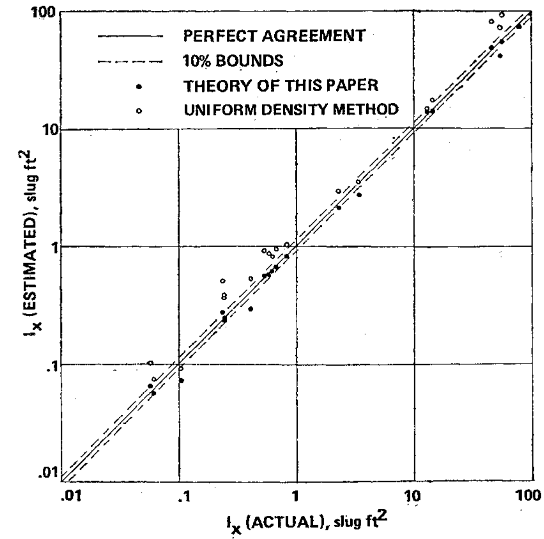

Fig. 5 Comparison between estimated and actual I_x values.

design curves are used as follows. For a given a/L read into Fig. 1 at the required x_{cg}/L and determine KL (it is not necessary to solve for K explicitly). Read into Fig. 2 at this KL, determine the weight parameter, and by appropriate substitution estimate either the maximum value of W using the tungsten value for ρ_o or the maximum allowable ρ_o if W has been defined by other system constraints. Proceed in similar fashion to Figs. 3 and 4 thereby estimate I_x, I_y' and, hence, I_y.

Accuracy of the Method

The equations have been tested against a large matrix of cone-sphere entry vehicles having known mass properties. A KL value and ρ_o were selected commensurate with the known c.g. location and weight. I_x and I_y were then estimated and plotted vs their actual values. The results are shown in Figs. 5 and 6, and good agreement is seen to exist, with 75% of I_x and 65% of I_y within $\pm 10\%$ of the line of perfect agreement. Those I_x cases outside these bounds are on the low side which is correct from the standpoint of a conservative approach to roll dynamics. Shown also are the results obtained by using a uniform density distribution. This is a common technique for estimating I_x and I_y in preliminary design studies wherein I_y is calculated about the c.g. with uniform mass and then transferred to the true c.g. using the parallel axis theorem. Except in a few isolated cases the agreement is poor.

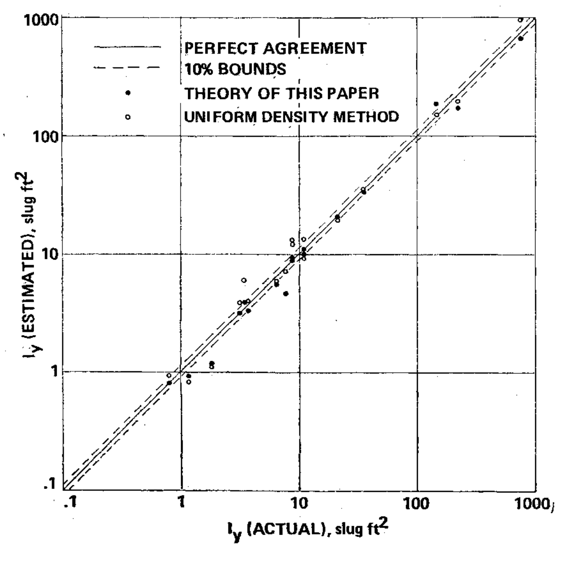

Fig. 6 Comparison between estimated and actual I_y values.

Although the method described here is intended for sphere-cones it can be used for shapes of close resemblance such as blunt biconics. If the vehicle has an aft cover such as a hemisphere, the curves may be used without significant error provided one uses total vehicle length for L rather than the length to maximum diameter. In general the curves are restricted to vehicles with base diameters in excess of 5 in. Below this value the volume constraints imposed by shell thickness and the dominant contribution of the shell to the total weight become significant.

