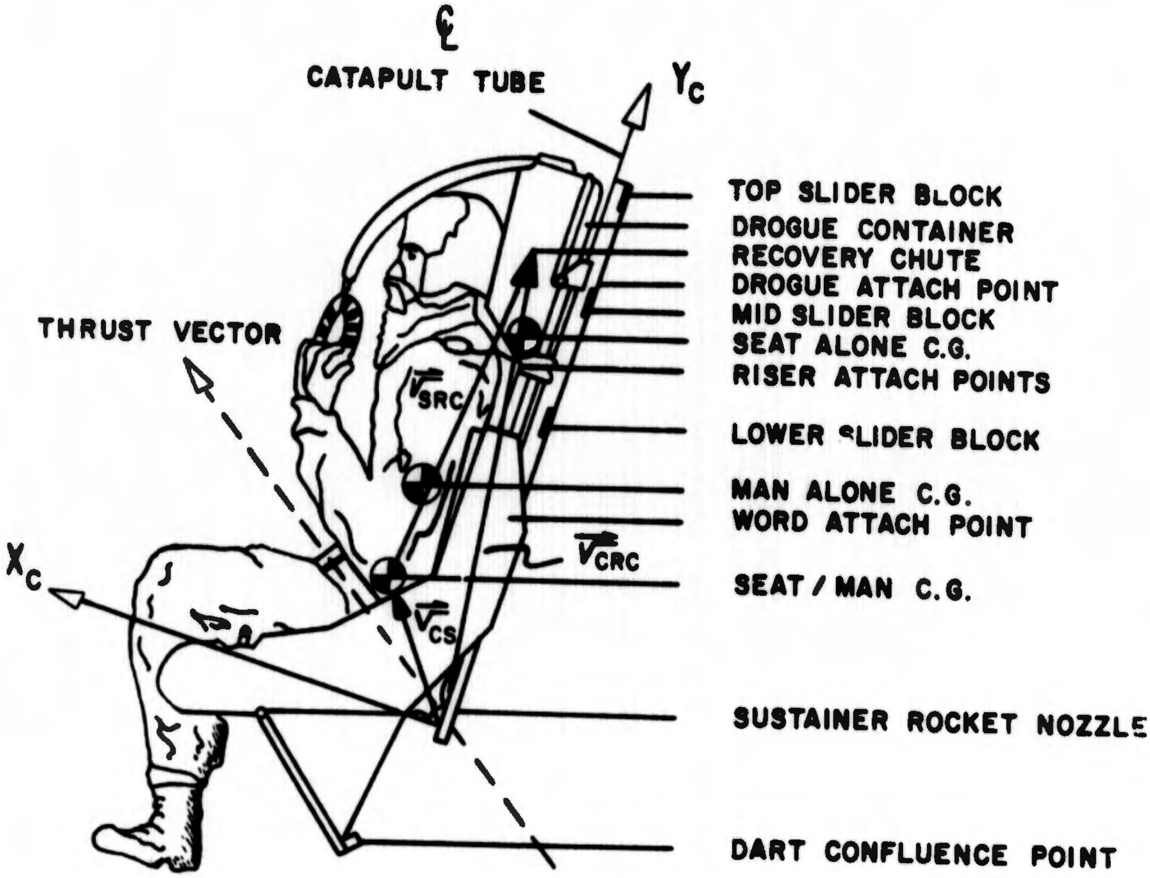
$$\vec{r}_{SWRDA} = D_{SC}(\vec{r}_{CWRDA} - \vec{r}_{CS}).$$

Vector from the seat/man C.G. to the WORD-drogue line attach point:

$$\vec{r}_{SWRDR} = D_{SC}(\vec{r}_{CWRDR} - \vec{r}_{CS}).$$

Vector from the seat/man C.G. to the WORD lanyard attach point on the recovery chute container:

FIGURE 6. TRANSFORMATION OF POSITION VECTORS FROM CCS TO SMCS



$$\vec{V}_{SRC} = D_{SC} \left(\vec{V}_{CRC} - \vec{V}_{CS} \right)$$

$$\vec{r}_{SRCC} = D_{SC}(\vec{r}_{CRCC} - \vec{r}_{CS}).$$

Vectors from the seat/man C.G. to the right and left DART confluence points in the SMCS:

$$\vec{r}_{SRCP} = D_{SC}(\vec{r}_{CRCP} - \vec{r}_{CS})$$

$$\vec{r}_{SLCP} = D_{SC}(\vec{r}_{CLCP} - \vec{r}_{CS}).$$

Vectors from the seat/man C.G. to the right and left sustainer rocket nozzles in the SMCS:

$$\vec{r}_{SRSBR} = D_{SC}(\vec{r}_{CRSBR} - \vec{r}_{CS})$$

$$\vec{r}_{SLSBR} = D_{SC}(\vec{r}_{CLSBR} - \vec{r}_{CS})$$

Vectors from the seat/man C.G. to the right and left rail ends:

$$\vec{r}_{SRRE} = D_{SC}(\vec{r}_{CRREO} - \vec{r}_{CS})$$

$$\vec{r}_{SLRE} = D_{SC}(\vec{r}_{CLREO} - \vec{r}_{CS}).$$

Vectors from the seat/man C.G. to the right and left riser attach points in the SMCS:

$$\vec{r}_{SRR} = D_{SC}(\vec{r}_{CRR} - \vec{r}_{CS})$$

$$\vec{r}_{SLR} = D_{SC}(\vec{r}_{CLR} - \vec{r}_{CS})$$

Vectors from the seat/man C.G. to the right and left catapult tubes:

$$\vec{r}_{SRCMA} = D_{SC}(\vec{r}_{CRCMA} - \vec{r}_{CS})$$

$$\vec{r}_{SLCMA} = D_{SC}(\vec{r}_{CLCMA} - \vec{r}_{CS})$$

Vector from the seat/man C.G. to the seat alone C.G. in the SMCS:

$$\vec{r}_{SSA} = D_{SC}(\vec{r}_{CSA} - \vec{r}_{CS}).$$

Vector from the seat/man C.G. to the man alone C.G. in the SMCS:

$$\vec{r}_{SM} = D_{SC}(\vec{r}_{CM} - \vec{r}_{CS}).$$

Vector from the seat/man C.G. to the seat/man reference C.G. for aerodynamic data in the SMCS:

$$\vec{r}_{SSCG} = D_{SC}(\vec{r}_{CSCG} - \vec{r}_{CS}).$$

Vector from the man alone C.G. to the man alone reference C.G. for aerodynamic data in the Man Alone Coordinate System (MACS):

$$\vec{r}_{MMCG} = D_{SC}(\vec{r}_{CMCG} - \vec{r}_{CM}).$$

Vector from the seat alone C.G. to the seat alone reference C.G. for aerodynamic data in the Seat Alone Coordinate System (SACS):

$$\vec{r}_{SASCG} = D_{SC}(\vec{r}_{CSACG} - \vec{r}_{CSA})$$

Vectors from the man alone C.G. to the right and left riser attach points:

$$\vec{r}_{MRR} = \vec{r}_{SRR} - \vec{r}_{SM}$$

$$\vec{r}_{MLR} = \vec{r}_{SLR} - \vec{r}_{SM}$$

Vectors from the seat/man and man alone C.G.'s to the midpoint of the riser attach points in the SMCS and MACS, respectively:

$$\vec{r}_{SR} = (x_{SRR}, 0, z_{SRR})^T$$

$$\vec{r}_{MR} = (x_{MRR}, 0, z_{MRR})^T .$$

Unit vectors for the right and left sustainer rocket thrust lines in the SMCS:

$$\vec{u}_{RR} = D_{SC}(\cos\alpha_{RSBR}, \cos\beta_{RSBR}, \cos\gamma_{RSBR})^T$$

$$\vec{u}_{LR} = D_{SC}(\cos\alpha_{LSBR}, \cos\beta_{LSBR}, \cos\gamma_{LSBR})^T \quad (6)$$

where,

$(\alpha_{RSBR}, \beta_{RSBR}, \gamma_{RSBR})$ = direction cosine angles of the right sustainer rocket thrust line with respect to the CCS.

$(\alpha_{LSBR}, \beta_{LSBR}, \gamma_{LSBR})$ = direction cosine angles of the left sustainer rocket thrust line with respect to the CCS.

The initial conditions for the seat/man configuration are determined as follows:

$$\vec{r}_S = (x_S, y_S, z_S)^T = \vec{r}_A + A_{AE}^T \vec{r}_{AS}$$

$$\vec{\omega}_S = (p_S, q_S, r_S)^T = D_{AS}^T \vec{\omega}_A$$

$$\vec{V}_S = (u_S, v_S, w_S)^T = D_{AS}^T (\vec{V}_A + \vec{\omega}_A \times \vec{r}_{AS})$$

where,

$$\vec{V}_A = (u_A, v_A, w_A)^T$$
$$\vec{\omega}_A = (p_A, q_A, r_A)^T \, .$$

B. Seat/Man Equations of Motion

The seat/man configuration is assumed to be a rigid body, and consequently the equations of motion of the seat/man are given by:

$$m_s\left(\dot{\vec{V}}_s + \vec{\omega}_s \times \vec{V}_s\right) = \Sigma\vec{F}_s \tag{7}$$

$$[I]\dot{\vec{\omega}}_s + \vec{\omega}_s \times [I]\vec{\omega}_s = \Sigma\vec{M}_s \tag{8}$$

where,

$\Sigma\vec{F}_s$ = summation of the external forces acting on the seat/man

$[I]$ = moment of inertia tensor for the seat/man

$\Sigma\vec{M}_s$ = summation of the external moments acting on the seat/man.

Equation (7) can be rewritten in component form:

$$\dot{u}_s = r_s v_s - q_s w_s - g a_{sE12} + F_{xs}/m_s \tag{9}$$

$$\dot{v}_s = p_s w_s - r_s u_s - g\, a_{sE22} + F_{ys}/m_s \tag{10}$$

$$\dot{w}_s = q_s u_s - p_s v_s - g\, a_{sE32} + F_{zs}/m_s \tag{11}$$

The angular momentum Equation (8) can be expanded as follows:

$$\begin{bmatrix} I_{xxs} & -I_{xys} & -I_{xzs} \\ -I_{xys} & I_{yys} & -I_{yzs} \\ -I_{xzs} & -I_{yzs} & I_{zzs} \end{bmatrix} \begin{bmatrix} \dot{p}_s \\ \dot{q}_s \\ \dot{r}_s \end{bmatrix} = -\begin{bmatrix} p_s \\ q_s \\ r_s \end{bmatrix} \times \begin{bmatrix} I_{xxs} & -I_{xys} & -I_{xzs} \\ -I_{xys} & I_{yys} & -I_{yzs} \\ -I_{xzs} & -I_{yzs} & I_{zzs} \end{bmatrix} \begin{bmatrix} p_s \\ q_s \\ r_s \end{bmatrix} + \begin{bmatrix} L_s \\ M_s \\ N_s \end{bmatrix} \tag{12}$$

Before solving for $(\dot{p}_s, \dot{q}_s, \dot{r}_s)^T$ we define the following quantities for convenience.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = -\begin{bmatrix} p_s \\ q_s \\ r_s \end{bmatrix} \times \begin{bmatrix} I_{xx_s} & -I_{xy_s} & -I_{xz_s} \\ -I_{xy_s} & I_{yy_s} & -I_{yz_s} \\ -I_{xz_s} & -I_{yz_s} & I_{zz_s} \end{bmatrix} \begin{bmatrix} p_s \\ q_s \\ r_s \end{bmatrix} + \begin{bmatrix} L_s \\ M_s \\ N_s \end{bmatrix}$$

$$A = I_{xy_s} I_{zz_s} + I_{xz_s} I_{yz_s}$$

$$B = I_{xx_s} I_{zz_s} - I_{xz_s}^2$$

$$C = I_{xx_s} I_{yz_s} + I_{xy_s} I_{xz_s}$$

Solving Equation (12) by Cramer's rule, we obtain

$$\dot{q}_s = (XA + YB + ZC)/(-I_{xy_s} A + I_{yy_s} B - I_{yz_s} C) \tag{13}$$

$$\dot{p}_s = \left[I_{zz_s} (X + I_{xy_s} \dot{q}_s) + I_{xz_s} (Z + I_{yz_s} \dot{q}_s) \right] / B \tag{14}$$

$$\dot{r}_s = (Z + I_{xz_s} \dot{p}_s + I_{yz_s} \dot{q}_s)/I_{zz_s} \tag{15}$$

Equations (9) through (11) and (13) through (15) are combined with the following differential equations for the quaternion components to completely specify the six degree-of-freedom motion of the seat/man configuration.

$$\begin{bmatrix} \dot{\lambda}_{0s} \\ \dot{\lambda}_{1s} \\ \dot{\lambda}_{2s} \\ \dot{\lambda}_{3s} \end{bmatrix} = -\frac{1}{2} \begin{bmatrix} 0 & p_s & q_s & r_s \\ -p_s & 0 & -r_s & q_s \\ -q_s & r_s & 0 & -p_s \\ -r_s & -q_s & p_s & 0 \end{bmatrix} \begin{bmatrix} \lambda_{0s} \\ \lambda_{1s} \\ \lambda_{2s} \\ \lambda_{3s} \end{bmatrix}$$

The various forces and moments acting on the seat/man configuration during the ejection sequence are considered next. Each of these forces and moments will be considered in detail in subsequent sections.

$$\Sigma\vec{F}_S = \vec{F}_C + \vec{F}_R + \vec{F}_{SB} + \vec{F}_{AS} + \vec{F}_{DART} + \vec{F}_{DCS} + \vec{F}_{WRDS} + \vec{F}_{RCS} + \vec{F}_{APS}$$

$$\Sigma\vec{M}_S = \vec{M}_C + \vec{M}_R + \vec{M}_{SB} + \vec{M}_{AS} + \vec{M}_{DART} + \vec{M}_{DCS} + \vec{M}_{WRDS} + \vec{M}_{RCS}$$

where the subscripts are defined as follows:

C = catapult

R = sustainer rocket

AS = seat/man aerodynamic

DCS = drogue chute on seat/man

WRDS = WORD rocket on seat/man

RCS = recovery chute on seat/man

APS = airplane on seat/man

The new position and orientation of the seat/man with respect to the EFCS is obtained by integrating the following set of thirteen differential equations.

$$u_S = \int \dot{u}_S dt \qquad p_S = \int \dot{p}_S dt \qquad \lambda_{iS} = \int \dot{\lambda}_{iS} dt \qquad i = 0,1,2,3$$

$$v_S = \int \dot{v}_S dt \qquad q_S = \int \dot{q}_S dt$$

$$w_S = \int \dot{w}_S dt \qquad r_S = \int \dot{r}_S dt \qquad \lambda_{iS} = \lambda_{iS}/|\lambda_{iS}| \qquad i = 0,1,2,3$$

$$A_{SE} = \begin{bmatrix} 2(\lambda_{0S}^2 + \lambda_{1S}^2) - 1 & 2(\lambda_{1S}\lambda_{2S} + \lambda_{0S}\lambda_{3S}) & 2(\lambda_{1S}\lambda_{3S} - \lambda_{0S}\lambda_{2S}) \\ 2(\lambda_{1S}\lambda_{2S} - \lambda_{0S}\lambda_{3S}) & 2(\lambda_{0S}^2 + \lambda_{2S}^2) - 1 & 2(\lambda_{2S}\lambda_{3S} + \lambda_{0S}\lambda_{1S}) \\ 2(\lambda_{1S}\lambda_{3S} + \lambda_{0S}\lambda_{2S}) & 2(\lambda_{2S}\lambda_{3S} - \lambda_{0S}\lambda_{1S}) & 2(\lambda_{0S}^2 + \lambda_{3S}^2) - 1 \end{bmatrix}$$

$$\begin{bmatrix} \dot{x}_S \\ \dot{y}_S \\ \dot{z}_S \end{bmatrix} = A_{SE}^T \begin{bmatrix} u_S \\ v_S \\ w_S \end{bmatrix} \qquad \begin{aligned} x_S &= \int \dot{x}_S dt \\ y_S &= \int \dot{y}_S dt \\ z_S &= \int \dot{z}_S dt \end{aligned}$$

$$\theta_S = \arcsin(a_{SE12}), \quad -\pi/2 < \theta_S < \pi/2$$

$$\phi_S = \arctan(-a_{SE32}/a_{SE22}), \quad 0 < \phi_S < 2\pi$$

$$\psi_S = \arctan(a_{SE13}/a_{SE11}), \quad 0 < \psi_S < 2\pi$$

C. Seat/Man Forces and Moments

The forces and moments acting on the seat/man are considered separately in the following subsections. These forces and moments are produced by the following:

(1) Aircraft
(2) Catapult
(3) Sustainer rocket
(4) Slider block
(5) Aerodynamic
(6) Stabilization

The interactive forces between parachutes and seat/man or man alone are considered in later sections which include the equations describing the parachute dynamics as well.

1. Aircraft

The forces on the seat/man due to load factors on the aircraft are computed prior to unlocking of the catapult tubes. After the catapult tubes have unlocked, these forces are zero. The acceleration in g's at the seat/man C.G. due to load factors at the aircraft C.G. is given by

$$\vec{n} = \vec{n}_A + \frac{1}{g}\left[\vec{\omega}_A \times (\vec{\omega}_A \times \vec{r}_{AS}) + \dot{\vec{\omega}}_A \times \vec{r}_{AS}\right]$$

Neglecting $\dot{\vec{\omega}}_A \times \vec{r}_{AS}$ and expanding the triple cross product, we obtain

$$\vec{n} = \vec{n}_A + \frac{1}{g}\left[(\vec{\omega}_A \cdot \vec{r}_{AS})\vec{\omega}_A - (\vec{\omega}_A \cdot \vec{\omega}_A)\vec{r}_{AS}\right].$$

The force in the SMCS due to this acceleration is given by:

$$\vec{F}_{APS} = -\frac{D^T_{AS}}{W_s}\vec{n}$$

where W_S is the weight of the seat/man combination.

