Inflation of a Parachute

KENNETH E. FRENCH*
Lockheed Missiles and Space Company, Sunnyvale, Calif.

Theoretical considerations of the inflation of a parachute in incompressible flow indicate that a given parachute should open in a fixed distance, regardless of the altitude or the velocity at which it is deployed. Limited test data on solid, flat, and 15% flat extended-skirt-type parachutes of 24-ft diam deployed at conditions ranging from Mach 0.2 at low altitude to Mach 0.86 at 52,000-ft altitude indicate that this theoretical prediction is correct.

Nomenclature

A = area, ft^2
d = differential operator
k_j = dimensionless factors further defined in text ($j = d, i, 0, 1,$ and 2)
m = mass, slug
Q = volume rate of flow, ft^3/sec
r = maximum projected radius of parachute, ft
r_0 = r at beginning of inflation, ft
r_s = radius at skirt (mouth) of parachute canopy, ft
R = r for parachute at full blossom during steady descent, ft
R_c = constructed radius of parachute, ft
t = time, sec
V = velocity, fps
x = displacement along flight path, ft
X = displacement during inflation from r_0 to R, ft
ρ = air mass density, slug/ft^3
$\dot{}$ = (superscript dot) denotes differentiation with respect to time

Introduction

A KNOWLEDGE of parachute inflation characteristics is of importance in calculating parachute opening forces. Unfortunately, however, current incompressible-flow theories for parachute opening force are based largely upon various assumed, deduced, or quasiempirical inflation characteristics that do not appear to be substantiated by test data. Examples of models that have been used for parachute inflation studies are those in which parachute radius varies linearly with time[1, 2] or distance,[3] parachute drag area varies linearly with time,[4] parachute inflation time varies with size and deployment conditions in accordance with an empirically established relationship,[4] parachute rate of inflation varies directly as the product of size and velocity,[5] and other, more complex relationships.[6]

The purpose of this paper is to demonstrate that a more rational model for incompressible flow inflation of a parachute is attained by considering parachute radius as a function of distance traveled during the inflation process.

Theory

The system considered in this paper is defined in Fig. 1. If it is assumed that the parachute inflates symmetrically in incompressible, inviscid flow and that air enters the mouth of the chute at freestream velocity, then the rate of mass flow into the chute is

$$\dot{m}_{\text{in}} = \rho A_{\text{in}} V = \rho(\pi r_s^2 k_i) V \tag{1}$$

Received August 9, 1963. I. H. Culver of the Lockheed California Company was the first to suggest that a parachute opens in a fixed distance. The writer is, therefore, indebted to Culver for posing the problem, and to M. J. Lindgren and R. C. Norton of Lockheed Missiles and Space Company for providing some of the basic test data needed to verify the solution discussed in this paper.

* Research Specialist. Member AIAA.

where k_i is a factor to account for differences between effective entrance area and the area at the mouth of the chute during the inflation sequence.

With the assumption of inviscid, incompressible flow, the velocity of efflux above the plane of maximum inflation is also the freestream velocity V. The volume rate of flow out of the top of the canopy is therefore

$$Q = k_d A_{\text{out}} V \tag{2}$$

with corresponding mass rate of outflow

$$\dot{m}_{\text{out}} = \rho Q = \rho k_d [\lambda k_0 (2\pi r^2)] V \tag{3}$$

where k_d is the discharge coefficient, λ is the canopy porosity (the ratio of open to total canopy area above the plane of maximum inflation), and k_0 is a factor to account for differences between the true shape and the assumed hemispherical shape of the canopy above the plane of maximum inflation during the inflation sequence.