An Advanced Technique for the Prediction of Decelerator System Dynamics

THEODORE A. TALAY,* W. DOUGLAS MORRIS,*
AND CHARLES H. WHITLOCK†
NASA Langley Research Center, Hampton, Va.

Introduction

IN the field of nonstationary aerodynamics, few subjects approach the degree of difficulty of the parachute opening process. The prediction of the influence of a decelerator system on an entry vehicle has heretofore been largely an empirical process. With parachute applications now probing far past the realm of previous test experiences—as evidenced in Project Viking—it has become useful to model the very complex behavior of parachute opening dynamics for extrapolation to new flight conditions. This has been aided by the rapid advancements in computer capabilities to accept complex models. This Note describes an advanced two-body, six-degree-of-freedom, computerized, analytical model for the parachute opening process and presents a sample case.

Background

The interval from the beginning of parachute deployment until a stable inflation represents a transient regime of greatest concern in terms of forces and moments on an entry vehicle. These forces and moments influence the parachute system design, vehicle trajectory, and the guidance and control system.

For Viking, the opening process consists of an unfurling phase, where the parachute deploys in a lines-first manner following mortar fire, and a canopy inflation phase—the inflation phase is assumed to begin with the parachute fully strung out. The canopy opens to full inflation and is usually followed by a series of breathing motions until a stable inflation is reached.

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* Aerospace Engineer, Space Applications and Technology Division.

† Senior Aerospace Engineer, Space Applications and Technology Division. Member AIAA.

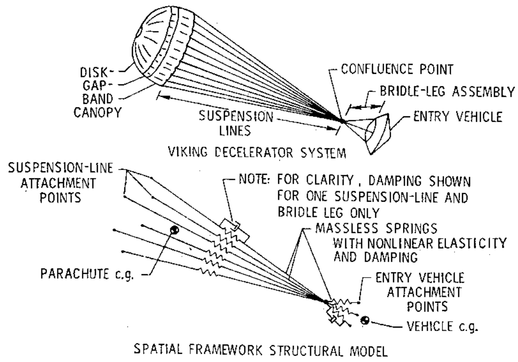

Fig. 1 Viking decelerator system and structural model employed.

Simulation Technique

Although originally intended for stable inflation studies,[1] the developed analytical program has been modified to simulate the entire parachute opening process. Figure 1 presents the Viking decelerator system and the simulation model. To predict the system dynamics, it is necessary to determine the forces in each of the lines of the suspension system. The model is three-dimensional, and the suspension system forms a nonrigid spatial framework. With more members then needed for equilibrium, the problem is statically indeterminate. Solution requires a knowledge of the elasticity of the members. Fortunately, test data for the Viking bridle leg and suspension line elasticity were available.

The technique of solution assumes at any particular time the framework is in static equilibrium, and equilibrium equations in terms of forces at the confluence point of the suspension system may be written. Together with the six-degree-of-freedom equations of motion of the parachute and the towing vehicle, and knowledge of the elasticity of the framework members, the problem becomes determinate. An iterative technique is employed to solve three nonlinear equations for the three unknown coordinates of the confluence point.

With the confluence and attachment point coordinates determined, the force in each frame member is calculated. These line forces, along with aerodynamic and gravitational force, are used in the equations of motion for the parachute and the entry vehicle to determine the positions and velocities of both bodies for each integration step.

Model Description

The model may be considered in three stages: 1) the entry vehicle, 2) the suspension system (consisting of the suspension lines and bridle legs) and, 3) the parachute (canopy and suspension lines). Particular features of the model include:

Entry vehicle—a) axial and normal force coefficients, and static and dynamic stability coefficients as functions of Mach number and total angle-of-attack; b) offset center of gravity and asymmetric inertia capabilities; c) threshold, rate-controlled, vehicle damping reaction control system (optional).

Suspension system—a) up to seven suspension-line groupings (Viking model uses six groupings with eight lines per grouping); b) up to four bridle legs (Viking model uses three bridle legs); c) nonlinear elasticity as a function of the strain for the suspension lines and bridle legs; d) nonlinear damping as a function of strain rate for the suspension lines; e) capability for permanent set in the suspension lines; f) capability of modeling suspension-line and bridle leg collapse.