2. Catapult

The right and left catapult thrust time histories are tabulated separately to allow greater flexibility in simulating catapult system anomalies. Termination of the catapult thrust imparted to the seat is determined by the distance the seat rails have travelled. In the SMCS the components of right and left catapult thrust are given by

$$\vec{F}_{RC} = -(0,0,T_{RC})^T$$

$$\vec{F}_{LC} = -(0,0,T_{LC})^T$$

$$\vec{F}_{C} = \vec{F}_{RC} + \vec{F}_{LC}$$

The corresponding moment is

$$\vec{M}_C = \vec{r}_{SRCMA} \times \vec{F}_{RC} + \vec{r}_{SLCMA} \times \vec{F}_{LC} .$$

Figure 7 illustrates the force and moment on the seat/man due to catapult thrust.

3. Sustainer Rocket

The sustainer rocket thrust is handled in a manner similar to the catapult thrust, i.e., the thrust for the right and left rocket motors is tabulated separately. The components of the unit vectors along the right and left rocket thrust lines, presented in the SMCS, are given by Equations (6). Figure 8 illustrates the direction cosine angles specifying the rocket thrust line orientation with respect to the CCS as well as the components of the unit vectors in the SMCS.

The sustainer rocket thrust components in the SMCS are given by

FIGURE 7. **CATAPULT FORCES AND MOMENTS**

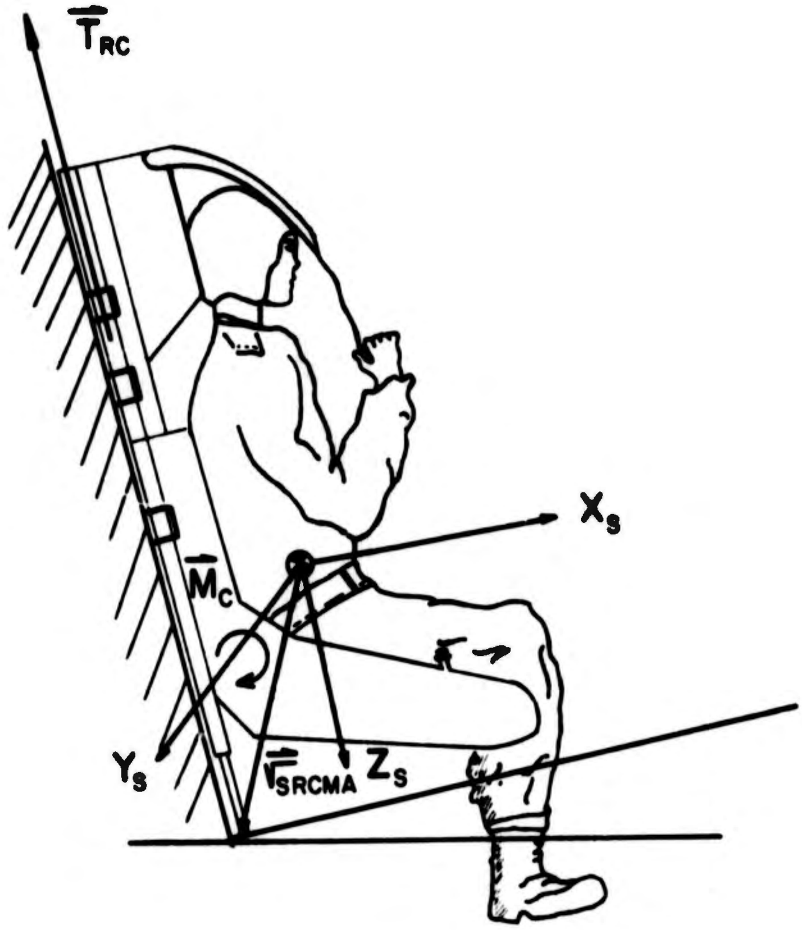
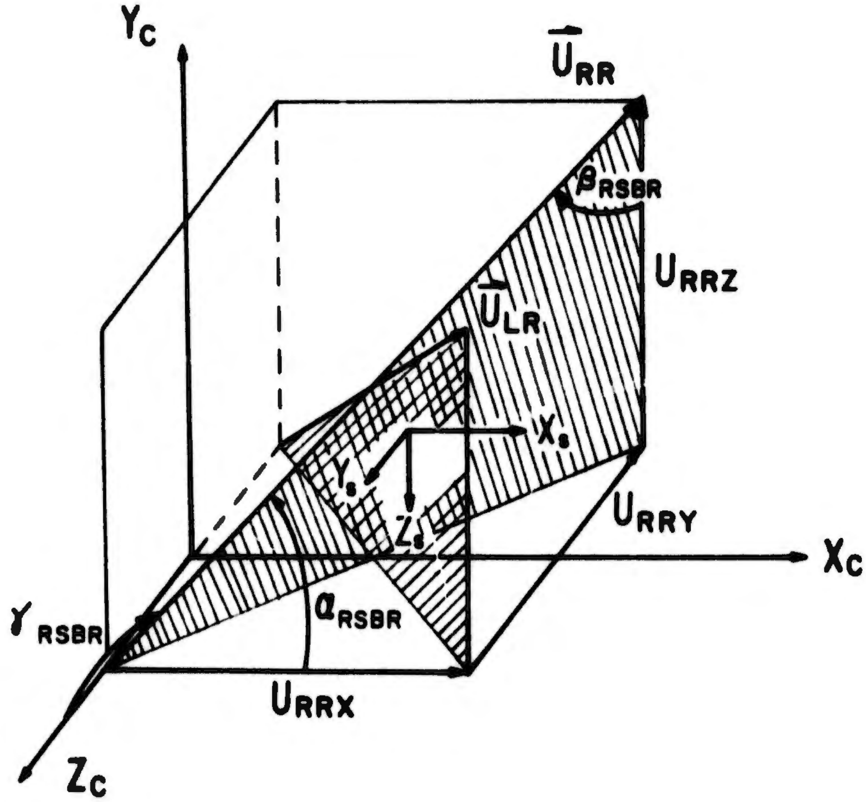


FIGURE 8. <u>SUSTAINER ROCKET THRUST LINE UNIT VECTORS</u>



$$\begin{bmatrix} F_{xR} \\ F_{yR} \\ F_{zR} \end{bmatrix} = T_{RR} \begin{bmatrix} U_{RRx} \\ U_{RRy} \\ U_{RRz} \end{bmatrix} + T_{LR} \begin{bmatrix} U_{LRx} \\ U_{LRy} \\ U_{LRz} \end{bmatrix}$$

The corresponding moments are

$$\begin{bmatrix} L_R \\ M_R \\ N_R \end{bmatrix} = \begin{bmatrix} x_{SRSBR} \\ y_{SRSBR} \\ z_{SRSBR} \end{bmatrix} \times \left(\Gamma_{RR} \begin{bmatrix} U_{RRx} \\ U_{RRy} \\ U_{RRz} \end{bmatrix} \right) + \begin{bmatrix} x_{SLSBR} \\ y_{SLSBR} \\ z_{SLSBR} \end{bmatrix} \times \left(T_{LR} \begin{bmatrix} U_{LRx} \\ U_{LRy} \\ U_{LRz} \end{bmatrix} \right) .$$

4. Slider Blocks

The seat rails move through slider blocks attached to the aircraft as the seat/man and aircraft equations of motion are integrated. The displacement of the rails from each slider block in a plane perpendicular to the Y_C axis is determined. Based on this displacement, a restoring force is computed constraining the seat rails to the slider blocks. The vectors from the catapult to the right and left rail ends are determined as follows (See Figure 9):

$$\vec{r}_{CRRE} = \vec{r}_{CS} + D_{SC}^T \vec{r}_{SRRE}$$

$$\vec{r}_{CLRE} = \vec{r}_{CS} + D_{SC}^T \vec{r}_{SLRE}$$

where the vector from the catapult to the seat/man C.G. is given by

$$\vec{r}_{CS} = \vec{r}_{CA} - D_{CE}(\vec{r}_A - \vec{r}_S)$$

and D_{CE} is the direction cosine matrix relating the EFCS to the CCS.

The six slider blocks are numbered 1 through 6; the right hand blocks are indexed 1 through 3 beginning with the lower right hand block, while the left hand blocks are indexed 4 through 6 beginning with the lower left hand block. The vector from the i^{th} slider block to the seat rails which is perpendicular to the Y_C axis is denoted by $\vec{\Delta r}_{SB_i} = (\Delta x_{SB_i}, 0, \Delta z_{SB_i})$, when presented in the CCS. From Figure 10, it is evident that

FIGURE 9. SLIDER BLOCK VECTOR RELATIONSHIPS

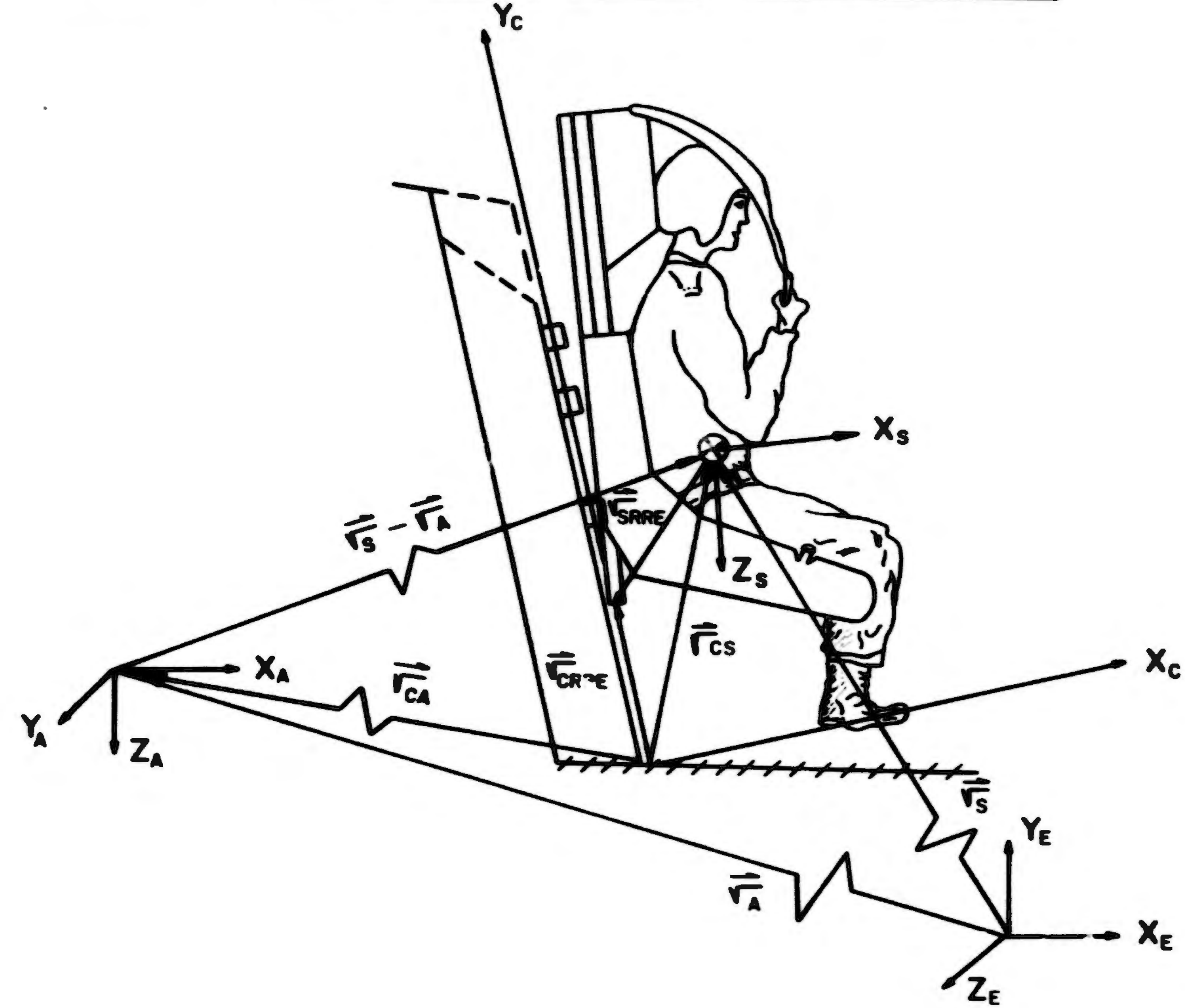
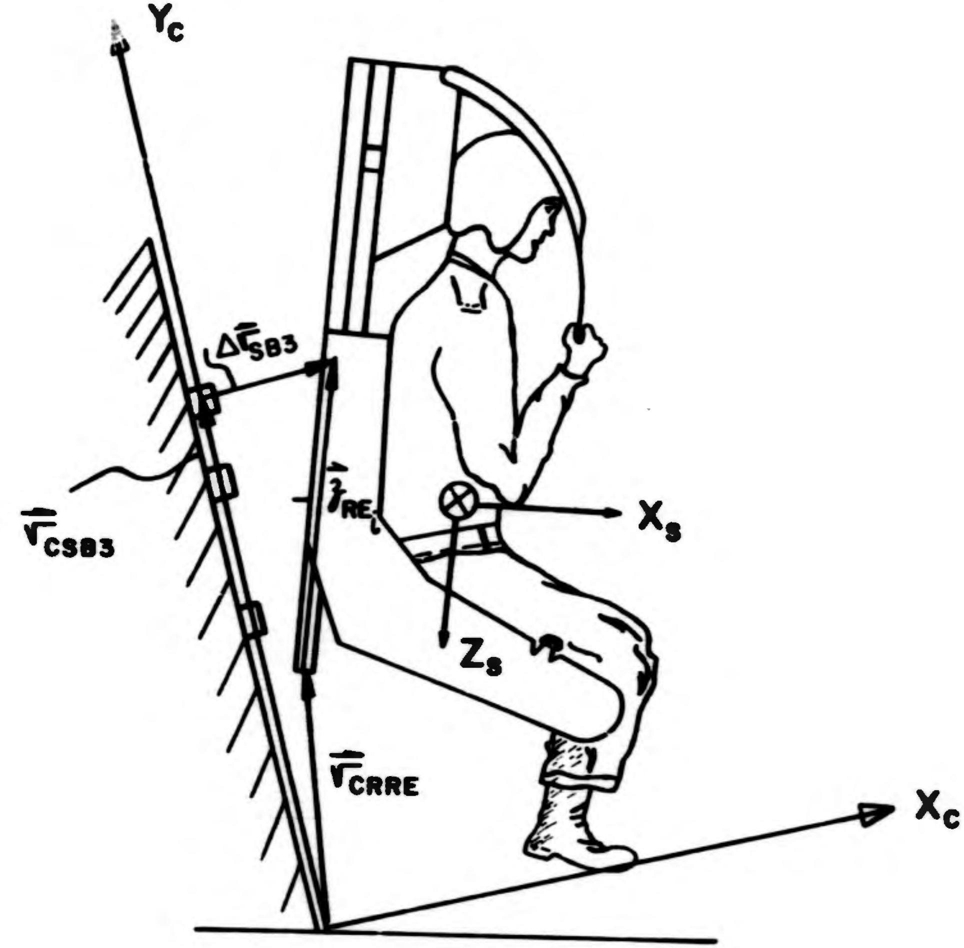


FIGURE 10. DISPLACEMENT OF RAILS FROM SLIDER BLC



$$\vec{r}_{CSB_i} + \vec{\Delta r}_{SB_i} + D_{SC}^T \vec{z}_{RE_i} = \vec{r}_{CRRE}, \quad i = 1,2,3$$

$$\vec{r}_{CSB_i} + \vec{\Delta r}_{SB_i} + D_{SC}^T \vec{z}_{RE_i} = \vec{r}_{CLRE}, \quad i = 4,5,6 \tag{16}$$

where, z_{RE_i} is the vector from the bottom end of the right rail to the i^{th} slider block contact point on the rail. Solving for $\vec{\Delta r}_{SB_i}$, we obtain

$$\begin{bmatrix} \Delta x_{SB_i} \\ \Delta z_{SB_i} \end{bmatrix} = \begin{cases} \begin{bmatrix} x_{CRRE} \\ z_{CRRE} \end{bmatrix} - \begin{bmatrix} x_{CSB_i} \\ z_{CSB_i} \end{bmatrix} - \begin{bmatrix} d_{SC31}\, z_{RE_i} \\ d_{SC33}\, z_{RE_i} \end{bmatrix}, & i = 1,2,3 \\ \begin{bmatrix} x_{CLRE} \\ z_{CLRE} \end{bmatrix} - \begin{bmatrix} x_{CSB_i} \\ z_{CSB_i} \end{bmatrix} - \begin{bmatrix} d_{SC31}\, z_{RE_i} \\ d_{SC33}\, z_{RE_i} \end{bmatrix}, & i = 4,5,6 \end{cases}$$

where,

$$z_{RE_i} = \begin{cases} \dfrac{1}{d_{SC32}} (y_{CRRE} - y_{CSB_i}) & i = 1,2,3 \\ \dfrac{1}{d_{SC32}} (y_{CLRE} - y_{CSB_i}) & i = 4,5,6 \end{cases}$$