Assume that the volume of the parachute canopy during the inflation process can be approximated by a hemisphere of radius r and a right circular cylinder of height $R_c - \pi r/2$ and radius r, as indicated in Fig. 1. The mass of air contained in the parachute canopy is then

$$m_{\text{air}} = \rho k_1 (\tfrac{2}{3}) \pi r^3 + \rho k_2 \pi r^2 (R_c - \pi r/2) \tag{4}$$

where k_1 is a factor to account for the fact that the shape of the canopy above the plane of maximum inflation may differ from the assumed hemispherical shape during the inflation sequence, and k_2 is a factor to account for the fact that the shape of the canopy below the plane of maximum inflation may differ from the assumed cylindrical shape during the inflation sequence.

We now wish to calculate the net rate of change of mass of the chute during the inflation sequence. To do so, assume that variations in k_i, k_d, λ, k_0, k_1, and k_2 are negligible during the inflation sequence, differentiate Eq. (4) with respect to time, and set the result equal to the difference between mass inflow and mass outflow. That is,

$$\dot{m}_{\text{air}} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}} \tag{5}$$

or, remembering our assumption that $r_s \approx r$

$$[(4k_1 - 3\pi k_2) r^2 + (4k_2 R_c) r] dr = [2(k_i - 2k_d \lambda k_0) r^2] V dt \tag{6}$$

Noting that $V = dx/dt$ and that the maximum inflated radius R is about two-thirds the constructed radius R_c for

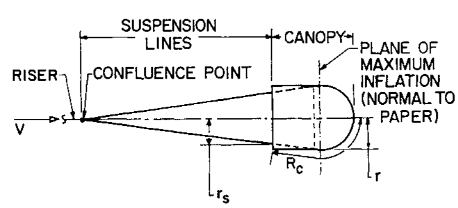

Fig. 1 Model used for inflation of parachute.

Table 1 Summary of tests

Test	Parachute	Deployment conditions: Altitude, ft	Velocity, fps TAS	Mach no.	System weight, lb
LMSC[7] June 23, 1960[a]	24-ft diam 15% flat extended skirt	52,000	815 ± 10	0.86	140
LMSC[7] August 2, 1960	24-ft diam 15% flat extended skirt	47,700	200 ± 10	0.21[b]	140
LMSC[7] August 30, 1960	24-ft diam 15% flat extended skirt	51,660	235 ± 10	0.25[b]	122
RAE[8]	24-ft diam solid flat	800	228 ± 12	0.21	200

[a] Parachute riser failed at $r/R = 0.58$ in this test. No reefing.
[b] Deployment conditions at time of unreefing. Parachute reefed to $r/R = 0.35$ for approximately 4 sec.

typical flat parachutes, one may then integrate Eq. (6) between the limits $r(0) = r_0$ and $r(x) = r$ to obtain

$$\alpha x = (\beta/R)(r - r_0) + \ln(r/r_0) \tag{7}$$

where

$$\alpha = (k_i - 2k_d\lambda k_0)/3k_2R \tag{8}$$

and

$$\beta = (\tfrac{2}{3})(k_1/k_2) - \pi/2 \tag{9}$$

Subject to the assumptions made in its derivation, Eq. (7) gives the interesting result that the distance in which a parachute inflates is a function only of parachute configuration. Stated another way: *a given parachute inflates in a fixed distance regardless of the velocity or altitude at which it is deployed and regardless of the weight that it carries.* From Eq. (7) it also follows that opening distance varies directly with size for a given type of parachute and that a given parachute will traverse a fixed portion of its opening distance for inflation between any two given radii.

It is convenient to eliminate α from Eq. (7). This may be accomplished by taking the ratio of Eq. (7) to itself with $r = R$ and $x = X$. The result is

$$K\,(x/X) = (\beta/R)(r - r_0) + \ln(r/r_0) \tag{10}$$

where

$$K = \beta[1 - (r_0/R)] + \ln(R/r_0) \tag{11}$$

It is of interest to establish a range of numerical values for the constants appearing in Eq. (10), that is, for β and r_0/R. If elasticity of the parachute canopy is neglected, then both parachute radius and distance traveled should increase continuously during the inflation sequence. Hence, dx/dr is greater than zero in the region $r_0 < r < R$. By differentiating Eq. (10) with respect to r and considering the limiting value for $dx/dr = 0$ in the region $r_0 < r < R$, it is found that the least value for β is -1. Then, in Eq. (9), note that $k_1 < 1$ (because the assumed hemispherical shape gives maximum volume for a fixed canopy surface area above the plane of maximum inflation) and that, conservatively, $k_2 > \frac{1}{2}$. With

