A Method of Load Prediction for Parachutes in Cluster

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Minimum weight and volume requirements for spacecraft recovery systems dictate the need for accurate load-prediction methods for the parachutes employed. The use of clustered parachutes presents a particular problem, because of the wide variation in individual parachute peak loads which can occur during the opening sequence. Nonuniform opening of Ringsail parachutes in cluster has been observed and analyzed. Major factors affecting nonuniform opening and the associated variations between individual parachute peak loads have been identified. A method is presented for predicting peak disreef loads for individual parachutes in cluster using opening-shock-factor data, together with other measured operational characteristics of the parachute and its associated hardware.

Nomenclature

C_DS = parachute "drag area," equal to the instantaneous measured force divided by the instantaneous measured dynamic pressure, ft²
C_DS_r = parachute drag area during the reefed interval or at the instant of disreef, ft²
C_DS_F = parachute drag area at the instant of peak disreef force on the lead (or highest loaded) parachute in cluster, ft²
$C_{D_o}S_o$ = fully opened, steady-state drag area, ft²
$(C_DA)_v$ = vehicle drag area, ft²
F_c = $q_r\, C_{D_o}S_o$, lb
$\dot{m}$ = mass rate of inflow, equal to ρVC_DS, measured at the instant of disreef of the individual parachute, slugs/sec
q = dynamic pressure, $\rho V^2/2$, psf
t_f = disreef filling time, measured from disreef to peak force, sec
V = true air speed, fps or knots
V_e = equivalent air speed, equal to $V \times (\rho/\rho_0)^{1/2}$, fps or knots
W = recoverable weight, lb
W^* = portion of recoverable weight carried by the individual parachute, lb
$W^*/C_{D_o}S_o$ = unit canopy loading, psf
X = opening shock factor, equal to F_F/F_c
Δt_r = differential disreef time, equal to the disreef time of the parachute in question minus the disreef time of the lead (highest loaded) parachute in cluster, sec
ρ = air density, slugs/ft³
ρ_0 = standard, sea-level air density, slugs/ft³

Subscripts

r = measured during the reefed interval or at the instant of disreef for the individual parachute
F = measured at the instant of peak disreef load on the lead (or highest loaded) parachute in cluster
L = lead parachute, i.e., parachute taking highest disreef load
l = first lag parachute, i.e., parachute taking next highest load
ll = second lag parachute, i.e., parachute taking lowest load in a 3-parachute cluster

1. Introduction

IN the design of recovery systems for spacecraft, minimum weight and bulk are necessarily important constraints. To meet these requirements, maximum loads for the recovery-system components, including the parachutes, must be accurately predicted. The use of clustered parachutes as the main landing system for the spacecraft presents a special problem in load evaluation. Individual parachutes operating in cluster generally do not provide identical performance during the parachute deployment and inflation process. Large peak load variations occur between individual parachutes in cluster in apparently random fashion, particularly following disreef. However, detailed analysis of the deployment and inflation sequence shows that load inequality between parachutes following disreef of a cluster is due to two primary factors: 1) aerodynamic interference (or blanketing) between individual canopies during the reefed interval, and 2) nonsynchronous disreefing (i.e., the severing of the reefing lines) of the clustered parachutes.

For applications where weight and bulk are not critical, the parachutes might simply be designed with sufficient strength to meet the most severe load conditions conceivable. (For most parachute-cluster applications this would be the case of one parachute taking nearly the entire opening load following disreef.) For the recovery system discussed herein, this was not feasible because of space and weight constraints. As a result, the primary factors affecting cluster nonuniformity were identified and suitable improvements incorporated in the system to minimize nonuniformity. Parallel to this, improved load-prediction techniques were developed to permit more accurate evaluation of the peak loads imposed on the individual parachutes in cluster for all the various modes of recovery-system operation.

2. Parachute Test Specimen

The parachute discussed in this paper is an 83.5-ft D_o Ringsail parachute. The parachute has 68 gores and 12 rings, the top four rings of which are ringslot design. The parachute dimensions and gore layout are shown in Fig. 1. Distinctive features of this parachute are a wide annular slot produced by removal of 75% of the material from the fifth ring, and unusually long (1.49 D_o) suspension lines.