The reaction forces at the slider blocks are computed as follows:

$$F_{XSB_i} = \begin{cases} 0 & y_{CRRE} > y_{CSB_i} \quad i = 2,3 \\ -k_x \Delta x_{SB_i} & y_{CRRE} < y_{CSB_i} \end{cases}$$

$$F_{XSB_1} = \begin{cases} 0 & y_{CRRE} > y_{CSB_1} \\ -k_x \Delta x_{SB_1} & y_{CRRE} < y_{CSB_1} \text{ and } F_{XSB_2} > 0 \\ -F_{XSB_2} - F_{XSB_3} & y_{CRRE} < y_{CSB_1} \text{ and } F_{XSB_2} < 0 \end{cases}$$

$$F_{XSB_i} = \begin{cases} 0 & y_{CLRE} > y_{CSB_i} \quad i = 5,6 \\ -k_x \Delta x_{SB_i} & y_{CLRE} < y_{CSB_i} \end{cases}$$

$$F_{XSB4} = \begin{cases} 0 & y_{CLRE} > y_{CSB4} \\ -k_x \Delta x_{SB4} & y_{CLRE} < y_{CSB4} \quad \text{and} \quad F_{XSB5} > 0 \\ -F_{XSB5} - F_{XSB6} & y_{CLRE} < y_{CSB4} \quad \text{and} \quad F_{XSB5} < 0 \end{cases}$$

$$F_{ZSB_i} = \begin{cases} 0 & y_{CRRE} > y_{CSB_i} \quad i = 1,2,3 \\ -k_z \Delta z_{SB_i} & y_{CRRE} < y_{CSB_i} \quad i = 1,2,3 \end{cases}$$

$$F_{ZSB_i} = \begin{cases} 0 & y_{CLRE} > y_{CSB_i} \quad i = 4,5,6 \\ -k_z \Delta z_{SB_i} & y_{CLRE} < y_{CSB_i} \quad i = 4,5,6 \end{cases}$$

The frictional force at the i^{th} slider block is given by

$$fr_i = -\mu_f (F^2_{XSB_i} + F^2_{ZSB_i})^{1/2} \qquad \text{for } i = 1,2,\cdots,6$$

The summation of the rail/slider block forces in the SMCS is given by

$$\begin{bmatrix} F_{XSB} \\ F_{YSB} \\ F_{ZSB} \end{bmatrix} = D_{SC} \begin{bmatrix} \sum_{i=1}^{6} F_{XSB_i} \\ \sum_{i=1}^{6} fr_i \\ \sum_{i=1}^{6} F_{ZSB_i} \end{bmatrix}$$

The vectors from the seat/man C.G. to the rail/slider block contact points are given by

$$\begin{bmatrix} x_{SSB_i} \\ y_{SSB_i} \\ z_{SSB_i} \end{bmatrix} = D_{SC}^T \left\{ \begin{bmatrix} x_{SRRE} \\ y_{SRRE} \\ z_{SRRE} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ z_{RE_i} \end{bmatrix} \right\} \quad i = 1,2,3$$

$$\begin{bmatrix} x_{SSB_i} \\ y_{SSB_i} \\ z_{SSB_i} \end{bmatrix} = D_{SC}^T \left\{ \begin{bmatrix} x_{SRRE} \\ y_{SRRE} \\ z_{SRRE} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ z_{RE_i} \end{bmatrix} \right\} \quad i = 4,5,6$$

The slider block moments about the seat/man C.G. presented in the CCS are given by

$$\begin{bmatrix} L_{SB_i} \\ M_{SB_i} \\ N_{SB_i} \end{bmatrix} = \begin{bmatrix} x_{SSB_i} \\ y_{SSB_i} \\ z_{SSB_i} \end{bmatrix} \times \begin{bmatrix} F_{XSB_i} \\ fr_i \\ F_{ZSB_i} \end{bmatrix}$$

The slider block moments presented in the SMCS

$$\begin{bmatrix} L_{SB} \\ M_{SB} \\ N_{SB} \end{bmatrix} = D_{SC} \begin{bmatrix} \sum_{i=1}^{6} L_{SB_i} \\ \sum_{i=1}^{6} M_{SB_i} \\ \sum_{i=1}^{6} N_{SB_i} \end{bmatrix}$$

5. Aerodynamic

The seat/man static aerodynamic data are assumed to be available in tabular form, e.g., References 17 through 19 and 4, as a function of angle of attack, angle of sideslip, and Mach number. As explained below, these coefficients are then modified when the seat is still partially within the cockpit. The velocity of the seat/man with respect to the wind is first determined as follows:

$$\begin{bmatrix} u_{AS} \\ v_{AS} \\ w_{AS} \end{bmatrix} = \begin{bmatrix} u_S \\ v_S \\ w_S \end{bmatrix} - A_{SE} \begin{bmatrix} w_x \\ 0 \\ w_z \end{bmatrix}$$

$$V_{AS} = \left(u_{AS}^2 + v_{AS}^2 + w_{AS}^2\right)^{1/2}$$

The angle of attack, α_S, and angle of sideslip, β_S, are given by (see Figure 11)

$$\alpha_S = \tan^{-1}(w_{AS}/u_{AS}), \qquad 0 < \alpha_S < 2\pi$$

$$\beta_S = \sin^{-1}(v_{AS}/V_{AS}), \qquad -\pi < \beta_S < \pi$$

Curve fits for temperature, T, and pressure, P, as a function of altitude were obtained from standard ICAO atmosphere data.[21] Air density, ρ, and Mach number, MN, are then obtained from the following formulas:

$$T = 518.67 - .00356616 y_S \quad (\text{for } y_S < 36{,}000 \text{ ft})$$

$$P = 1013.25(518.67/T)^{-5.255877}$$

$$\rho_S = .00121668402\ P/T$$

$$MN_S = \frac{V_{AS}}{1116.44}\left(\frac{518.67}{T}\right)^{1/2}$$

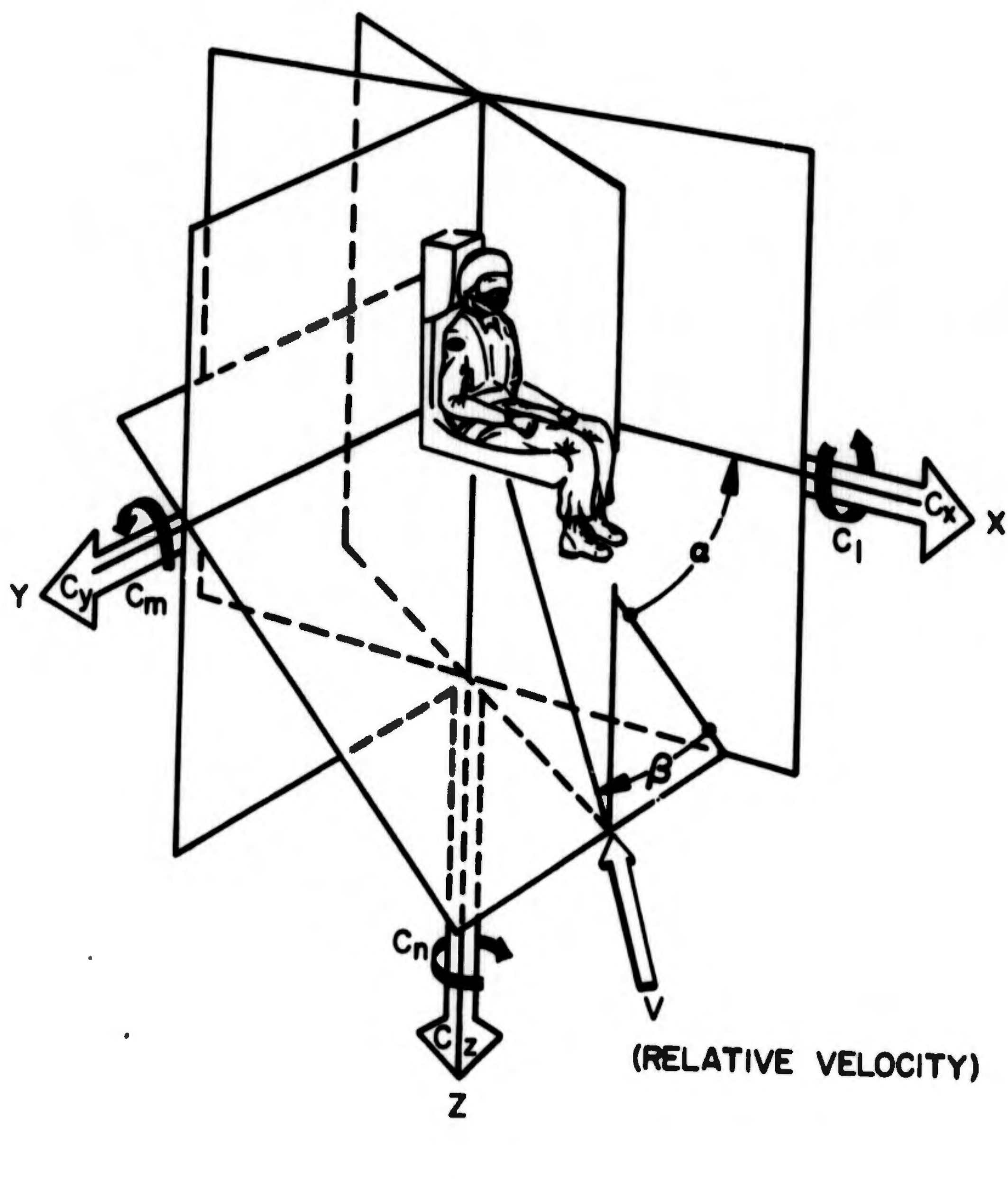
The aerodynamic forces are given by

$$\begin{bmatrix} F_{XAS} \\ F_{YAS} \\ F_{ZAS} \end{bmatrix} = q_{AS} S_S \begin{bmatrix} C_{XS} \\ C_{YS} \\ C_{ZS} \end{bmatrix}$$

where, $q_{AS} = .5\rho_S V_{AS}^2$ is the dynamic pressure. The aerodynamic moments are

$$\begin{bmatrix} L_{AS} \\ M_{AS} \\ N_{AS} \end{bmatrix} = q_{AS} S_S \left\{ \begin{bmatrix} x_{SSCG} \\ y_{SSCG} \\ z_{SSCG} \end{bmatrix} \times \begin{bmatrix} C_{XS} \\ C_{YS} \\ C_{ZS} \end{bmatrix} + \bar{b}_S \begin{bmatrix} C_{lS} \\ C_{mS} \\ C_{nS} \end{bmatrix} \right\}$$

FIGURE 11. SEAT/MAN AERO FORCES AND MOMENTS



where, S_s and $\bar{b}_s$ are the reference area and reference length, respectively, for the seat/man configuration.

As the seat moves from the cockpit into the airstream the reference area, reference length, and center of pressure are modified to account for the seat partially exposed to the airstream:

$$S_s = \begin{cases} \left(\dfrac{y_{CRRE} - y_{CRREO}}{y_{CSB3} - y_{CRREO}}\right) S_{S_{FULL\ OUT}}, & y_{CRRE} < y_{CSB3} \\ S_{S_{FULL\ OUT}}, & y_{CRRE} > y_{CSB3} \end{cases}$$

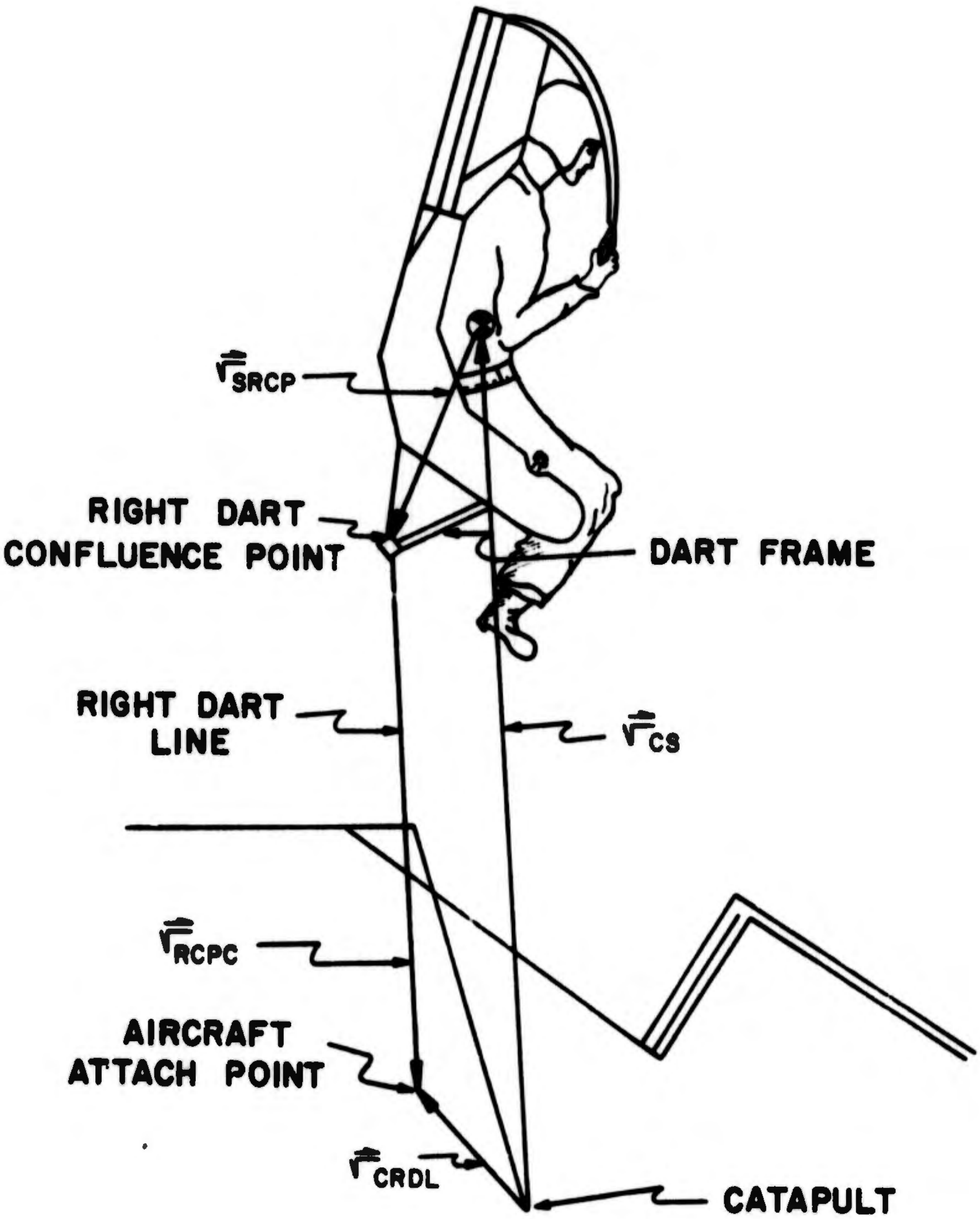
$$\bar{b}_s = \begin{cases} \left(\dfrac{y_{CRRE} - y_{CRREO}}{y_{CSB3} - y_{CRREO}}\right) \bar{b}_{S_{FULL\ OUT}}, & y_{CRRE} < y_{CSB3} \\ \bar{b}_{S_{FULL\ OUT}}, & y_{CRRE} > y_{CSB3} \end{cases}$$

$$\begin{bmatrix} x_{SSCG} \\ y_{SSCG} \\ z_{SSCG} \end{bmatrix} = \begin{cases} \begin{bmatrix} x_{SSCG} \\ y_{SSCG} \\ z_{SSCG} \end{bmatrix}_{FULL\ OUT} + \left(\dfrac{y_{CSB3} - y_{CRRE}}{y_{CSB3} - y_{CRREO}}\right) \begin{bmatrix} x_{SRC} \\ y_{SRC} \\ z_{SRC} \end{bmatrix}, & y_{CRRE} < y_{CSB3} \\ \begin{bmatrix} x_{SSCG} \\ y_{SSCG} \\ z_{SSCG} \end{bmatrix}_{FULL\ OUT}, & y_{CRRE} > y_{CSB3} \end{cases}$$

6. Stabilization

The DART system is used in the SEU-3/A Escape System to stabilize the ejection seat during sustainer rocket burn time. As the seat moves away from the aircraft, the DART lines play out through a brake mechanism in the DART frame. The brake force is assumed to act along the DART lines from the time that the DART lines first become stretched to the time that the lines separate from the seat (see Figure 12). The vector from the right DART frame confluence point to the right DART line attach point on the aircraft is given by

FIGURE 12. DART PARAMETERS



$$\overrightarrow{r_{RCPC}} = D_{SC}(\overrightarrow{r_{CRDL}} - \overrightarrow{r_{CS}}) - \overrightarrow{r_{SRCP}} \,.$$

Similarly, the vector from the left DART frame confluence point to the left DART line attach point on the aircraft is given by

$$\overrightarrow{r_{LCPC}} = D_{SC}(\overrightarrow{r_{CLDL}} - \overrightarrow{r_{CS}}) - \overrightarrow{r_{SLCP}} \,.$$

The DART forces in the right and left DART lines, presented in the SMCS, are given by

$$\overrightarrow{F_{RD}} = \frac{F_{ADART}}{2} \frac{\overrightarrow{r_{RCPC}}}{|\overrightarrow{r_{RCPC}}|}$$

$$\overrightarrow{F_{LD}} = \frac{F_{ADART}}{2} \frac{\overrightarrow{r_{LCPC}}}{|\overrightarrow{r_{LCPC}}|}$$

where, F_{ADART} is the average DART force in both lines. The total DART force is then $\overrightarrow{F_{DART}} = \overrightarrow{F_{RD}} + \overrightarrow{F_{LD}}$. The corresponding DART moments are given by

$$\overrightarrow{M_{DART}} = \overrightarrow{r_{SRCP}} \times \overrightarrow{F_{RD}} + \overrightarrow{r_{SLCP}} \times \overrightarrow{F_{LD}} \,.$$

D. Drogue Container Equations of Motion

The initial conditions for the drogue container in the EFCS are given by:

$$\overrightarrow{r_{DC}} = \overrightarrow{r_S} + A_{SE}^T \overrightarrow{r_{SDC}}$$

$$\dot{\overrightarrow{r_{DC}}} = A_{SE}^T(\overrightarrow{V_S} + \overrightarrow{\omega_S} \times \overrightarrow{r_{SDC}} + \overrightarrow{V_{DP}})$$

where, $\overrightarrow{V_{DP}}$ is the projection velocity of the drogue container with respect to the SMCS.