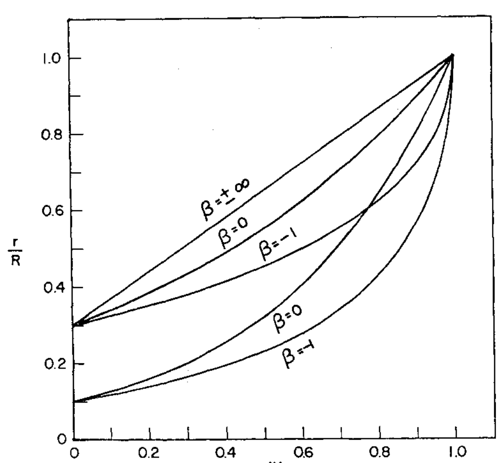

Fig. 2 Calculated variation of radius with distance.

these values for k_1 and k_2, a conservative upper bound on β is zero. Finally, from parachute test data, the limits on r_0/R are from about 0.10 to 0.30.

The foregoing numerical values can be used to calculate values of r/R vs x/X. The results of such calculations are presented in Fig. 2. If our theory is approximately correct, the inflation characteristic for a real parachute should lie somewhere within the envelope in Fig. 2 defined by the curves with $r_0/R = 0.10$, $\beta = -1$ and with $r_0/R = 0.30$, $\beta = 0$.

Test Data

Some tests for which sufficient data were available to check the results of the theory developed in the foregoing section are listed in Table 1. The test data cover 24-ft diam parachutes of two basic types deployed at conditions ranging from Mach 0.2 at 800-ft altitude to about Mach 0.9 at 52,000 ft. It is important to note that the parachutes in the Lockheed Missiles and Space Company (LMSC) tests of 2 and 30 August 1960 were used with reefing.†

For the LMSC tests indicated in Table 1, parachute size vs time was determined from measurements of films made by vehicleborne cameras running at frame rates of 64 or 16 frames/sec. Displacement vs time during the parachute inflation sequence was taken from White Sands Missile Range tracking data.

In the Royal Aircraft Establishment (RAE) test, parachute size vs time is given (see Fig. 12 of Ref. 8), but displacement vs time during the inflation sequence had to be obtained by this writer by numerical integrations of a force vs time curve also given in Fig. 12 of Ref. 8. An uncertainty of ±12 fps in the initial velocity term and an uncertainty as to the correct value for R in the test caused a rather substantial spread in the displacement data derived from Ref. 8.

Figure 3 shows nondimensional parachute radius vs time for the tests of Table 1. The fact that values of r/R greater than unity are shown in Fig. 3 is, of course, a consequence of the elasticity of the parachute canopy. Figure 3 illustrates the well-known facts that time for inflation of a chute decreases with increasing velocity and decreases with increasing altitude and shows also that neither r nor r^2 is linear with time.

Figure 4 shows nondimensional parachute radius vs displacement for the tests of Table 1. The large spread of values shown in Fig. 4 for the RAE test of Table 1 is due to the uncertainty in initial velocity and full-blossom parachute radius for that test, as already noted.

Discussion

Figure 4 indicates that the inflation characteristic deduced for a parachute (cf. Fig. 2) is approximately correct and

† Reefing is a system in which the parachute is either temporarily or permanently restrained from opening to full blossom; e.g., this can be done by passing a restricting line around the skirt of the canopy. For details, see Sec. 5 of Ref. 4.