As the main landing system for the spacecraft, three parachutes are deployed in cluster, with each parachute initially reefed to $9\frac{1}{2}$% midgore skirt, and disreefed after a nominal 8 sec. The system is designed to safely land the spacecraft with only two of the three main parachutes functioning.

3. Factors Affecting Parachute-Cluster Disreef Uniformity

Analysis of numerous 2- and 3-parachute-cluster drop tests has identified the primary factors affecting uniformity of parachute cluster disreef inflation to be 1) aerodynamic blanketing during the reefed interval and 2) nonsynchronous disreefing. Each of these factors is discussed below.

Presented at the AIAA Aerodynamic Deceleration Systems Conference, Houston, Texas, September 7–9, 1966 (no paper number; presented in bound volume of papers of the meeting); submitted September 16, 1966; revision received March 9, 1967. The author acknowledges the contribution of W. C. Buhler, who first suggested the application of opening shock factors to parachute-cluster loads prediction. [6.01]

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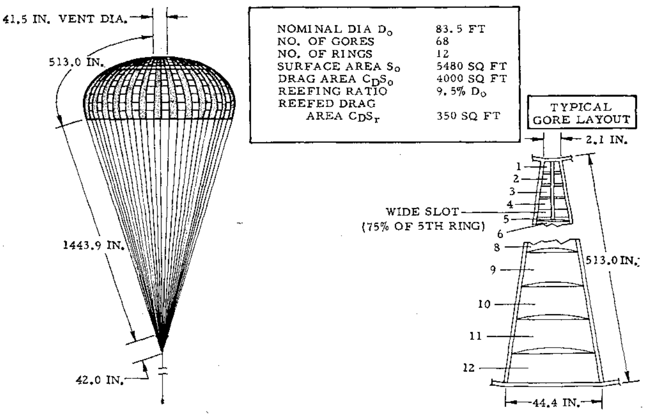

Fig. 1 83.5-ft D_o Ringsail parachute canopy configuration.

3.1 Reefed Aerodynamic Blanketing

Reefed blanketing is simply a reduction in the nominal reefed drag area of one or more of the individual canopies by an adjacent canopy. Figure 2 shows the appearance of a 2-Ringsail-parachute cluster in which one parachute is blanketed. The unblanketed (or "lead") parachute inflates to its full reefed shape, presenting a generally rounded, taut canopy. The blanketed (or "lag") parachute inflates to a lesser degree, tending to be flattened and flaccid in appearance. Knowing that the Ringsail parachute fills through its peripheral, scoop-like sails as well as through its mouth, the phenomenon of reefed blanketing might be thought of as a condition in which the lead parachute tends to hog the air in the flowfield between adjacent canopies to the detriment of the blanketed or lag parachute(s). However, the actual mechanics of reefed blanketing are not currently understood. This discussion is thus limited to known factors affecting the occurrence and degree of reefed blanketing. These factors are 1) the planform shape of the reefed canopy and 2) the relative orientation of the canopies to the flightpath for ballistic trajectories.

Canopies that inflate in the reefed condition to a bulbous shape tend to promote blanketing when deployed in cluster. This is in contrast to canopies that, because of their canopy design, canopy porosity, or degree of reefing, inflate to a more slender, cylindrical reefed shape. For the 83.5-ft D_o Ringsail parachute shown in Fig. 1, removal of 75% of the fifth ring was a design modification introduced to reduce the bulbous reefed shape and the associated reefed blanketing.

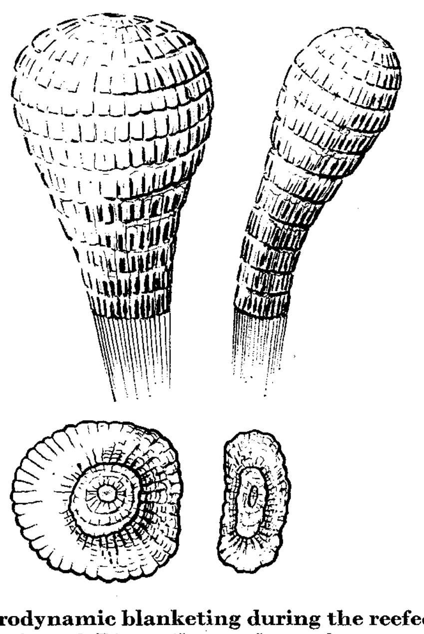

Fig. 2 Aerodynamic blanketing during the reefed interval for a 2-Ringsail-parachute cluster.