The particle equations of motion of the drogue container are given by

$$\ddot{x}_{DC} = -E_C \dot{x}_{ADC}$$

$$\ddot{y}_{DC} = -E_C \dot{y}_{DC} - g$$

$$\ddot{z}_{DC} = -E_C \dot{z}_{ADC}$$

where,

$$\dot{x}_{ADC} = \dot{x}_{DC} - w_x$$

$$\dot{z}_{ADC} = \dot{z}_{DC} - w_z$$

$$V_{ADC} = \left(\dot{x}^2_{ADC} + \dot{y}^2_{DC} + \dot{z}^2_{ADC}\right)^{1/2}$$

$$E_C = .5\rho_s C_{DC} V_{ADC}/m_C$$

$$MN_C = \frac{V_{ADC}}{1116.44}\left(\frac{518.67}{T_s}\right)^{1/2}$$

C_{DC} is a function of Mach number, MN_C.

Prior to WORD rocket ignition, the vector from the WORD to the drogue container is given by

$$\vec{r}_{WRDDC} = \vec{r}_{DC} - A^T_{SE}\vec{r}_{SWRDR} - \vec{r}_S .$$

The extraction of the drogue chute from its container is dependent on whether drogue chute line stretch occurs prior to or after WORD rocket ignition. If the condition $|r_{WRDDC}| < \ell_{DCL}$ is always satisfied prior to WORD ignition, the drogue chute opening equations are not computed. This corresponds to the Inertia - WORD (low speed) mode of operation.

On the other hand, if drogue line stretch occurs prior to WORD ignition (i.e., $|r_{WRDDC}| \geq \ell_{DCL}$), the drogue chute will be extracted from its container and subsequently will open. This condition corresponds to the Drogue - WORD (high speed) mode of operation.

E. **Drogue Parachute Equations of Motion**

As explained previously, when the drogue chute lanyard stretches prior to WORD ignition, the drogue chute is deployed from its container. In this situation, the initial conditions for the drogue chute will be the same as the final conditions of the drogue container. In addition, a filling time is computed for the drogue chute as follows[12]

$$t_{fDC} = k_{DC}/V_{AS} \cdot$$

This filling time expression is based on the assumption that the parachute must travel a constant distance (k_{DC}), under all conditions, in order to fill completely. Following the development of the parachute opening equations presented in Reference 8, it is assumed that the parachute can be approximated by a flat circular parachute of nominal diameter, D_0. The geometry for the parachute model is pictured in Figure 13. During opening, the canopy shape is approximated by a hemisphere of projected diameter D_P, and a frustrum of diameters, D_P and d. Assuming a linear increase in projected area S_P during the filling process, we obtain

$$S_P = \pi D_P^2/4 = K(t - t_{LS}),$$

where, t_{LS} = time at line stretch. At $t = t_{LS} + t_f$ the projected diameter is a maximum for the fully inflated canopy, i.e., $D_P = 2D_0/\pi$. Therefore,

$$K = \frac{\pi D_P^2}{4(t - t_{LS})} = \frac{D_0^2}{\pi t_f}$$

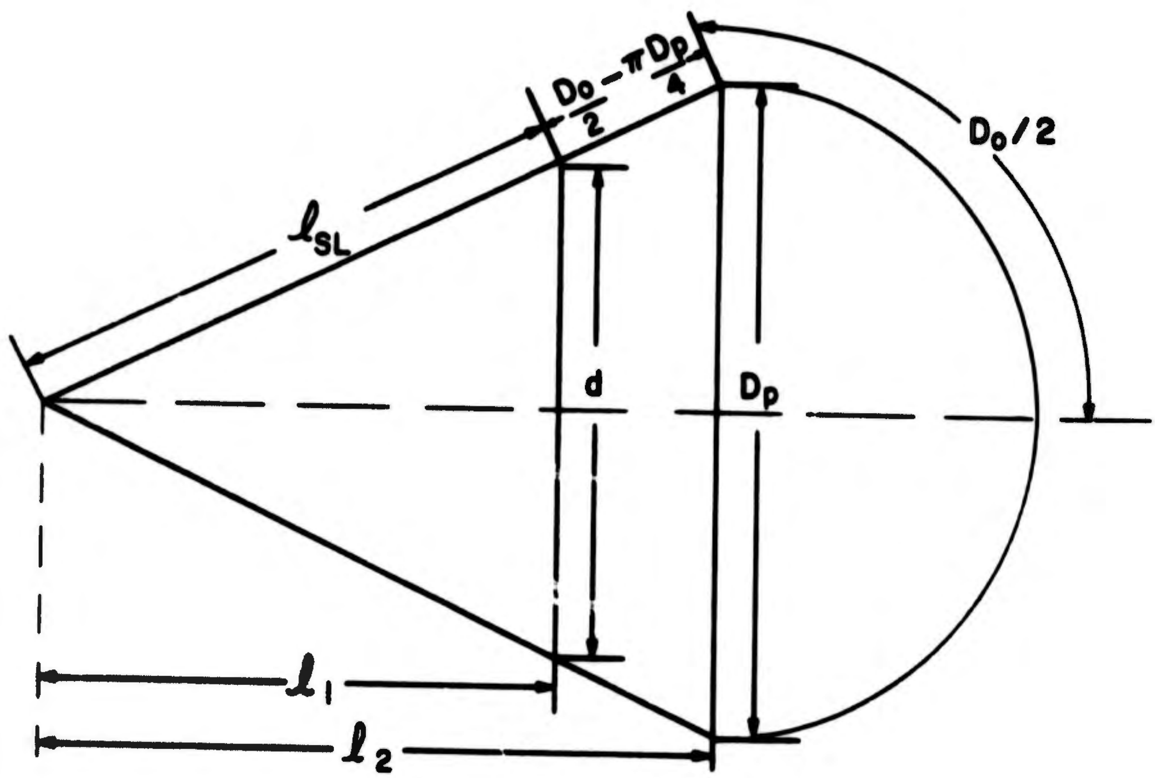
and

$$S_P = \frac{D_0^2}{\pi t_f}(t - t_{LS}) = \frac{D_0^2}{\pi}\tau$$

where, $\tau = (t - t_{LS})/t_f$ is a non-dimensional time parameter. The "included mass" of air in the canopy is ρV, where V is the volume of the hemisphere and frustrum.

$$V = \frac{2}{3}\pi\left(\frac{D_P}{2}\right)^3 + \frac{1}{3}\pi\left[\left(\frac{D_P}{2}\right)^2 \ell_2 - \left(\frac{d}{2}\right)^2 \ell_1\right]$$

FIGURE 13. PARACHUTE GEOMETRIC MODEL



where,

$$\ell_1 = \left(\ell_{SL}^2 - d^2/4 \right)^{1/2}$$

$$\ell_2 = \left[(\ell_{SL} + D_0/2 - \pi D_p/4)^2 - D_p^2/4 \right]^{1/2}$$

$$d = \frac{4\ell_{SL} D_0 \tau^{1/2}}{\pi(2\ell_{SL} + D_0 - D_0\tau^{1/2})} .$$

The empirical formula for apparent mass is given in Reference 8 as $.25\pi\rho(D_p/2)^3$ for a fully inflated canopy. Assuming a linear increase in the apparent mass during the filling process, we obtain, for this term, $.25\pi\rho(D_p/2)^3\tau$ or

$$.25\rho D_0^3 \tau^{5/2}/\pi^2 ,$$

where, $D_p = (2D_0/\pi)\tau^{1/2}$. Combining the terms for included and apparent air mass, we obtain

$$m_a = \pi\rho \left\{ \frac{2}{3}\left(\frac{D_0\tau^{1/2}}{\pi} \right)^3 + \frac{1}{3}\left[\left(\frac{D_0}{\pi} \right)^2 \tau\ell_2 - \left(\frac{d}{2} \right)^2 \ell_1 \right] + \frac{D_0^3 \tau^{5/2}}{4\pi^3} \right\}$$

Reference 8 gives the following approximation for m_a, valid when $D_0 \sim \ell_{SL}$

$$m_a = \frac{D_0^3}{\pi^2} \rho_S \left[\frac{\tau^{5/2}}{4} - \frac{2}{3(1.62)}(\tau - 1.31)^2 + .7062 \right], \quad 0 < \tau < 1$$

$$m_a = \frac{11}{12} \frac{D_0^3}{\pi^2} , \quad \tau > 1 .$$

Differentiating with respect to time,

$$\dot{m}_a = \begin{cases} \dfrac{D_0^3}{\pi^2 t_f} \rho_S \left[\dfrac{5}{8} \tau^{3/2} - \dfrac{4}{3(1.62)}(\tau - 1.31) \right], & 0 < \tau < 1 \\ 0, \ \tau > 1 & \end{cases}$$

These approximations for m_a and $\dot{m}_a$ are used in this math model. The equations of motion of the drogue chute are

$$\ddot{x}_{DC} = \left[-(E_{DC} + \dot{m}_{a_{DC}})\dot{x}_{A_{DC}} + L_{DC}u_{LDC_x} + F_{xSDC} + F_{xWDC} \right] \Big/ (m_{DC} + m_{a_{DC}})$$

$$\ddot{y}_{DC} = \left[-(E_{DC} + \dot{m}_a)\dot{y}_{DC} + L_{DC}u_{LDC_y} + F_{ySDC} + F_{yWDC} - W_{DC} \right] \Big/ (m_{DC} + m_{a_{DC}})$$

$$\ddot{z}_{DC} = \left[-(E_{DC} + \dot{m}_{a_{DC}})\dot{z}_{A_{DC}} + L_{DC}u_{LDC_z} + F_{zSDC} + F_{zWDC} \right] \Big/ (m_{DC} + m_{a_{DC}})$$

where

$$\dot{x}_{A_{DC}} = \dot{x}_{DC} - w_x$$

$$\dot{z}_{A_{DC}} = \dot{z}_{DC} - w_z$$

$$V_{A_{DC}} = \left(\dot{x}^2_{A_{DC}} + \dot{y}^2_A + \dot{z}^2_{A_{DC}} \right)^{1/2}$$

$$E_{DC} = .5\rho(SC_D)_{DC} V_{A_{DC}}$$

$$L_{DC} = .5\rho(SC_L)_{DC} V^2_{A_{DC}}$$

The angle of attack of the drogue chute is taken to be the angle between the vector from the drogue chute to the WORD and the drogue chute velocity vector:

$$\alpha_{DC} = \cos^{-1}(-\vec{r}_{WRDDC} \cdot \vec{V}_{A_{DC}} / |\vec{r}_{WRDDC}|\,|\vec{V}_{A_{DC}}|)$$

where, prior to WORD ignition,

$$\vec{r}_{WRDDC} = \vec{r}_{DC} - A^T_{SE}\vec{r}_{SWRDR} - \vec{r}_S$$

and after WORD ignition,

$$\vec{r}_{WRDDC} = \vec{r}_{DC} - \vec{r}_{WRD} .$$

The drogue chute drag and lift coefficients are computed in terms of the tangential and normal force coefficients which can be obtained from tables in Reference 12.

$$C_{D_{DC}} = C_{T_{P_{DC}}} \cos \alpha_{DC} + C_{N_{P_{DC}}} \sin \alpha_{DC}$$

$$C_{L_{DC}} = -C_{T_{P_{DC}}} \sin \alpha_{DC} + C_{N_{P_{DC}}} \cos \alpha_{DC}$$

$C_{T_{P_{DC}}}$ and $C_{N_{P_{DC}}}$ are the tangential and normal force coefficients corresponding to a projected reference area. These coefficients are tabulated for α_{DC} in the range $0 < \alpha_{DC} < 90°$. For α_{DC} outside these limits the canopy is assumed to collapse, in which case

$$(SC_D)_{DC} = \frac{D^2_{0_{DC}}}{\pi k_{SQDC}} \cdot C_{T_{P_{DC}}}(\alpha_{DC} = 0)$$

$$(SC_L)_{DC} = 0$$

where, k_{SQDC} is a coefficient > 1. Reference 12 (p. 367) suggests a value of $k_{SQDC} = 16$. For α_{DC} within the table limits

$$(SC_D)_{DC} = \begin{cases} \pi D^2_{P_{DC}} C_{D_{DC}} \tau/4, & 0 < \tau < 1 \\ \pi D^2_{P_{DC}} C_{D_{DC}}/4, & \tau > 1 \end{cases}$$

$$(SC_L)_{DC} = \begin{cases} \pi D^2_{P_{DC}} C_{L_{DC}} \tau/4, & 0 < \tau < 1 \\ \pi D^2_{P_{DC}} C_{L_{DC}}/4, & \pi > 1 \end{cases}$$

The lift unit vector, $\overrightarrow{u_{LDC}}$, is perpendicular to the drogue chute velocity vector and lies in the plane formed by the drogue lanyard and velocity vector (i.e., in the plane of α_{DC})..

$$\overrightarrow{u_{LDC}} = [\overrightarrow{V_{A_{DC}}} \times (\overrightarrow{V_{A_{DC}}} \times \overrightarrow{r_{WRDDC}})] / |\overrightarrow{V_{A_{DC}}} \times (\overrightarrow{V_{A_{DC}}} \times \overrightarrow{r_{WRDDC}})|$$

or

$$\vec{u}_{LDC} = \frac{(\vec{V}_{ADC} \cdot \vec{r}_{WRDDC})\vec{V}_{ADC} - |V_{ADC}|^2 \vec{r}_{WRDDC}}{|(\vec{V}_{ADC} \cdot \vec{r}_{WRDDC})\vec{V}_{ADC} - |V_{ADC}|^2 \vec{r}_{WRDDC}|}$$

Figure 14 illustrates the vectors involved in this computation. Prior to WORD ignition the drogue chute is attached to the seat via the WORD rocket, and as such exerts a force and moment on the seat/man. The drogue chute suspension lines and bridle are assumed to act like a linear spring. Under this assumption, the force that the seat/man exerts on the drogue chute, presented in the EFCS, is given by

$$\vec{F}_{SDC} = \begin{cases} -k_{SDC}(|\vec{r}_{WRDDC}| - \ell_{DCL} - \ell_{SLDC})\dfrac{\vec{r}_{WRDDC}}{|\vec{r}_{WRDDC}|}, & |\vec{r}_{WRDDC}| > \ell_{DCL} + \ell_{SLDC} \\ 0, \text{ otherwise} & \end{cases}$$

where,

k_{SDC} is the coefficient of elasticity for the drogue lanyard and suspension lines.