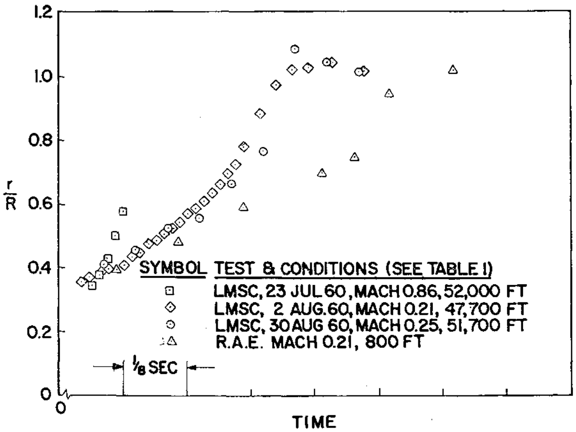

Fig. 3 Parachute radius vs time.

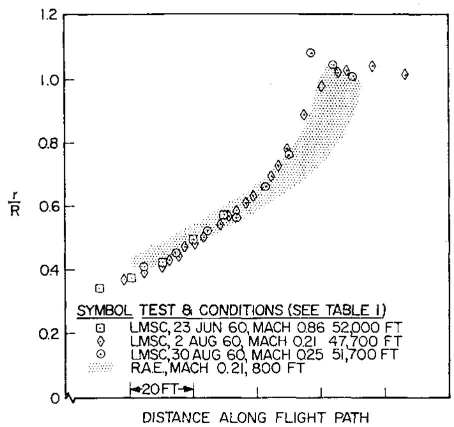

Fig. 4 Parachute radius vs distance.

that opening distance may indeed be considered one of the fundamental parameters in the parachute inflation process. That is, the test data confirm the theoretical prediction that parachute opening distance is relatively insensitive to changes in altitude and velocity of deployment. It would, of course, be desirable to buttress this conclusion with further test data and to determine opening distances, α, β, and r_0/R values for various types of parachute for which test data are extant.

In Fig. 4, it is somewhat surprising that the 15% flat extended skirt parachute appears to have a shorter opening distance than the solid flat chute, since one familiar with the characteristics of these two types of parachute would predict a slightly greater opening distance for the extended skirt-type chute (both types having the same nominal diameter). This apparent difference may be a consequence of different materials used in the two types of chute, of different r_0/R values for the two types of chute, or of some other unknown factor. At any rate, the data of Fig. 4 are still sufficiently well correlated to indicate that a parachute opens in a fixed distance that is relatively insensitive to large changes in altitude and velocity of deployment.

With regard to the assumptions made in development of the theory, tests on nylon fabric show that porosity does not vary appreciably with pressure drop across the fabric and that the assumption of inviscid, incompressible flow is valid for pressures up to about 150 lb/ft^2, and that fabric porosity does not vary appreciably with load at loads up to about one-third of the material tensile strength (Ref. 1, pp. 55–58). Other tests on 50-in.-diam fabric scale-model parachutes (Ref. 4, p. 4-4-4) show that the pressure distribution above the plane of maximum inflation in the canopy is essentially constant for steady velocity at velocities up to 100 fps. The remaining assumptions in the analysis of this paper involve mostly "shape factors," among which is the assumption that the parachute skirt and maximum projected radii are equal during the inflation process. This latter assumption does not appear to be correct (cf. Ref. 8, Fig. 12); however, the results of Fig. 4 indicate that the shape factors k_i do indeed remain sensibly constant during the inflation process.

An obvious and desirable extension of the results of this paper is calculation of parachute inflation force ("opening shock") using the more rational model of inflation-in-fixed-distance in place of the time-varying inflation models heretofore most frequently used. In this connection, it is interesting to note that Schilling[3] has calculated opening shock for the case of parachute radius varying linearly with distance [which corresponds to the case of $\beta = \pm\infty$ in Eq. (8)] whereas O'Hara[5] has calculated opening shock for the case of parachute rate of inflation varying directly with the product of radius and velocity [which corresponds to the case of $\beta = 0$ in Eq. (8)].

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