C80-097

# Flight Simulation of a Vehicle with a Two-Stage Parachute System

00008
00027

P.R. Schatzle* and W.H. Curry†
*Sandia Laboratories, Albuquerque, N.M.*

## Nomenclature

| | |
|---|---|
| $F$ | = applied force, N |
| $I_{xx}$ | = roll inertia about $x$ axis, kg-m$^2$ |
| $I_{yy}$ | = pitch and yaw inertia about $y$ and $z$ axes, kg-m$^2$ |
| $l$ | = distance from forebody base to parachute center of mass, m |
| $m$ | = mass, kg |
| $M$ | = applied moment, N-m |
| $p,q,r$ | = angular velocity components, rad/s |
| $u,v,w$ | = linear velocity components, m/s |
| $x,y,z$ | = Cartesian coordinates |
| $\bar{x}$ | = distance between forebody center of mass and forebody base, m |
| $\gamma_1,\gamma_2,\gamma_3$ | = trigonometric functions of parachute rotation angles |
| $\theta,\psi,\varphi$ | = forebody rotation angles relative to inertial space, rad |
| $\sigma,\eta,\xi$ | = parachute rotation angles relative to forebody, rad |

*Subscripts*

| | |
|---|---|
| $F$ | = forebody |
| $I$ | = inertial reference frame |
| $P$ | = parachute |
| $x,y,z$ | = vector components |

## Abstract

A QUICK response, 9-DOF (degree-of-freedom) hybrid computer code has been developed to simulate the flight of an aircraft-delivered, parachute-retarded vehicle. The mathematical model and its implementation are discussed. The particular case of a vehicle with a first-stage lifting parachute and second-stage descent parachute is investigated. Results compare well with those obtained from an existing 12-DOF digital code and from full-scale flight test.

## Contents

A hybrid computer code has been developed to simulate the flight characteristics of an aircraft-delivered vehicle with a two-stage parachute system. The simulation was designed to model a low-level weapon delivery concept in which a first-stage lifting parachute provides altitude gain sufficient for a second-stage parachute to slow and turn the system for survivable impact. A roll control system on the vehicle, actuated prior to lifting parachute deployment, keeps the system properly oriented to maximize altitude gain and minimize lateral dispersion. The sequence of events from release to impact is shown in Fig. 1.

Certain coordinate systems were utilized in the mathematical modeling. The inertial coordinate system $(x,y,z)_I$ has its origin fixed in space at the location occupied by the forebody center of mass at the time of first-stage parachute line stretch. The positive $z_I$ axis is directed toward the center of the Earth. The $(x,y,z)_F$ coordinate system is fixed at and moves with the forebody center of mass. The instantaneous angular position of $(x,y,z)_F$ relative to $(x,y,z)_I$ is given by the ordered rotation sequence of pitch, yaw, and roll $(\theta,\psi,\phi)$ about the forebody center of mass. The origin of the $(x,y,z)_P$ system is located at the geometric center of the base of the forebody, and the $x_P$ axis is coincident with the parachute longitudinal centerline. The $(x,y,z)_P$ axis system is permanently aligned with the parachute such that the coordinate axes and the canopy pivot as a unit about the base of the forebody. The angular orientation of $(x,y,z)_P$ with respect to $(x,y,z)_F$ is given by the ordered rotation sequence of yaw, negative pitch, and roll $(\sigma,-\eta,\xi)$ about the base of the forebody.