The force and moment that the drogue chute exerts on the seat/man, presented in the SMCS are given by:

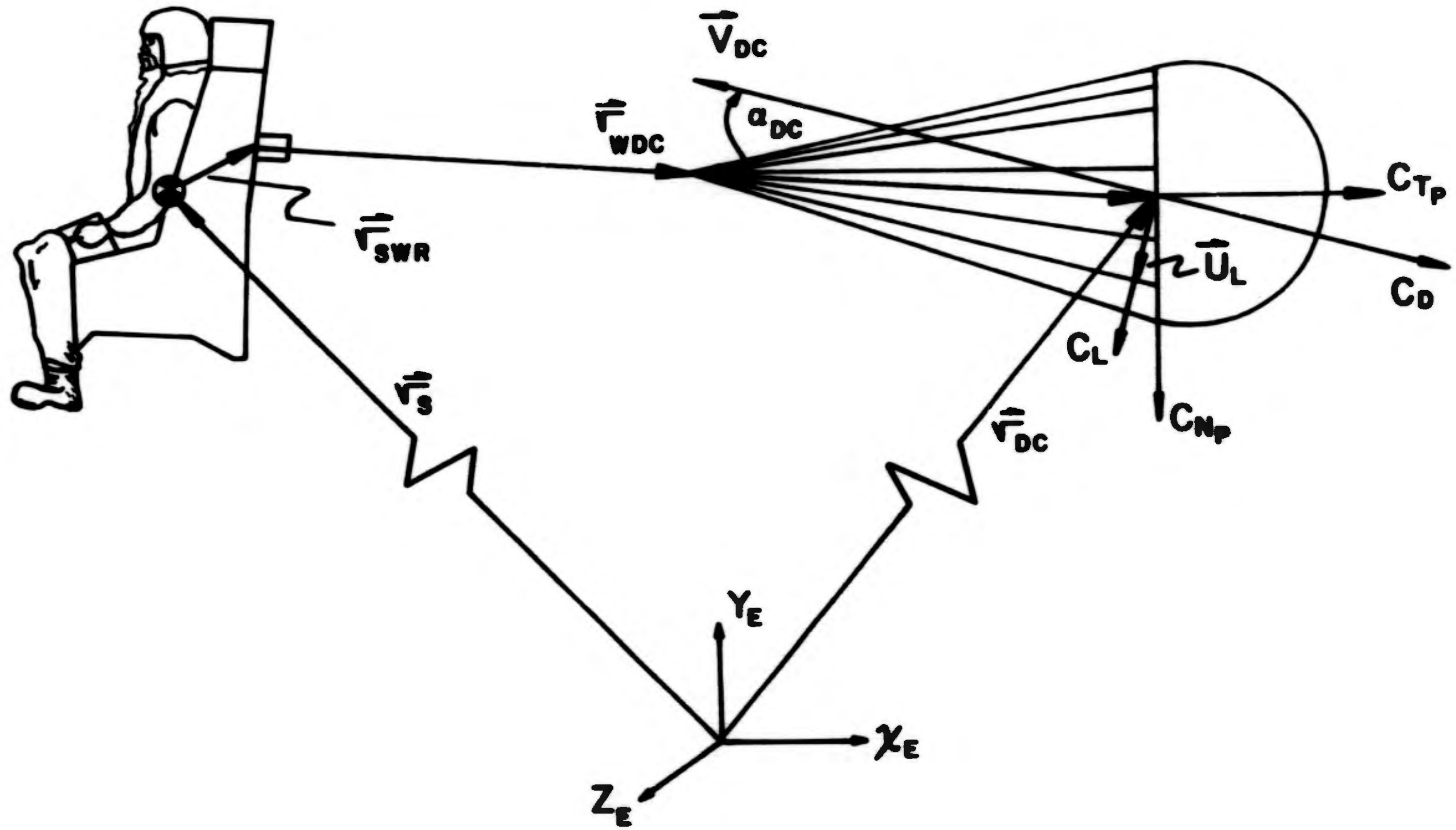
$$\vec{F}_{DCS} = \begin{cases} -A_{SE}\vec{F}_{SDC}, & \text{prior to WORD ignition} \\ 0 & , \text{ after WORD ignition} \end{cases}$$

$$\vec{M}_{DCS} = \begin{cases} \vec{r}_{SWRDR} \times \vec{F}_{DCS}, & \text{prior to WORD ignition} \\ 0 & , \text{ after WORD ignition} \end{cases}$$

F. Deployment Rocket Equations of Motion

A Wind Oriented Rocket Deployment (WORD) subsystem is employed in the SEU/3A Escape System to deploy the recovery chute. At WORD rocket ignition the initial conditions of the WORD rocket are given by

FIGURE 14. DROGUE CHUTE LIFT VECTOR



$$\vec{r}_{WRD} = \vec{r}_S + A_{SE}^T \vec{r}_{SWRDA} + d_{WRDCG} \vec{u}_{WRD}$$

$$\dot{\vec{r}}_{WRD} = A_{SE}^T (\vec{V}_S + \vec{\omega}_S \times \vec{r}_{SWRDA})$$

The unit vector $\vec{u}_{WRD}$ specifies the direction of the WORD longitudinal axis, which coincides with the WORD thrust vector, presented in the EFCS. For the low speed or Inertia-WORD mode of operation (when drogue chute line stretch does not occur prior to WORD rocket ignition), $\vec{u}_{WRD}$ is assumed to align opposite to the sustainer rocket thrust vector.

$$\vec{u}_{WRD} = -A_{SE}^T (\vec{u}_{RR} + \vec{u}_{LR}) / |\vec{u}_{RR} + \vec{u}_{LR}|$$

For the high speed or Drogue-WORD mode of operation (when drogue chute line stretch occurs prior to WORD ignition), $\vec{u}_{WRD}$ is assumed to align with the vector from the WORD to the drogue chute, $\vec{r}_{WRDDC}$.

$$\vec{u}_{WRD} = \vec{r}_{WRDDC} / |\vec{r}_{WRDDC}| .$$

The particle equations of motion of the WORD rocket are given by

$$\ddot{x}_{WRD} = (-E_{WRD}\dot{x}_{AWRD} + T_{WRD}u_{xWRD} + F_{xDCW} + F_{xRCW} + F_{xSW})/m_w$$

$$\ddot{y}_{WRD} = (-E_{WRD}\dot{y}_{WRD} + T_{WRD}u_{yWRD} + F_{yDCW} + F_{yRCW} + F_{ySW})/m_w - g$$

$$\ddot{z}_{WRD} = (-E_{WRD}\dot{z}_{AWRD} + T_{WRD}u_{zWRD} + F_{zDCW} + F_{zRCW} + F_{zSW})/m_w$$

where

$$\dot{x}_{AWRD} = \dot{x}_{WRD} - w_x$$

$$\dot{z}_{AWRD} = \dot{z}_{WRD} - w_z$$

$$V_{AWRD} = \left(\dot{x}_{AWRD}^2 + \dot{y}_{WRD}^2 + \dot{z}_{AWRD}^2\right)^{1/2}$$

$$E_{WRD} = .5\rho_S C_{D_{WRD}} S_{WRD} V_{A_{WRD}}$$

$$MN_{WRD} = \frac{V_{A_{WRD}}}{1116.44}\left(\frac{518.67}{T_S}\right)^{1/2}$$

$$C_{D_{WRD}} = f(MN_{WRD}).$$

For the Drogue - WORD or high speed mode of operation, the WORD rocket will exert forces on the drogue chute after WORD ignition. In this case, the force that the WORD exerts on the drogue chute is given by

$$\vec{F}_{WDC} = \begin{cases} -k_{SDC}(|\vec{r}_{WRDDC}| - \ell_{DCL} - \ell_{SLDC})\dfrac{\vec{r}_{WRDDC}}{|\vec{r}_{WRDDC}|}, & |\vec{r}_{WRDDC}| > \ell_{DCL} + \ell_{SLDC} \\ 0, \text{ otherwise} \end{cases}$$

The equal and opposite force that the drogue chute exerts on the WORD is given by

$$\vec{F}_{DCW} = -\vec{F}_{WDC}$$

The opening of the recovery chute container is dependent on the altitude of the seat. The altitude below which the container will open is designated by Y_{RCO}. Above this altitude the seat/man combination descends under the influence of the drogue chute which is attached to the WORD rocket which, in turn, is attached to the back of the seat head rest. For $Y_S > Y_{RCO}$, the WORD exerts a force and moment on the seat. The vector from the recovery chute contairer to the WORD is given by

$$\vec{r}_{RCWRD} = \vec{r}_{WRD} - \vec{r}_S - A^T_{SE}\vec{r}_{SRCC}$$

The force that the seat/man exerts on the WORD is given by

$$\vec{F}_{SWRD} = \begin{cases} -k_{SWRD}(|\vec{r}_{RCWRD}| - \ell_{WRDL})\dfrac{\vec{r}_{RCWRD}}{|\vec{r}_{RCWRD}|}, |\vec{r}_{RCWRD}| > \ell_{WRDL} \\ 0, \text{ otherwise} \end{cases}$$

where

k_{SWRD} is the coefficient of elasticity of the WORD lanyard.

The equal and opposite force that the WORD exerts on the seat/man is then

$$\vec{F}_{WRDS} = -A_{SE}\vec{F}_{SWRD}$$

$$\vec{M}_{WRDS} = \vec{r}_{SRCC} \times \vec{F}_{WRDS}$$

Whenever $y_S < Y_{RCO}$, $\vec{F}_{WRDS} = \vec{F}_{SWRD} = \vec{M}_{WRDS} = 0$.

G. Recovery Parachute Equations of Motion

The initial conditions for the recovery chute are computed when the recovery chute container opens and WORD/recovery chute line stretch occurs (i.e., $y_S < Y_{RCO}$ and $|\vec{r}_{RCWRD}| = \ell_{WRDL}$):

$$\vec{r}_{RC} = \vec{r}_S + A_{SE}^T\vec{r}_{SRC}$$

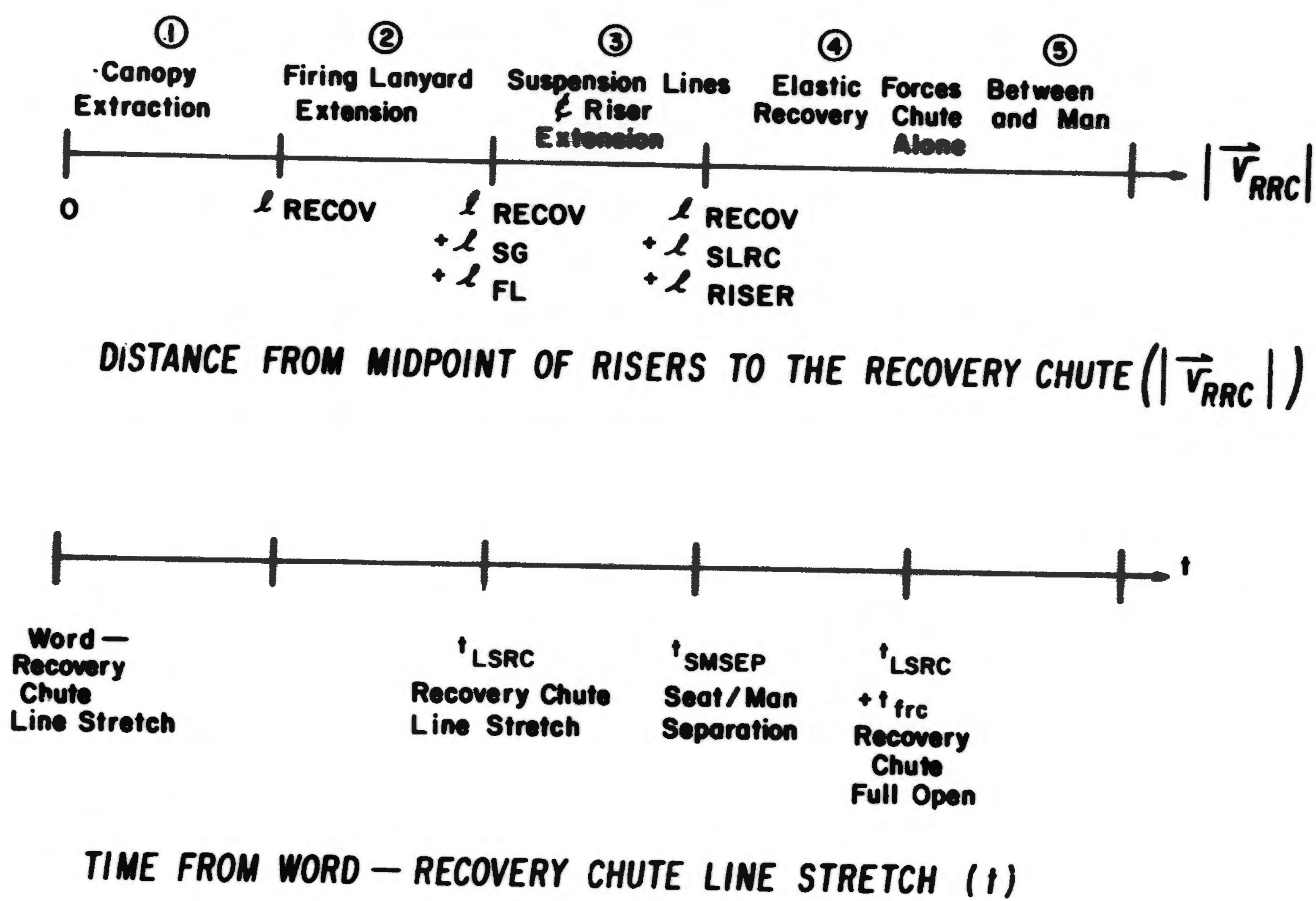
$$\dot{\vec{r}}_{RC} = A_{SF}^T(\vec{V}_S + \vec{\omega}_S \times \vec{r}_{SRC}).$$

The recovery chute simulation is divided into five phases, illustrated in Figure 15.

Phase 1 – Canopy extraction:

Canopy extraction occurs during the period that the condition $0 < |\vec{r}_{RRC}| < \ell_{RECOV}$ holds, where the vector from the midpoint of the riser attach points to the recovery chute is given by

FIGURE 15. RECOVERY CHUTE SIMULATION



$$\overrightarrow{r_{RRC}} = \overrightarrow{r_{RC}} - \overrightarrow{r_S} - A^T_{SE}\overrightarrow{r_{SR}}$$

and ℓ_{RECOV} is the length of the recovery chute canopy. During this phase the WORD/recovery chute lanyard is treated as an elastic line of modulus of elasticity k_{SWRD}. As this line stretches, tension develops which pulls the recovery chute from its container. A strip-out force, $\overrightarrow{F_{OSO}}$, exerted by the seat on the recovery chute opposes the extraction of the canopy. Figure 16 depicts the recovery chute deployment model used. Following a method similar to that of References 10 and 14, we first determine the equation of motion of the unfurling parachute relative to the seat. From this equation, we can then obtain the equation of motion of the recovery chute relative to the earth.

$$m_{RCX}(\ddot{\overrightarrow{r_{RC}}} - \ddot{\overrightarrow{r_{RCC}}}) + \dot{m}(\dot{\overrightarrow{r_{RC}}} - \dot{\overrightarrow{r_{RCC}}}) = -E_{RC}\overrightarrow{r_{ARC}} + \overrightarrow{F_{WRC}} - \overrightarrow{F_{OSO}} - m_{RCX}\overrightarrow{g}$$

where,

$$m_{RCX} = m_{RC}|\overrightarrow{r_{RRC}}|/\ell_{RECOV}$$

$\dot{m}$ = mass flow rate of the parachute from its container

The expressions for the velocity, $\dot{\overrightarrow{r_{RRC}}}$, and acceleration, $\ddot{\overrightarrow{r_{RCC}}}$, of the furled portion of the recovery chute are given by

$$\dot{\overrightarrow{r_{RCC}}} = A^T_{SE}(\overrightarrow{V_S} + \overrightarrow{\omega_S} \times \overrightarrow{r_{SRC}})$$

$$\ddot{\overrightarrow{r_{RCC}}} = A^T_{SE}\left[\dot{\overrightarrow{V_S}} + 2\overrightarrow{\omega_S} \times \overrightarrow{V_S} + \overrightarrow{\omega_S} \times (\overrightarrow{\omega_S} \times \overrightarrow{r_{SRC}}) + \dot{\overrightarrow{\omega_S}} \times \overrightarrow{r_{SRC}}\right]$$

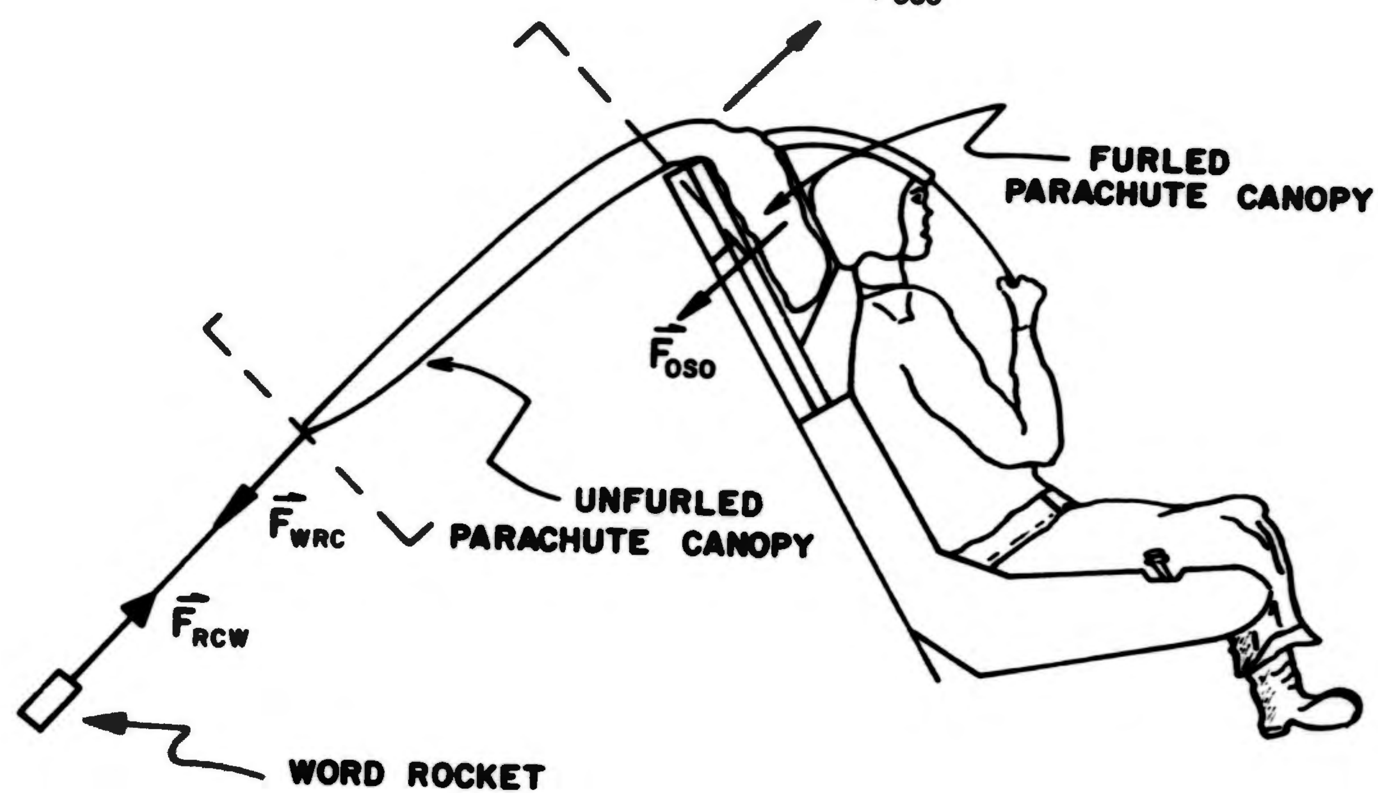
The vector from the midpoint of the riser attach points to the recovery chute, presented in the EFCS, is given by

$$\overrightarrow{r_{RRC}} = \overrightarrow{r_{RC}} - A^T_{SE}\overrightarrow{r_{SR}} - \overrightarrow{r_S},$$

and

$$E_{RC} = .5\rho_S \frac{D^2_{0RC}}{\pi k_{SQRC}} C_{T_{PRC}}(\alpha = 0)V_{ARC} \frac{|\overrightarrow{r_{RRC}}|}{\ell_{RECOV}}.$$

FIGURE 16. RECOVERY CHUTE DEPLOYMENT MODEL



The elastic force that the recovery chute exerts on the WORD is given by

$$\vec{F}_{RCW} = -k_{SWRD}(|\vec{r}_{RCWRD}| - \ell_{WRDL})$$

where, the vector from the recovery chute to the WORD is

$$\vec{r}_{RCWRD} = \vec{r}_{WRD} - \vec{r}_{RC} \cdot$$

The equal and opposite force that the WORD exerts on the recovery chute is then

$$\vec{F}_{WRC} = -\vec{F}_{RCW} \cdot$$

Rewriting the equation of motion of the unfurled canopy, we obtain

$$\ddot{\vec{r}}_{RC} = \ddot{\vec{r}}_{RCC} - \left[m' |\dot{\vec{r}}_{RC} - \dot{\vec{r}}_{RCC}| (\dot{\vec{r}}_{RC} - \dot{\vec{r}}_{RCC}) + E_{RC}\dot{\vec{r}}_{ARC} + \vec{F}_{OSO} - \vec{F}_{WRC}\right]/m_{RCX} - \vec{g}$$

When $|\vec{r}_{RRC}| = \ell_{RECOV}$, the canopy is completely extracted, completing phase 1.