Parachute—a) axial and normal force coefficients and static and dynamic stability coefficients as functions of Mach number, total angle-of-attack, and instantaneous radius of the canopy projected area; b) canopy radius input history; c) a cylinder-hemisphere canopy inflation model; d) included and apparent atmospheric mass computed as a function of the canopy radius and atmospheric density; e) rotational inertias computed as a function of the canopy radius and atmospheric density; f) computed variable c.g. position; g) asymmetric inflation capability (by utilizing separate suspension-line attachment point coordinate histories).

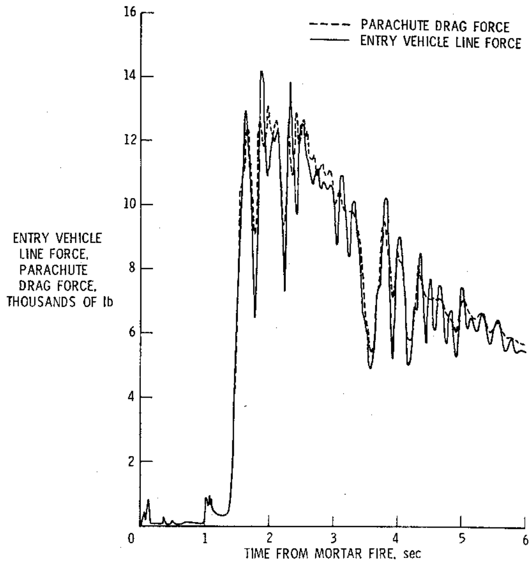

Fig. 2 Computed vehicle, canopy force histories (AV-4 case).

System Dynamics

The results which may be obtained using this simulation technique are demonstrated by examining a sample case simulation. The vehicle mortar fire inputs were those of the balloon-launched decelerator test (BLDT) AV-4 (Ref. 2). These are altitude: 147,186 ft (44,860 m); velocity: 2290 fps (698 m/sec); pitch rate: $-14°$/sec; yaw rate: $4°$/sec; roll rate: $-30°$/sec.

Aerodynamic characteristics and mass property inputs used for the vehicle and parachute are the most recent obtainable for the BLDT and/or Viking system. Suspension-system characteristics are those obtained from recent testing at NASA Langley Research Center.[3]

Figure 2 presents the computed force histories at the canopy and in the suspension lines. The canopy generates a drag force (the forcing function), but suspension-line elasticity (modeled as nonlinearly elastic massless springs) causes dynamic overrun conditions such that the forces measured in the lines (the response function), that is, at the vehicle, is different from that at the canopy.

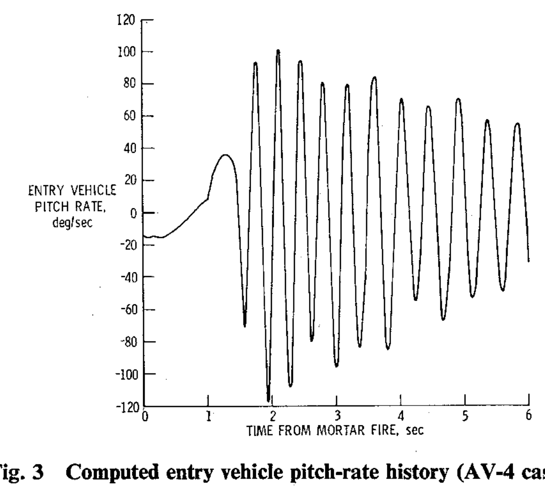

Fig. 3 Computed entry vehicle pitch-rate history (AV-4 case).

Figure 3 illustrates the computed entry vehicle pitch rate history. This together with the other computed rates are of importance to the guidance and control system and have been found, from case studies, to be dependent on numerous factors, many of which are concerned with parachute initial conditions and subsequent inflation motion. This demonstrates one important problem area in the simulation process—that of determining the parachute aerodynamic input. Little data are available for an inflating parachute trailing in the wake of a large diameter forebody under supersonic and transonic conditions. While sensitivity studies using the simulation program may be useful, wind-tunnel tests to determine the aerodynamic coefficients at the proper Mach numbers would contribute greatly to accurate computer simulations.