For cases in which clustered parachutes are deployed reefed on a curving or ballistic flightpath, orientation of the parachutes to the flightpath appears to significantly affect the degree of reefed blanketing which can occur. Orientation of the parachutes in an over-under arrangement promotes reefed blanketing of the lower parachute. Orientation of the parachutes in a side-by-side arrangement tends to provide uniformity of individual canopy-reefed operation. These observations suggest the possibility of an angle-of-attack effect, tending to partially collapse the lower parachute canopy.

3.2 Nonsynchronous Disreefing

Use of mechanically actuated, pyrotechnic-time-delay, reefing line cutters results in nonsynchronous disreefing of the individual parachutes in cluster. The magnitude of the disreef time differential that can occur between individual parachutes is a function of 1) the tolerance of the reefing cutter pyrotechnic time delay, 2) the temperature uniformity between reefing cutters on separate parachutes as it affects the burning time of the pyrotechnic time delays, and 3) the degree of uniformity with which the individual parachutes reach line stretch—the instant at which the reefing cutter time delays are initiated in each parachute. In evaluating the importance of nonsynchronous disreefing on peak disreef loads for the individual parachutes in cluster, the significant parameter to be considered is the ratio of the disreef time differential to the time from disreef to peak load for the lead (or highest loaded) parachute.

4. Parachute-Cluster Disreef Loads Analysis

Use of opening shock factors for predicting peak parachute loads, particularly for infinite mass applications, is well-established.[1] For applications where the mass cannot be considered infinite (i.e., where pronounced deceleration occurs during the parachute opening event), the variation of opening shock factor X with unit canopy loading $W/C_{D_o}S_o$ must currently be established experimentally. Figure 3, for example, presents curves of opening shock factor vs unit canopy loading, based on experimental test data for a variety of single-Ringsail parachutes. As seen in Fig. 3, opening shock factor varies with equivalent air speed as well as unit canopy loading for a given altitude range.

The primary difficulty in utilizing opening-shock-factor data for clustered parachutes is one of establishing the effective unit canopy loading of each parachute in the cluster. In the method of load prediction subsequently discussed, a means is described for evaluating the unit canopy loading of each parachute in cluster during disreef opening. Further, a procedure is outlined for computing the individual lead-

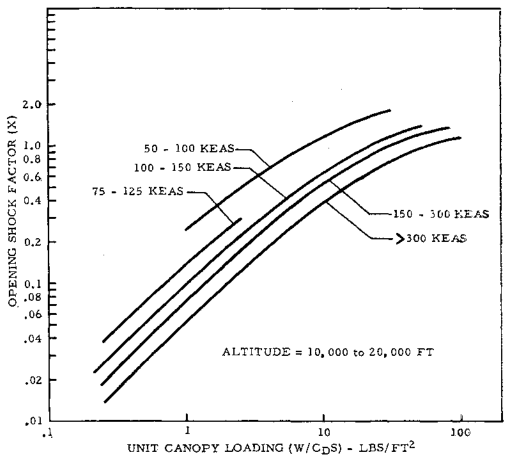

Fig. 3 Opening-shock-factor curves for various single-Ringsail parachutes.

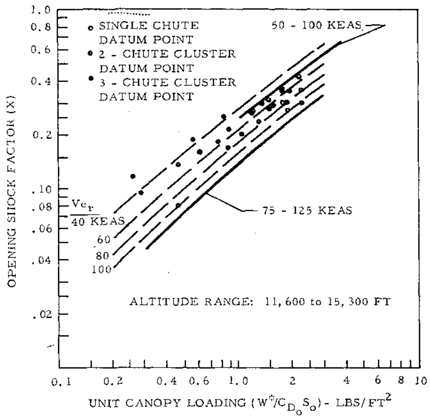

Fig. 4 Opening-shock-factor data for 83.5-ft D_o Ringsail parachute, single and clusters.