Phase 2 – Firing lanyard extension:

The equations of motion of the recovery chute during firing lanyard extension are given by:

$$\ddot{\vec{r}}_{RC} = (-E_{RC}\dot{\vec{r}}_{ARC} + \vec{F}_{WRC})/m_{RC} - \vec{g}$$

where

$$E_{RC} = .5\rho_S \frac{D_{0_{RC}}^2}{\pi} C_{T_{RC}}(\alpha = 0)V_{ARC}/k_{SQRC}$$

$$\dot{\vec{r}}_{ARC} = \dot{\vec{r}}_{RC} - \vec{W}$$

When $d_{RRC} = \ell_{RECOV} + \ell_{SG} + \ell_{FL}$, the firing lanyard is fully extended completing phase 2.

Phase 3 – Suspension lines and riser extension:

When the firing lanyard stretches, the spreader gun fires, opening the canopy mouth. At spreader gun fire a filling time is computed for the recovery chute using the same formula that was used for the drogue chute.

$$t_{f_{RC}} = k_{RC}/V_S$$

$$\tau_{RC} = (t - t_{LSRC})/t_{f_{RC}},$$

where, t_{LSRC} is the time at spreader gun fire. The equations of motion of the recovery chute for this phase of the simulation are given by

$$\ddot{\vec{r}}_{RC} = [-(E_{RC} + \dot{m}_{a_{RC}})\dot{\vec{r}}_{ARC} + L_{RC}\vec{u}_{L_{RC}} - m_{RC}\vec{g}]/(m_{RC} + m_{a_{RC}})$$

where,

$$m_{a_{RC}} = \frac{D_{0_{RC}}^3}{\pi^2}\rho_S\left[\frac{\tau_{RC}}{4}^{5/2} - \frac{2}{3(1.62)}(\tau_{RC} - 1.31) + .7062\right]$$

$$\dot{m}_{a_{RC}} = \frac{D_{0_{RC}}^3\rho_S}{\pi^2 t_{f_{RC}}}\left[\frac{5}{8}\tau_{RC}^{3/2} - \frac{4}{3(1.62)}(\tau_{RC} - 1.31)\right]$$

The recovery chute angle of attack, drag, and lift coefficients are determined in the same manner as for the drogue chute:

$$\alpha_{RC} = \cos^{-1}(-\vec{r}_{RRC} \cdot \vec{V}_{ARC})/|\vec{r}_{RRC}|\,|\vec{V}_{ARC}|$$

$$C_{DRC} = C_{T_{PRC}} \cos\alpha_{RC} + C_{N_{PRC}} \sin\alpha_{RC}$$

$$C_{LRC} = -C_{T_{PRC}} \sin\alpha_{RC} + C_{N_{PRC}} \cos\alpha_{RC} \qquad 0 \le \alpha_{RC} < 90°$$

$$(SC_D)_{RC} = \pi D^2_{PRC} \tau^n_{RC} C_{DRC}/4 \qquad 0 \leq \alpha_{RC} \leq 90°$$

$$(SC_L)_{RC} = \pi D^2_{PRC} \tau^n_{RC} C_{LRC}/4$$

The presence of the magnification factor, n, (n = 1,2,3,4) was suggested by Reference 16. For α_{RC} outside the table limits, the canopy is assumed to collapse giving

$$(SC_D)_{RC} = \frac{D^2_{0RC}}{\pi k_{SQRC}} C_{TRC}(\alpha = 0)$$

$$(SC_L)_{RC} = 0$$

$$E_{RC} = .5\rho_S (SC_D)_{RC} V_{ARC}$$

$$L_{RC} = .5\rho_S (SC_L)_{RC} V^2_{ARC}$$

The unit vector in the direction of lift is determined from the triple cross product

$$\vec{u}_{LRC} = \vec{V}_{ARC} \times (\vec{V}_{ARC} \times \vec{r}_{RRC})/|\vec{V}_{ARC} \times (\vec{V}_{ARC} \times \vec{r}_{RRC})|$$

or

$$\vec{u}_{LRC} = (\vec{V}_{ARC} \cdot \vec{r}_{RRC})\vec{V}_{ARC} - |\vec{V}_{ARC}|^2 \vec{r}_{RRC}$$

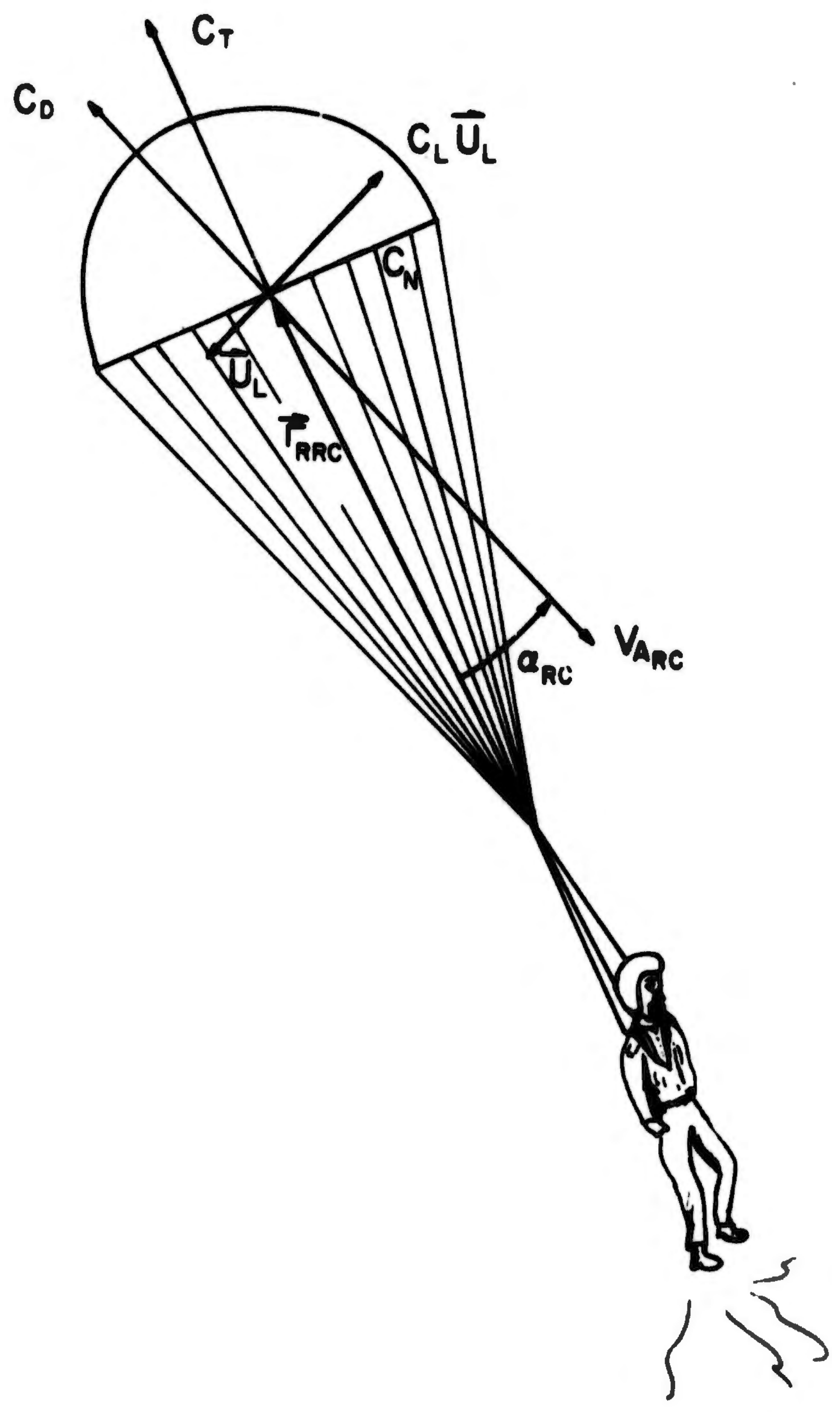
The aerodynamic terms used in the above equations are illustrated in Figure 17.

When the risers play out and develop tension (i.e., $|\vec{r}_{RRC}| = \ell_{RISER} + \ell_{SLRC}$), seat/man separation occurs. This completes Phase 3 of the recovery chute simulation.

Phase 4 – Man alone/recovery chute simulation during opening:

After seat/man separation, the recovery chute/man alone combination is modelled as two bodies connected by elastic suspension lines and risers. The equations of motion of the recovery chute now incorporate these forces:

FIGURE 17. RECOVERY CHUTE LIFT AND DRAG



$$\ddot{\vec{r}}_{RC} = \left[-(E_{RC} + \dot{m}_{a_{RC}})\vec{\dot{r}}_{ARC} + L_{RC}\vec{u}_{L_{RC}} + \vec{F}_{SRC} - m_{RC}\vec{g}\right] \Big/ (m_{RC} + m_{a_{RC}})$$

where,

E_{RC}, L_{RC}, $m_{a_{RC}}$, $\dot{m}_{a_{RC}}$, $\vec{u}_{L_{RC}}$ are the same as in phase 3.

Elastic forces are computed in the right and left risers as follows:

The vectors from the right and left riser attach points to the recovery chute are

$$\vec{r}_{RRRC} = \vec{r}_{RC} - A_{SE}^{T}\vec{r}_{MRR} - \vec{r}_{M}$$

$$\vec{r}_{LRRC} = \vec{r}_{RC} - A_{SE}^{T}\vec{r}_{MLR} - \vec{r}_{M}$$

The forces exerted on the parachute through the right and left risers are given by

$$\vec{F}_{MRR} = \begin{cases} -k_{SRC}(|\vec{r}_{RRRC}| - \ell_{SLRC} - \ell_{RISER})\dfrac{\vec{r}_{RRRC}}{|\vec{r}_{RRRC}|}, & |\vec{r}_{RRRC}| > \ell_{SLRC} + \ell_{RISER} \\ 0, \text{ otherwise} \end{cases}$$

$$\vec{F}_{MLR} = \begin{cases} -k_{SRC}(|\vec{r}_{LRRC}| - \ell_{SLRC} - \ell_{RISER})\dfrac{\vec{r}_{LRRC}}{|\vec{r}_{LRRC}|}, & |\vec{r}_{LRRC}| > \ell_{LSRC} + \ell_{RISER} \\ 0, \text{ otherwise} \end{cases}$$

Total force on recovery chute

$$\vec{F}_{MRC} = \vec{F}_{MRR} + \vec{F}_{MLR}.$$

Forces in the MACS

$$\vec{F}_{RCRR} = -A_{ME}\vec{F}_{MRR}$$

$$\vec{F}_{RCLR} = -A_{ME}\vec{F}_{MLR}$$

Total force and moment on man

$$\vec{F}_{RCM} = \vec{F}_{RCRR} + \vec{F}_{RCLR}$$

$$\vec{M}_{RCM} = (\vec{r}_{MRR} \times \vec{F}_{RCRR}) + (\vec{r}_{MLR} \times \vec{F}_{RCLR})$$

Phase 4 of the simulation is complete when the recovery chute reaches full inflation, i.e., $t = t_{LSRC} + t_{fRC}$.

Phase 5 – Man alone/recovery chute simulation after full inflation

The equations of motion of the recovery chute are the same as those for Phase 4 with the following exceptions,

$$m_{aRC} = \frac{11}{12} \frac{D_{0RC}^3}{\pi^2} \rho_S$$

$$\dot{m}_{aRC} = 0$$

$$(SC_D)_{RC} = \frac{D_{0RC}^2}{\pi} C_{DRC}$$

$$(SC_L)_{RC} = \frac{D_{0RC}^2}{\pi} C_{LRC}$$

$$E_{RC} = .5\rho_S (SC_D)_{RC} V_{ARC}$$

$$L_{RC} = .5\rho_S (SC_L)_{RC} V_{ARC}^2 .$$

H. Man Alone Equations of Motion

The man alone initial conditions at seat/man separation are given by

$$\vec{r}_M = \vec{r}_S + A_{SE}^T \vec{r}_{SM}, \quad \vec{\lambda}_M = \vec{\lambda}_S$$

$$\vec{V}_M = \vec{V}_S + \vec{\omega}_S \times \vec{r}_{SM}, \quad \vec{\omega}_M = \vec{\omega}_S, \quad A_{ME} = A_{SE}.$$

The six-degree-of-freedom rigid body equations of motion for the man alone are:

$$\dot{u}_M = (r_M v_M - q_M w_M - ga_{M\,E\,12} + F_{XMA} + F_{XRCM})/m_M$$

$$\dot{v}_M = (p_M w_M - r_M u_M - ga_{M\,E\,22} + F_{YMA} + F_{YRCM})/m_M$$

$$\dot{w}_M = (q_M u_M - p_M v_M - ga_{M\,E\,32} + F_{ZMA} + F_{ZRCM})/m_M$$

$$\dot{q}_M = (XA + YB + ZC)/(-I_{XY_M} A + I_{YY_M} B - I_{YZ_M} C)$$

$$\dot{p}_M = I_{ZZ_M}(A + I_{XY_M}\dot{q}_M) + I_{XZ_M}(Z + I_{YZ_M}\dot{q}_M)\ \ B$$

$$\dot{r}_M = (Z + I_{XZ_M}\dot{p}_M + I_{YZ_M}\dot{q}_M)/I_{ZZ_M}$$

where,

$$(X,T,Z)^T = -\vec{\omega}_M \times [I]_M \vec{\omega}_M + \vec{M}_{MRC} + \vec{M}_{MA}$$

$$A = I_{XY_M} I_{ZZ_M} + I_{XZ_M} I_{YZ_M}$$

$$B = I_{XX_M} I_{ZZ_M} - I^2_{XZ_M}$$

$$C = I_{XX_M} I_{YZ_M} + I_{XY_M} I_{XZ_M}$$

Aerodynamic coefficients are tabulated as a function of angle of attack ($0 < \alpha_M < 360°$) and angle of sideslip ($0 < \beta_M < 180°$).

$$q_{A_M} = .5\rho_m V^2_{A\,M}$$

$$T = 518.67 - .00356616\, y_M$$

$$P = 1013.25(518.67/T)^{-5.255877}$$

$$\rho_M = .00121668402\ P/T$$

$$\begin{bmatrix} F_{X_{AM}} \\ F_{Y_{AM}} \\ F_{Z_{AM}} \end{bmatrix} = q_{A_M} S_M \begin{bmatrix} C_{X_M} \\ C_{Y_M} \\ C_{Z_M} \end{bmatrix}$$

$$\begin{bmatrix} L_{A_M} \\ M_{A_M} \\ N_{A_M} \end{bmatrix} = q_{A_M} S_M \left\{ \begin{bmatrix} x_{MMCG} \\ y_{MMCG} \\ z_{MMCG} \end{bmatrix} \times \begin{bmatrix} C_{X_M} \\ C_{Y_M} \\ C_{X_M} \end{bmatrix} + \bar{b}_M \begin{bmatrix} C_{l_M} \\ C_{m_M} \\ C_{n_M} \end{bmatrix} \right\}$$

Reference 22 contains aerodynamic coefficients for the man alone as a function of angle of attack and angle of sideslip.