Conclusions

An advanced two-body six-degree-of-freedom computer model employing an indeterminate structures approach has been developed for the parachute opening process. The program determines vehicular responses and trajectories based on known input. Where uncertainty exists in the input, sensitivity analysis may be performed to isolate the important variables. The program has demonstrated the importance of suspension-line elasticity and parachute aerodynamics in the parachute opening process.

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Jet Penetration at a Sonic Throat

Robert H. Nunn* and Kenneth E. Frick†
Naval Postgraduate School, Monterey, Calif.

Nomenclature

a = sonic velocity
$A(M)$ = area ratio function for one-dimensional isentropic flow
B = duct height
C = injection parameter defined in Eq. (2)
d = jet slot width
F_x = x-component of force acting on jet face
h = depth of jet penetration
m = mass flowrate
M = Mach number
p,P = static and stagnation pressure, respectively
V = velocity
y = coordinate of jet face normal to duct wall
α = angle of injection (positive for upstream injection)
γ = ratio of specific heats
$\pi(M)$ = pressure ratio function for one dimensional isentropic flow

Subscripts

j,m,o = jet, mainstream and initial quantity, respectively
r = reference mainstream condition (without jet flow)

Superscript

$*$ = sonic conditions

THE problem of a transverse jet issuing into the sonic throat of a nozzle for the purpose of throttling the primary flow has been studied by numerous investigators. Reviews of these works are available in the literature.[1] Nunn and Brandt[2] have presented an analysis for the two-dimensional case that assumes that a normal shock occurs in the jet flow at the point of maximum jet penetration. This simplification does not take into account the effect of the curvature of the jet plume upon jet shock location and is, therefore, a poor model of the actual jet penetration process. This note describes an improved analysis that avoids the explicit description of the jet shock. In addition, new experimental data are given for increased values of the jet/freestream total pressures, P_j/P_m.

A two-dimensional control volume (dashed line in Fig. 1) is defined as bounded by the windward face of the jet plume from the point of injection to the jet sonic line (dotted line in Fig. 1), the jet sonic line to the wall, and the plane of the wall. A momentum balance yields

$$F_x - p_j{}^*h = m(a_j + V_{jo}\sin\alpha) \tag{1}$$

where F_x is the x-component of the force per unit depth acting on the windward face of the jet and will be evaluated in subsequent paragraphs. Following simplifications similar to those utilized by Barnes et al.[3] (the jet is assumed to behave as an ideal gas undergoing an adiabatic process), Eq. (1) reduces to

$$\frac{F_x}{P_j d} = \frac{1}{A(M_{jo})}\left(\frac{2}{\gamma+1}\right)^{\gamma/\gamma-1}\left[\gamma(1+M_{jo}\sin\alpha)+1\right] \equiv C \tag{2}$$

Neglecting shear forces acting on the windward face of the jet,[1,2] the remaining pressure force may be written

$$F_x/P_j d = 1/P_j d \int_0^y p\,dy = C \tag{3}$$

It is assumed that the pressure p acting on the jet face can be reasonably approximated by the static pressure, p_m, calculated on the basis of one-dimensional isentropic mainstream flow. This assumption is clearly justifiable near maximum jet penetration where jet and mainstream flows are parallel, but is less

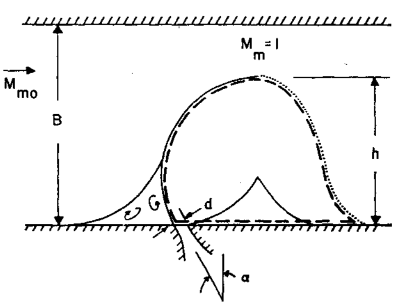

Fig. 1 Control volume.

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* Associate Professor of Mechanical Engineering. Member, AIAA.

† Lt. U. S. Navy; presently stationed aboard USS Forrestal, CVA 59.