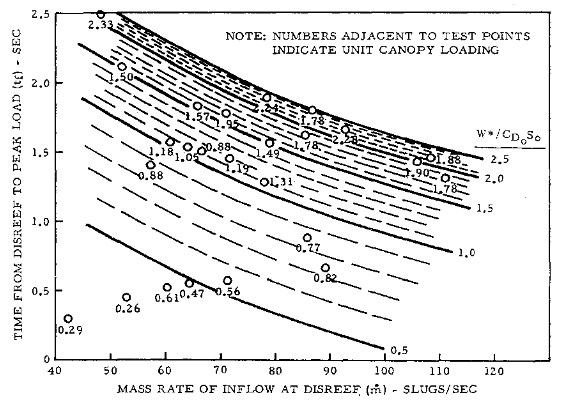

Fig. 6 Disreef inflation time for 83.5-ft D_o Ringsail parachute.

parachute peak disreef load under any set of known or assumed cluster operational nonuniformities.

4.1 Technique for Evaluating Disreef Opening Shock Factors for Clustered Parachutes

Analysis of drop test data for the 83.5-ft D_o Ringsail parachute in cluster shows that correlation of the measured shock factors occurs when the individual parachute unit canopy loading is evaluated at the instant of peak load following disreef on the lead parachute in cluster. The method consists of apportioning the total recoverable weight W by the ratio of each parachute's C_DS to the total C_DS of all parachutes in cluster, measured at the instant of peak disreef load on the lead parachute. That is,

$$W_1^* = [(C_DS_F)_1/(C_DS_F)_{\text{total}}] \times W \quad (1)$$

$$W_2^* = [(C_DS_F)_2/(C_DS_F)_{\text{total}}] \times W, \text{ etc.} \quad (2)$$

and

$$(C_DS_F)_{\text{total}} = (C_DS_F)_1 + (C_DS_F)_2 \ldots + (C_DS_F)_n \quad (3)$$

Having evaluated W^* for each parachute in the cluster, the unit canopy loading for each parachute is simply $W^*/C_{D_o}S_o$. The opening shock factor X for each parachute is computed from the relation

$$X = F_F/F_c = F_F/q_rC_{D_o}S_o \quad (4)$$

where the peak opening load on each parachute, F_F, and the dynamic pressure at disreef, q_r, are measured in test. The results of this evaluation for the 83.5-ft D_o Ringsail parachute are shown in Fig. 4. Figure 4 presents individual parachute opening shock factor vs unit canopy loading from both 2- and 3-parachute-cluster tests. The 50- to 100-knots equivalent air speed (KEAS) and 75- to 125-KEAS curves from Fig. 3 are reproduced in Fig. 4 to substantiate the trend of the faired curves.

Establishing the previous correlation immediately provides a means for predicting the individual parachute peak disreef load under any set of known or assumed parachute cluster operational nonuniformities. The only requirement is to be able to predict the drag area of each parachute at the instant of peak disreef load on the lead parachute in cluster. Figures 5–7 present data that permit this evaluation for the 83.5-ft D_o Ringsail parachute in either a 2- or 3-parachute cluster.

Figure 5 presents a plot of lead-parachute drag area at peak load (C_DS_F) vs unit canopy loading. Figure 6 provides the lead-parachute time from disreef to peak load, t_{fL}, vs mass rate of inflow at disreef, $\dot{m}$, and unit canopy loading.

Figure 7 presents a plot of the lag-parachute(s) disreef inflation characteristics. The data are presented in terms of the ratio of lag-parachute drag area at the instant of lead-parachute peak disreef load C_DS_F to the average reefed drag area C_DS_r vs the nondimensionalized disreef time differential $\Delta t_r/t_{fL}$. It may be noted that the quantity $\Delta t_r/t_{fL}$ can be either positive or negative, depending on the sign of Δt_r. If the lag parachute disreefs *before* the lead parachute disreefs, Δt_r is negative. If the lag parachute disreefs *after* the lead parachute disreefs, Δt_r is positive. As seen from Fig. 7, negative values of $\Delta t_r/t_{fL}$ promote cluster uniformity by allowing the lag parachute to "catch up" with the lead parachute during the disreef inflation process. In contrast, positive values of $\Delta t_r/t_{fL}$ promote cluster nonuniformity by inhibiting disreef inflation of the lag parachute. Maximum individual parachute load nonuniformity occurs when the lag parachute(s) disreefs at or after the instant when the peak disreef load is