Kinematic consideration of these axis systems gives the following equations of motion for the forebody-parachute combination. The components of forebody acceleration along and about the $(x,y,z)_F$ axes are, respectively:

$$\dot{u}_F = \Sigma F_{F_x}/m_F + r_F v_F - q_F w_F \tag{1}$$

$$\dot{v}_F = \Sigma F_{F_y}/m_F + p_F w_F - r_F u_F \tag{2}$$

$$\dot{w}_F = \Sigma F_{F_z}/m_F + q_F u_F - p_F v_F \tag{3}$$

$$\dot{p}_F = \Sigma M_{F_x}/I_{x_F x_F} \tag{4}$$

$$\dot{q}_F = [\Sigma M_{F_y} + (I_{y_F y_F} - I_{x_F x_F}) p_F r_F]/I_{y_F y_F} \tag{5}$$

$$\dot{r}_F = [\Sigma M_{F_z} - (I_{y_F y_F} - I_{x_F x_F}) p_F q_F]/I_{y_F y_F} \tag{6}$$

The translational acceleration of the parachute is also expressed in the $(x,y,z)_F$ system, while the angular acceleration is written about the $(x,y,z)_P$ axes. If it is assumed that the relative longitudinal acceleration between the two bodies is small, the equations of motion for the parachute

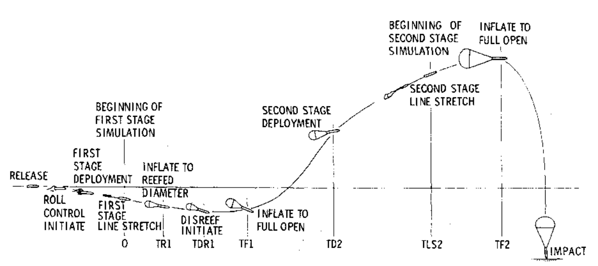


Fig. 1 Sequence of events in laydown delivery.

Presented as Paper 79-0448 at the AIAA 6th Aerodynamic Decelerator and Balloon Technology Conference, Houston, Texas, March 5-7, 1979; submitted April 10, 1979; synoptic received Dec. 21, 1979. Full paper available from AIAA Library, 555 West 57th St., New York, N.Y., 10019. Price: Microfiche, $3.00; hard copy, $7.00. **Order must be accompanied by remittance.** Copyright © 1979 by P.R. Schatzle and W.H. Curry. Published by the American Institute of Aeronautics and Astronautics with permission.

Index categories: Deceleration Systems; Simulation.

*Member of Technical Staff, Parachute Systems Division.
†Member of Technical Staff, Aerodynamics Simulation Division. Associate Fellow AIAA.

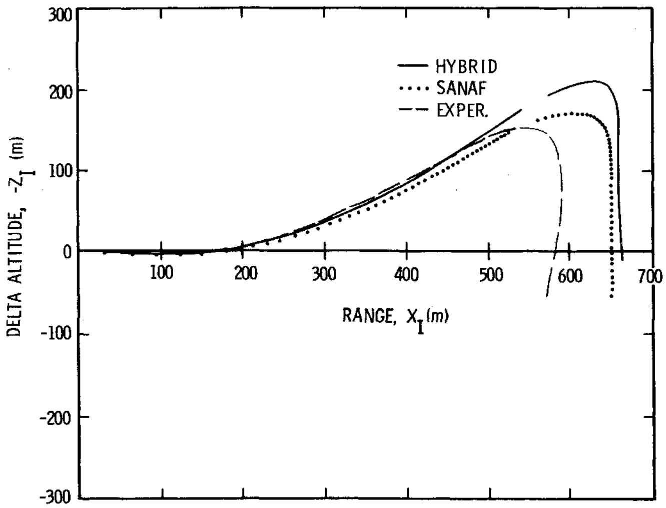


**Fig. 2 System trajectory.**

become

$$\ddot{\gamma}_2 = \Sigma F_{P_y}/m_P l - \Sigma F_{F_y}/m_F l - 2(r_F\dot{\gamma}_1 - p_F\dot{\gamma}_3) + (p_F^2 + r_F^2)\gamma_2 - (p_F q_F + \dot{r}_F)(\gamma_1 - \ddot{x}/l) - (q_F r_F - \dot{p}_F)\gamma_3 \tag{7}$$

$$\ddot{\gamma}_3 = \Sigma F_{P_z}/m_P l - \Sigma F_{F_z}/m_F l + 2(q_F\dot{\gamma}_1 - p_F\dot{\gamma}_2) + (p_F^2 + q_F^2)\gamma_3 - (p_F r_F - \dot{q}_F)(\gamma_1 - \ddot{x}/l) - (q_F r_F + \dot{p}_F)\gamma_2 \tag{8}$$

$$\xi = \Sigma M_{P_x}/I_{x_p x_p} + \gamma_1\dot{p}_F + \dot{\gamma}_1 p_F + \gamma_2\dot{q}_F + \dot{\gamma}_2 q_F + \gamma_3\dot{r}_F + \dot{\gamma}_3 r_F \tag{9}$$