I. Seat Alone Equations of Motion

The initial conditions for the seat alone six-degree-of-freedom rigid body equations of motion are determined also at seat/man separation:

$$\vec{r}_{SA} = \vec{r}_S + A_{SE}^T \vec{r}_{SSA}$$

$$\vec{V}_{SA} = \vec{V}_S + \vec{\omega}_S \times \vec{r}_{SSA}$$

$$\vec{\omega}_{SA} = \vec{\omega}_S$$

$$\vec{\lambda}_{SA} = \vec{\lambda}_S$$

$$A_{SAE} = A_{SE}$$

$$\dot{u}_{SA} = r_{SA} v_{SA} - q_{SA} w_{SA} - g a_{SAE12} + q_{A_{SA}} S_{SA} C_{X_{SA}}$$

$$\dot{v}_{SA} = p_{SA} w_{SA} - r_{SA} u_{SA} - g a_{SAE22} + q_{A_{SA}} S_{SA} C_{Y_{SA}}$$

$$\dot{w}_{SA} = q_{SA} u_{SA} - p_{SA} v_{SA} - g a_{SAE32} + q_{A_{SA}} S_{SA} C_{Z_{SA}}$$

$$\dot{q}_{SA} = (XA + YB + ZC)/(-I_{XY_{SA}} A + I_{YY_{SA}} B - I_{YZ_{SA}} C)$$

$$\dot{p}_{SA} = [I_{ZZ_{SA}}(A + I_{XY_{SA}} \dot{q}_{SA}) + I_{XZ_{SA}}(Z + I_{YZ_{SA}} \dot{q}_{SA})]/B$$

$$\dot{r}_{SA} = (Z + I_{XZ_{SA}} \dot{p}_{SA} + I_{YZ_{SA}} \dot{q}_{SA})/I_{ZZ_{SA}}$$

where

$$(X,Y,Z)^T = -\vec{\omega}_{SA} \times [I]_{SA} \vec{\omega}_{SA} + \vec{M}_{ASA}$$

$$A = I_{XY_{SA}} I_{ZZ_{SA}} + I_{XZ_{SA}} I_{YZ_{SA}}$$

$$B = I_{XX_{SA}} I_{ZZ_{SA}} - I^2_{XZ_{SA}}$$

$$C = I_{XX_{SA}} I_{YZ_{SA}} + I_{XY_{SA}} I_{XZ_{SA}}$$

$$\begin{bmatrix} L_{ASA} \\ M_{ASA} \\ N_{ASA} \end{bmatrix} = q_{A_{SA}} S_{SA} \left\{ \begin{bmatrix} x_{SASCG} \\ y_{SASCG} \\ z_{SASCG} \end{bmatrix} \times \begin{bmatrix} C_{X_{SA}} \\ C_{Y_{SA}} \\ C_{Z_{SA}} \end{bmatrix} + \bar{b}_{SA} \begin{bmatrix} C_{l_{SA}} \\ C_{m_{SA}} \\ C_{n_{SA}} \end{bmatrix} \right\}$$

IV. CONCLUDING REMARKS AND FUTURE PLANS

The formulation described herein, together with ICARUS and Reference 7, represent a "first step" toward achieving NWL's long range goal of developing a Navy capability to simulate the performance of any aircrew escape system. In view of this goal, ICARUS was programmed in modular form so that it could be used as a "working model." Escape system subsystems correspond to program subroutines so that different escape systems can be easily modified by recoding only appropriate subroutines. For example, to model a tractor rocket extraction system might only require modification of the catapult and sustainer rocket subroutines of the present ICARUS program. By modifying the basic program in this manner, it is hoped that a capability to simulate the performance of all ejection seats, extraction systems, and capsule systems can be achieved.

While preliminary simulations of the SEU/3A Escape System[7] indicate that the present ICARUS program adequately predicts test performance, certain segments of the program may require greater sophistication in the future. For example, 6D-0-F aircraft equations, modified crewman rigid body equations, and improved parachute equations may be warranted. Again, modifications of this type can be easily accomplished because of the modularity of the ICARUS program.

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ACRONYMS FOR THE SEU-3/A ESCAPE SYSTEM

The following is a list of acronyms associated with the SEU-3/A Escape System.

(1) DART is an acronym for Directional Automatic Realignment of Trajectory. The DART is designed to stabilize the ejection seat, utilizing brake lines, during sustainer rocket burn time.

(2) SBR is an acronym for Seat Back Rocket. The SBR subsystem consists of two rocket motors which provide sustainer rocket thrust to the ejection seat.

(3) WORD is an acronym for Wind Oriented Rocket Deployment. The WORD is a small rocket which, either by itself or in conjunction with the drogue chute, deploys the personnel recovery chute.

LIST OF SYMBOLS AND NOTATION

Coordinate Systems

The following notation is employed to identify the various coordinate systems used in the formulation:

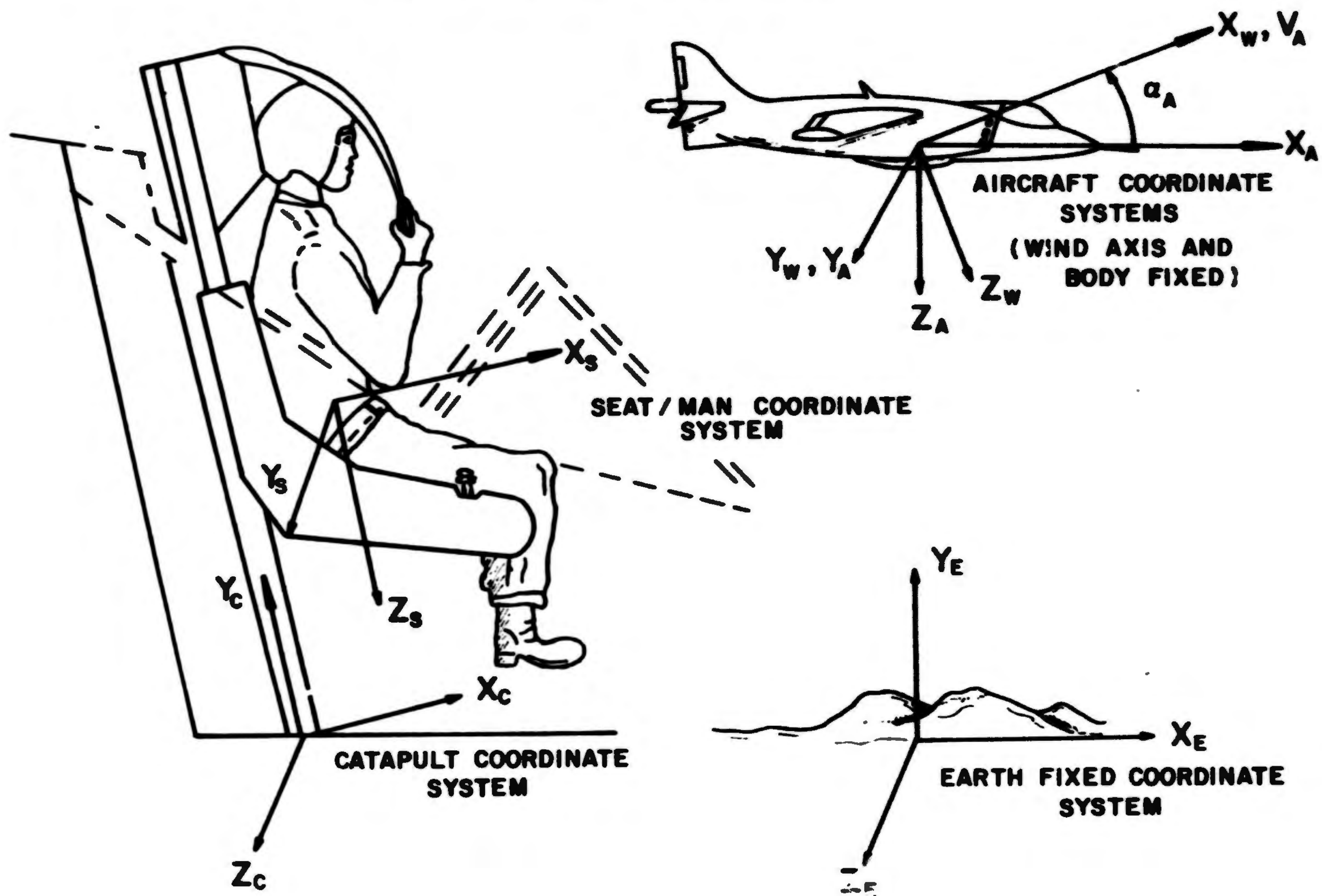
EFCS	earth fixed coordinate system
WAS	airplane wind axis system
APCS	airplane body fixed coordinate system
CCS	catapult coordinate system
SMCS	seat/man body fixed coordinate system
MACS	man alone body fixed coordinate system
SACS	seat alone body fixed coordinate system

Figure 1-B illustrates typical orientations for these coordinate systems as well as the labels attached to the coordinate axes. Not shown are the MACS and SACS which usually are chosen to coincide with the SMCS at seat/man separation.

Modified Euler Angles

χ, γ, μ	specify the orientation of the WAS with respect to the EFCS
ψ_C, θ_C, Φ_C	specify the orientation of the CCS with respect to the APCS
$\psi_{SC}, \theta_{SC}, \Phi_{SC}$	specify the orientation of the SMCS with respect to the CCS
ψ_S, θ_S, Φ_S	specify the orientation of the SMCS with respect to the EFCS
$\psi_{MA}, \theta_{MA}, \Phi_{MA}$	specify the orientation of the MACS with respect to the EFCS
$\psi_{SA}, \theta_{SA}, \Phi_{SA}$	specify the orientation of the SACS with respect to the EFCS

FIGURE I-B. COORDINATE SYSTEMS



Airplane Coordinate System (ACPS) Position Vectors:

$\vec{r}_{AC}$	vector from the aircraft C.G. to the origin of the CCS presented in the APCS
$\vec{r}_{AS}$	vector from the aircraft C.G. to the seat/man C.G. presented in the APCS

Catapult Coordinate System (CCS) Position Vectors:

$\vec{r}_{CS}$	vector from the catapult to the seat/man C.G. presented in the CCS
$\vec{r}_{CM}$	vector from the catapult to the man alone C.G. presented in the CCS
$\vec{r}_{CA}$	vector from the catapult to the aircraft C.G. presented in the CCS
$\vec{r}_{CSB_i}$	vector from the catapult to the i^{th} slider block presented in the CCS
$\vec{r}_{CDC}$	vector from the catapult to the drogue container presented in the CCS
$\vec{r}_{CRC}$	vector from the catapult to the recovery chute presented in the CCS
$\vec{r}_{CRDL}$ ($\vec{r}_{CLDL}$)	vector from the catapult to the right (respectively, left) DART line attach point on the aircraft presented in the CCS
$\vec{r}_{CRRE}$ ($\vec{r}_{CLRE}$)	vector from the catapult to the bottom end of the right (respectively, left) rail end presented in the CCS
$\vec{r}_{CRREO}$ ($\vec{r}_{CLREO}$)	initial value of $\vec{r}_{CRRE}$ (respectively, $\vec{r}_{CLRE}$)

$\vec{r}_{CRCMA}$ ($\vec{r}_{CLCMA}$)	vector from the catapult to the right (respectively, left) catapult tube presented in the CCS
$\vec{r}_{CRCC}$	vector from the catapult to the attach point of the WORD lanyard on the recovery chute container presented in the CCS
$\vec{r}_{CRR}$ ($\vec{r}_{CLR}$)	vector from the catapult to the right (respectively, left) riser attach point presented in the CCS
$\vec{r}_{CSA}$	vector from the catapult to the seat alone C.G. presented in the CCS
$\vec{r}_{CSCG}$	vector from the catapult to the seat/man aerodynamic reference C G. presented in the CCS
$\vec{r}_{CSACG}$	vector from the catapult to the seat alone aerodynamic reference C.G. presented in the CCS
$\vec{r}_{CMCG}$	vector from the catapult to the man alone aerodynamic reference C.G. presented in the CCS
$\vec{r}_{CWRDA}$	vector from the catapult to the WORD rocket presented in the CCS
$\vec{r}_{CWKDR}$	vector from the catapult to the WORD-drogue line attach point in the SMCS
$\vec{r}_{CRSBR}$ ($\vec{r}_{CLSBR}$)	vector from the catapult to the right (respectively, left) sustainer rocket nozzle presented in the CCS
$\vec{r}_{CRCP}$ ($\vec{r}_{CLCP}$)	vector from the catapult to the right (respectively, left) DART confluence point presented in the CCS

$\Delta\vec{r}_{SB_i}$	vector from the i^{th} slider block to the seat rails, which is perpendicular to the Y_C axis, presented in the CCS

Seat/Man Coordinate (SMCS) Position Vectors

$\vec{r}_{SSB_i}$	vector from the seat/man C.G. to the i^{th} slider block contact point presented in the CCS
$\vec{r}_{SRC}$	vector from the seat/man C.G. to the recovery chute in the SMCS
$\vec{r}_{SDC}$	vector from the seat/man C.G. to the drogue container in SMCS
$\vec{r}_{SRRE}$ ($\vec{r}_{SLRE}$)	vector from the seat/man C.G. to the bottom end of right (respectively, left) rail presented in the SMCS
$\vec{r}_{SRCMA}$ ($\vec{r}_{SLCMA}$)	vector from the seat/man C.G. to the right (respectively, left) catapult tube presented in the SMCS
$\vec{r}_{SRCC}$	vector from the seat/man C.G. to the attach point of the WORD lanyard to the recovery chute container presented in the SMCS
$\vec{r}_{SRR}$ ($\vec{r}_{SLR}$)	vector from the seat/man C.G. to the right (respectively, left) riser attach point presented in the SMCS
$\vec{r}_{SR}$	vector from the seat/man C.G. to the midpoint of the riser attach points presented in the SMCS
$\vec{r}_{SWRDA}$	vector from the seat/man C.G. to the WORD rocket presented in the SMCS
$\vec{r}_{SWRDR}$	vector from the seat/man C.G. to the WORD-drogue line attach point in the SMCS

$\vec{r}_{SRSBR}$ ($\vec{r}_{SLSBR}$)	vector from the seat/man C.G. to the right (respectively, left) sustainer rocket nozzle presented in the SMCS
$\vec{r}_{SRCP}$ ($\vec{r}_{SLCP}$)	vector from the seat/man C.G. to the right (respectively, left) DART confluence point presented in the SMCS
$\vec{r}_{RCPC}$ ($\vec{r}_{LCPC}$)	vector from the right (respectively, left) DART confluence point to the DART line attach point on the aircraft presented in the SMCS
$\vec{r}_{SM}$	vector from the seat/man C.G. to the man alone C.G. presented in the SMCS
$\vec{r}_{SSA}$	vector from the seat/man C.G. to the seat alone C.G. presented in the SMCS
$\vec{r}_{SSCG}$	vector from the seat/man C.G. to the seat/man aerodynamic reference C.G. presented in the SMCS
$(O, O, z_{REi})^T$	vector from the bottom of the right (respectively, left) rail end to the i^{th} slider block contact point for i = 1,2,3 (respectively, for i = 4,5,6).

Man Alone Coordinate System (MACS) and Seat Alone Coordinate System (SACS) Position Vectors:

$\vec{r}_{MRR}$ ($\vec{r}_{MLP}$)	vector from the man alone C.G. to the right (respectively, left) riser attach point in the MACS
$\vec{r}_{MR}$	vector from the man alone C.G. to the midpoint of the riser attach points in the MACS

$\vec{r}_{MMCG}$	vector from the man alone C.G. to the man alone aerodynamic reference C.G. presented in the MACS
$\vec{r}_{SASCG}$	vector from the seat alone C.G. to the seat alone aerodynamic reference C.G. presented in the SACS

Earth Fixed Coordinate System (EFCS) Position Vectors

$\vec{r}_{A}$	vector to the aircraft C.G. presented in the EFCS
$\vec{r}_{S}$	vector to the seat/man C.G. presented in the EFCS
$\vec{r}_{M}$	vector to the man alone C.G. presented in the EFCS
$\vec{r}_{SA}$	vector to the seat alone C.G. presented in the EFCS
$\vec{r}_{DC}$	vector to the drogue container/drogue chute presented in the EFCS
$\vec{r}_{RC}$	vector to the recovery chute presented in the EFCS
$\vec{r}_{WRD}$	vector to the WORD rocket presented in the EFCS
$\vec{r}_{WRDDC}$	vector from the WORD rocket to the drogue container/drogue chute presented in the EFCS
$\vec{r}_{RCWRD}$	vector from the recovery chute container/recovery chute to the WORD rocket presented in the EFCS
$\vec{r}_{RRC}$	vector from the midpoint of the riser attach points to the recovery chute

$\vec{r}_{RRRC}$ ($\vec{r}_{LRRC}$)	vector from the right (respectively, left) riser attach point to the recovery chute

Direction Cosine Matrices

$A_{AE} = (a_{AE})_{ij}$	direction cosine matrix from EFCS to APCS
$D_{CA} = (d_{CA})_{ij}$	direction cosine matrix from APCS to CCS
$D_{SC} = (d_{SC})_{ij}$	direction cosine matrix from CCS to SMCS
$D_{AS} = (d_{AS})_{ij}$	direction cosine matrix from SMCS to APCS
$A_{SE} = (a_{SE})_{ij}$	direction cosine matrix from EFCS to SMCS
$A_{ME} = (a_{ME})_{ij}$	direction cosine matrix from EFCS to MACS
$A_{SAE} = (a_{SAE})_{ij}$	direction cosine matrix from EFCS to SACS
$D_{CS} = (d_{CS})_{ij}$	direction cosine matrix from EFCS to CCS

Direction Cosine Angles/Unit Vectors

$(\alpha_{RSBR}, \beta_{RSBR}, \gamma_{RSBR})$ $(\alpha_{LSBR}, \beta_{LSBR}, \gamma_{LSBR})$	direction cosine angles of right (respectively, left) sustainer rocket thrust line with respect to the CCS
$\vec{u}_{RR}$ ($\vec{u}_{LR}$)	vector along right (respectively, left) sustainer rocket thrust line presented in the SMCS
$\vec{u}_{WRD}$	unit vector along WORD longitudinal axis presented in the EFCS

$\vec{u}_{LDC}$ $(\vec{u}_{LRC})$	unit vector in the direction of drogue chute (respectively, recovery chute) lift

Velocity Components

V_A	true airspeed of the aircraft
$(u_A, v_A, w_A)^T$	velocity of the aircraft presented in the APCS
$(\dot{x}_A, \dot{y}_A, \dot{z}_A)^T$	velocity of the aircraft presented in the EFCS
$\vec{\omega}_W = (p_W, q_A, r_W)^T$	angular velocity of the aircraft presented in the aircraft WAS
$\vec{\omega}_A = (p_A, q_A, r_A)^T$	angular velocity of the aircraft presented in the APCS
$\vec{V}_S = (u_S, v_S, w_S)^T$	velocity of the seat/man presented in the SMCS
$\vec{V}_{A_S} = (u_{A_S}, v_{A_S}, w_{A_S})^T$	velocity of the seat/man with respect to the wind presented in the SMCS
$(\dot{x}_S, \dot{y}_S, \dot{z}_S)^T$	velocity of the seat/man presented in the EFCS
$\vec{V}_M = (u_M, v_M, w_M)^T$	velocity of the man alone presented in the MACS
$\vec{V}_{A_M} = (u_{A_M}, v_{A_M}, w_{A_M})^T$	velocity of the man alone relative to the wind presented in the MACS
$\vec{V}_{SA} = (u_{SA}, v_{SA}, w_{SA})^T$	velocity of the seat alone presented in the SACS
$\vec{V}_{A_{SA}} = (u_{A_{SA}}, v_{A_{SA}}, w_{A_{SA}})^T$	velocity of the seat alone relative to the wind presented in the SACS
$\vec{\omega}_S = (p_S, q_S, r_S)^T$	angular velocity of the seat/man presented in the SMCS

$\vec{\omega}_M = (p_M, q_M, r_M)^T$	angular velocity of man alone presented in the MACS
$\vec{\omega}_{SA} = (p_{SA}, q_{SA}, r_{SA})^T$	angular velocity of seat alone presented in the SACS
MN_S	Mach number of the seat/man
$\dot{\vec{r}}_{DC} = (\dot{x}_{DC}, \dot{y}_{DC}, \dot{z}_{DC})^T$	velocity of the drogue container/drogue chute presented in the EFCS
$\vec{V}_{A_{DC}} = (\dot{x}_{A_{DC}}, \dot{y}_{DC}, \dot{z}_{A_{DC}})^T$	velocity of the drogue container/drogue chute with respect to the wind presented in the EFCS
MN_{DC}	Mach number of drogue container/drogue chute
$(\dot{x}_{RC}, \dot{y}_{RC}, \dot{z}_{RC})^T$	velocity of the recovery chute presented in the EFCS
$\vec{V}_{A_{RC}} = (\dot{x}_{A_{RC}}, \dot{y}_{RC}, \dot{z}_{A_{RC}})^T$	velocity of the recovery chute with respect to the wind presented in the EFCS
$(\dot{x}_{WRD}, \dot{y}_{WRD}, \dot{z}_{WRD})^T$	velocity of the WORD presented in the EFCS
$\vec{V}_{A_{WRD}} = (\dot{x}_{A_{WRD}}, \dot{y}_{A_{WRD}}, \dot{z}_{A_{WRD}})^T$	velocity of the WORD with respect to the wind presented in the EFCS
$\vec{V}_{DP} = (u_{DP}, v_{DP}, w_{DP})^T$	projection velocity of drogue container with respect to the seat presented in the SMCS
$\vec{W} = (w_X, O, w_Z)^T$	wind velocity components presented in the EFCS
$(u_{WS}, v_{WS}, \dot{w}_{WS})^T$	wind velocity components presented in the SMCS

$(u_{WM}, v_{WM}, w_{WM})^T$	wind velocity components presented in the MACS
$(u_{WSA}, w_{WSA}, w_{WSA})^T$	wind velocity components presented in the SACS
$\dot{r}_{RCC}$	velocity of the furled portion of the recovery chute canopy presented in the EFCS

Quaternions

$\vec{\lambda}_S = (\lambda_{0S}, \lambda_{1S}, \lambda_{2S}, \lambda_{3S})^T$	quaternion components defining the orientation of the SMCS
$\vec{\lambda}_M = (\lambda_{0M}, \lambda_{1M}, \lambda_{2M}, \lambda_{3M})^T$	quaternion components defining the orientation of the MACS
$\vec{\lambda}_{SA} = (\lambda_{0SA}, \lambda_{1SA}, \lambda_{2SA}, \lambda_{3SA})^T$	quarternion components defining the orientation of the SACS

Airplane, Seat/Man, Man Alone, and Seat Alone Parameters

$\vec{n} = (n_{XA}, n_{YA}, n_{ZA})$	airplane load factor in APCS
g	gravity constant
m_S, m_M, m_{SA}, m_A	mass of seat/man, man alone, seat alone and aircraft, respectively
W_S, W_M, W_{SA}, W_A	weight of seat/man, man alone, seat alone, and aircraft, respectively
$I_{XX_S}, I_{YY_S}, I_{ZZ_S}$ $I_{XY_S}, I_{XZ_S}, I_{YZ_S}$	moments of inertia of seat/man
$I_{XX_M}, I_{YY_M}, I_{ZZ_M}$ $I_{XY_M}, I_{XZ_M}, I_{YZ_M}$	moments of inertia of man alone
$I_{XX_{SA}}, I_{YY_{SA}}, I_{ZZ_{SA}}$ $I_{XY_{SA}}, I_{XZ_{SA}}, I_{YZ_{SA}}$	moments of inertia of seat alone

S_S, S_M, S_{SA}	reference area of seat/man, man alone, and seat alone, respectively

Parachute Parameters

m_{DC} (m_{RC})	mass of drogue chute (respectively, recovery chute)
$m_{a_{DC}}$ ($m_{a_{RC}}$)	included plus apparent air mass of the drogue chute (respectively, recovery chute)
$\dot{m}_{a_{DC}}$ ($\dot{m}_{a_{RC}}$)	time rate of change of $m_{a_{DC}}$ (respectively, $m_{a_{RC}}$)
W_{DC} (W_{RC})	weight of drogue chute (respectively, recovery chute) canopy
$D_{P_{DC}}$	projected diameter of drogue chute
$D_{O_{DC}}$	nominal diameter of drogue chute
S_{DC}	reference area of drogue chute
m_{RC_X}	mass of unfurled recovery chute canopy during the extraction process
m'	linear mass density of recovery chute canopy
$\ell_{SL_{DC}}$	distance from fully extended suspension lines to drogue chute C.G. along drogue chute axis of symmetry
ℓ_{DCL}	length of drogue lanyard
$k_{S_{DC}}$	coefficient of elasticity for drogue lanyard and suspension lines
k_{DC}	drogue chute filling time constant
$\ell_{SL_{RC}}$	distance from fully extended suspension lines to recovery chute C.G. along recovery chute axis of symmetry

ℓ_{RISER}	length of risers
ℓ_{SG}	length of spreader gun
k_{SRC}	coefficient of elasticity for recovery chute suspension lines and risers
k_{SQRC}	coefficient for collapsed recovery chute canopy drag area
ℓ_{FL}	length of firing lanyard
ℓ_{RECOV}	length of collapsed recovery chute canopy from apex to skirt
$D_{P_{RC}}$	projected diameter of recovery chute
$D_{O_{RC}}$	nominal diameter of recovery chute
k_{RC}	filling time constant for recovery chute
Y_{RCO}	altitude at which recovery chute container opens
$C_{D_{RC}}$ $C_{L_{RC}}$	drag and lift coefficients of recovery chute
$C_{D_{DC}}$ $C_{L_{DC}}$	drag and lift coefficients of drogue chute

DART System Parameters

ℓ_{DLO}	length of DART lines at beginning of DART action time
ℓ_{DL1}	length of DART lines at end of DART action time

WORD System Parameters

m_{WRD}	mass of WORD

W_{WRD}	weight of WORD
S_{WRD}	WORD reference area
$C_{D_{WRD}}$	drag coefficient of WORD
ℓ_{WRD}	length of WORD
$k_{S_{WRD}}$	coefficient of elasticity of WORD lanyard
d_{WRDCG}	distance from WORD pivot point to WORD C.G.

Drogue Container Parameters

m_C	mass of drogue container
W_C	weight of drogue container
S_C	reference area of drogue container
C_{DC}	drag coefficient of drogue container

Slider Block Parameters

k_X, k_Z	spring constants for slider blocks
μ_f	coefficient of friction for rail/slider block contacts

Event Times

t_{CI}	catapult ignition time
t_{CU}	catapult unlock time
t_{CS}	catapult separation time
t_{RI}	sustainer rocket ignition time
t_{RBO}	sustainer rocket burnout time

t_{DP}	drogue container projection time
t_{WRDR}	WORD release time
$t_{LS_{RC}}$	line stretch of recovery chute
$t_{LS_{DC}}$	line stretch of drogue chute
t_{SG}	spreader gun firing time
t_{DS}	start of DART action time
t_{DE}	end of DART action time
t_{WRDI}	WORD ignition time
$t_{f_{DC}}$	drogue chute filling time
$t_{f_{RC}}$	recovery chute filling time
τ_{DC}	drogue chute non-dimensional filling time parameter
τ_{RC}	recovery chute non-dimensional filling time parameter
t_{RCO}	recovery chute container opening time
t_{SMSEP}	seat/man separation time

Forces and Moments

$\vec{F}_S = (F_{X_S}, F_{Y_S}, F_{Z_S})^T$	summation of external forces on seat/man
$\vec{F}_C = (F_{X_C}, F_{Y_C}, F_{Z_C})^T$	catapult force on seat/man in SMCS
$\vec{F}_{AS} = (F_{X_{AS}}, F_{Y_{AS}}, F_{Z_{AS}})^T$	aerodynamic forces on seat/man in SMCS
$\vec{F}_{DCS} = (F_{X_{DCS}}, F_{Y_{DCS}}, F_{Z_{DCS}})^T$	drogue chute forces on seat/man in SMCS
$\vec{F}_{SDC} = (F_{X_{SDC}}, F_{Y_{SDC}}, F_{Z_{SDC}})^T$	seat/man forces on drogue chute in FFCS

$\vec{F}_{RCS} = (F_{X_{RCS}}, F_{Y_{RCS}}, F_{Z_{RCS}})^T$ $\{\vec{F}_{RCM} = (F_{X_{RCM}}, F_{Y_{RCM}}, F_{Z_{RCM}})^T\}$	recovery chute forces on seat/man {respectively, man alone} in SMCS {respectively, MACS}
$\vec{F}_{RCW} = (F_{X_{RCW}}, F_{Y_{RCW}}, F_{Z_{RCW}})^T$	recovery chute forces on WORD in EFCS
$\vec{F}_{WRC} = (F_{X_{WRC}}, F_{Y_{WRC}}, F_{Z_{WRC}})^T$	WORD forces on recovery chute in EFCS
$\vec{F}_{APS} = (F_{X_{APS}}, F_{Y_{APS}}, F_{Z_{APS}})^T$	airplane forces on seat/man in SMCS
$\vec{F}_{SRC} = (F_{X_{SRC}}, F_{Y_{SRC}}, F_{Z_{SRC}})^T$ $\{\vec{F}_{MRC} = (F_{X_{MRC}}, F_{Y_{MRC}}, F_{Z_{MRC}})^T\}$	seat/man respectively, {man alone} forces on recovery chute in SMCS {respectively MACS}
$\vec{F}_{DART} = (F_{X_{DART}}, F_{Y_{DART}}, F_{Z_{DART}})^T$	DART forces on seat/man in SMCS
$\vec{F}_{WDC} = (F_{X_{WDC}}, F_{Y_{WDC}}, F_{Z_{WDC}})^T$	WORD forces on drogue chute in EFCS
$\vec{F}_{DCW} = (F_{X_{DCW}}, F_{Y_{DCW}}, F_{Z_{DCW}})^T$	drogue chute forces on WORD in EFCS
$\vec{F}_{SWRD} = (F_{X_{SWRD}}, F_{Y_{SWRD}}, F_{Z_{SWRD}})^T$	seat/man force on WORD in EFCS
$\vec{F}_{WRDS} = (F_{X_{WRDS}}, F_{Y_{WRDS}}, F_{Z_{WRDS}})^T$	WORD force on seat/man in SMCS
$\vec{F}_{SB_i} = (F_{X_{SB_i}}, O, F_{Z_{SB_i}})^T$	i^{th} slider block force on seat/man in CCS for $i = 1,2,\cdots,6$
$\vec{F}_{SB} = (F_{X_{SB}}, F_{Y_{SB}}, F_{Z_{SB}})^T$	summation of forces on the seat/man from rail/slider block interaction in SMCS
f_{r_i}	frictional force at i^{th} slider block for $i = 1,2,\cdots,6$
$\vec{F}_{OSO}$	recovery chute strip out force
$\vec{F}_{ADART}$	average DART force in both lines
$\vec{F}_{MRR}$ ($\vec{F}_{MLR}$)	force exerted by the man alone on the right (respectively, left) recovery chute riser in the EFCS

$\vec{F}_{MRC} = (F_{X_{MRC}}, F_{Y_{MRC}}, F_{Z_{MRC}})^T$	total force man alone exerts on recovery chute in EFCS
$\vec{F}_{RCRR}$ $(\overrightarrow{F_{RCLR}})$	force that the recovery chute exerts on the right (respectively, left) riser in the MACS
$\vec{F}_{RCM} = (F_{X_{RCM}}, F_{Y_{RCM}}, F_{Z_{RCM}})^T$	total force recovery chute exerts on man alone in MACS
$\vec{F}_{AM} = (F_{X_{AM}}, F_{Y_{AM}}, F_{Z_{AM}})^T$	man alone aerodynamic forces in the MACS
$\vec{F}_{ASA} = (F_{X_{ASA}}, F_{Y_{ASA}}, F_{Z_{ASA}})^T$	seat alone aerodynamic forces in the SACS
$\vec{M}_S = (L_S, M_S, N_S)^T$	summation of external moments on seat/man in SMCS
$\vec{M}_C = (L_C, M_C, N_C)^T$	catapult moments on seat/man in SMCS
$\vec{M}_R = (L_R, M_R, N_R)^T$	sustainer rocket moments on seat/man SMCS
$\vec{M}_{SB_i} = (L_{SB_i}, M_{SB_i}, N_{SB_i})^T$	i^{th} slider block moments on seat/man in CCS for $i = 1,2,\cdots 6$
$\vec{M}_{SB} = (L_{SB}, M_{SB}, N_{SB})^T$	summation of rail/slider block moments on seat/man in SMCS
$\vec{M}_{AS} = (L_{AS}, M_{AS}, N_{AS})^T$	seat/man aerodynamic moments in SMCS
$\vec{M}_{RD} = (L_{RD}, M_{RD}, N_{RD})^T$ $\{\vec{M}_{LD} = (L_{LD}, M_{LD}, N_{LD})^T\}$	right {respectively, left} DART moments on seat/man in SMCS
$\vec{M}_{DART} = (L_{DART}, M_{DART}, N_{DART})^T$	summation of DART moments on seat/man in SMCS
$\vec{M}_{DCS} = (L_{DCS}, M_{DCS}, N_{DCS})^T$	drogue chute moments o seat/man in SMCS

$\vec{M}_{RCS} = (L_{RCS}, M_{RCS}, N_{RCS})^T$	recovery chute moments on seat/man in SMCS
$\vec{M}_{WRDS} = (L_{WRDS}, M_{WRDS}, N_{WRDS})^T$	WORD moments on seat/man in SMCS
$\vec{M}_{AM} = (L_{AM}, M_{AM}, N_{AM})^T$	man alone aerodynamic moments in MACS
$\vec{M}_{RCM} = (L_{RCM}, M_{RCM}, N_{RCM})^T$	recovery chute moments on man alone in MACS
$\vec{M}_{ASA} = (L_{ASA}, M_{ASA}, N_{ASA})^T$	seat alone aerodynamic moments in SACS

Dynamic Pressure, Aerodynamic Angles

q_{AS}	dynamic pressure on seat/man
α_A	angle-of-attack of airplane
α_S, β_S	angles of attack and sideslip for seat/man
α_M, β_M	angles of attack and sideslip for man alone
α_{SA}, β_{SA}	angles of attack and sideslip for seat alone
α_{DC}	angle of attack of drogue chute
α_{RC}	angle of attack of recovery chute
T	standard ICAO temperature at altitude y
P	standard ICAO pressure at altitude y

Tables

T_{RC}, T_{LC}	right (respectively, left) catapult thrust vs. time tables
T_{WRD}	thrust vs. time table for WORD

T_{RR}, T_{LR}	right (respectively, left) sustainer rocket thrust vs. time table
$C_{N_{P_{DC}}}$, $C_{T_{P_{DC}}}$	normal and tangential force coefficients for drogue chute (corresponding to projected area) vs. α_{DC}
$C_{N_{P_{RC}}}$, $C_{T_{P_{RC}}}$	normal and tangential force coefficients for recovery chute (corresponding to projected area) vs. α_{RC}
C_{X_S}, C_{Y_S}, C_{Z_S} C_{l_S}, C_{m_S}, C_{n_S}	aerodynamic force and moment coefficients for seat/man vs. α_S, β_S, and MN_S
C_{X_M}, C_{Y_M}, C_{Z_M} C_{l_M}, C_{m_M}, C_{n_M}	aerodynamic force and moment coefficients for man alone vs. α_M and β_M
$C_{X_{SA}}$, $C_{Y_{SA}}$, $C_{Z_{SA}}$ $C_{l_{SA}}$, $C_{m_{SA}}$, $C_{n_{SA}}$	aerodynamic force and moment coefficients for seat alone vs. α_{SA}, β_{SA}, and MN_{SA}