Equations (1-6) are integrated to give the linear and angular velocity components of the forebody directly, while Eqs. (7) and (8) are integrated to give $\gamma_2$ and $\gamma_3$ which are related to $\sigma$ and $\eta$ through the expressions: $\gamma_1 = -\cos\sigma\cos\eta$, $\gamma_2 = -\sin\sigma\cos\eta$, and $\gamma_3 = -\sin\eta$. Thus, yaw and pitch orientation of the parachute relative to the forebody are determined, and integration of Eq. (9) gives the relative roll orientation between the two bodies.

Supplementary equations required for the mathematical model include inertial, aerodynamic, and interactive loading acting on the forebody and parachute; angular and translational velocity components of the forebody with respect to inertial space, and the related trajectory information; parachute total velocity which consists of three parts: the translational velocity of the forebody, the transport velocity due to rotation of the forebody reference frame, and the velocity of the parachute relative to the forebody; dynamic pressure, aerodynamic angles, and related angular rates for both bodies; and deployment and inflation characteristics of the parachute system.

The complexity of the mathematical model coupled with the desire for quick turn-around indicates that the hybrid computer should be used rather than all-digital or all-analog machines. The problem is partitioned such that the equations of motion, forebody attitude, parachute attitude, and system trajectory are solved on two AD/FIVE analog machines, while the applied loads and remaining supplementary equations are solved on a PDP 11/45 digital machine.[1] Less than a minute of running time is required for each parachute stage, and the time between consecutive runs is usually only a few minutes. The 12-DOF code SANAF, obtained by modifying an existing 6-DOF code,[2] requires about 30 and 90 min for first- and second-stage simulation, respectively, on the CDC 6600.

Results of a simulation using the hybrid code were compared with those from the SANAF code and from an actual flight test. Nominal Mach number at aircraft release was 0.95, while nominal release height above ground was 60 m. First-stage parachute line stretch was assumed to occur 0.7 s from release with second-stage parachute deployment occurring 5.1 s from release. The roll control system was inactive and both parachutes were unreefed. The inflation characteristics of both parachutes were obtained from previous similar flights. The system mass was 1090 kg.

Based on this comparison with both full-scale flight test and a more complete analytical model, the hybrid computer model presented in this report appears to be a reasonable representation of a vehicle with a two-stage parachute system. Given realistic inflation histories for the parachute system, the code predicts velocity, dynamic pressure, and axial acceleration histories in close agreement with experiment. The computed and observed trajectories (Fig. 2) are in reasonably good agreement during the lifting phase of the flight. However, the predicted range and maximum altitude exceed the experimentally obtained values, possibly due to underestimating the drag produced by the second-stage parachute. The hybrid predictions for the dynamic characteristics of the system agree well with those predicted by the more rigorous SANAF digital code. Considering the short run time and quick turn-around available on the hybrid computer, the hybrid model is a useful tool for parachute design studies.

## Acknowledgment

This work was supported by the U.S. Department of Energy.

## References

[1] Curry, W.H., and French, R.E., "Sandia Laboratories Hybrid Computer and Motion Simulator Facilities," Albuquerque, N.M., SAND 80-0697, May 1980.

[2] Brown, R.C., Brulle, R.V., Combs, A.E., Giffin, G.D., and Vorwald, R.F., "Six-Degree-of-Freedom Flight-Path Study Generalized Computer Program," McDonnell Aircraft Corp. under Contract AF33(657)-8829 with Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, FDL-TDR-64-1, Oct. 1964.