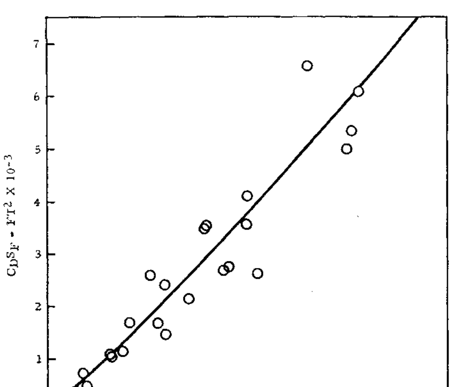

Fig. 5 Drag area at lead-parachute peak disreef load for 83.5-ft D_o Ringsail.

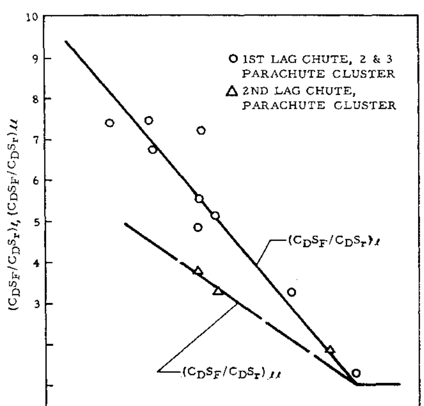

Fig. 7 Lag-parachutes' disreef inflation characteristics for 83.5-ft D_o Ringsail in 2- and 3-parachute clusters.

imposed on the lead parachute. For this condition the value of C_DS_F/C_DS_r for the lag parachute is equal to 1.0; i.e., C_DS_F equals C_DS_r.

4.2 Procedure for Predicting Lead-Parachute Peak Disreef Load

Predicting the lead-parachute peak disreef load is an iterative process in which the unit canopy loading for the lead parachute is initially estimated, a set of computations carried out, and the unit canopy loading of the lead parachute calculated. The calculated value of $(W^*/C_{D_o}S_o)_L$ is then compared with the initial estimate and the computation repeated until the initial and computed values agree. Convergence is quite rapid, so that with practice only one or two iterations are normally required.

To make a load calculation, the conditions at disreef of the lead parachute must be established, together with the degree of reefed blanketing and the disreef time differential. Conditions at disreef can be determined from the conditions at parachute-cluster deployment either by machine trajectory calculations or by assuming near-terminal reefed conditions at lead-parachute disreef. Drop test data are normally required to establish the degree of reefed blanketing. Knowledge of reefing cutter tolerance and the arrangement of cutters in terms of redundancy provides the probable (or possible) disreef time differential between parachutes. An example calculation will serve to illustrate some of these considerations.

Example calculation

Given: a cluster of two 83.5-ft D_o Ringsail parachutes deployed at 10,000 ft altitude and a dynamic pressure of 75 psf to recover an 11,000-lb spacecraft. The drag area of the spacecraft is 100 ft². The parachutes are initially reefed to $9\frac{1}{2}\%$, which provides a nominal reefed drag area (C_DS_r) on each parachute of 350 ft². Each parachute is rigged with a single, nominal 8-sec reefing line cutter whose pyrotechnic-time-delay tolerance is $\pm 7\frac{1}{2}\%$. Previous drop test data have established the worst reefed blanketing for these conditions to be 20%; i.e., $(C_DS_r)_l/(C_DS_r)_L = 0.80$.

Find: the peak individual parachute disreef load for these conditions.

Solution: for the worst conditions of reefing cutter operation, the lead parachute could disreef at the low end of the reefing cutter nominal time delay, or 7.40 sec after line stretch. Similarly, the lag parachute could disreef at the high end of the reefing cutter nominal time time delay, or 8.60 sec after line stretch.

Thus: $(\Delta t_r)_{\max} = 8.60 - 7.40 = 1.20$ sec.

Based on a reefed blanketing of 20%

$$(C_DS_r)_L = 350 \text{ ft}^2$$

$$(C_DS_r)_l = (0.8)(350) = 280 \text{ ft}^2 \qquad (C_DA)_v = 100 \text{ ft}^2$$

Using the foregoing reefed drag data in a point-mass trajectory computation, the conditions at disreef of the lead parachute are calculated to be: $q_r = 15.8$ psf, $h_r = 8300$ ft, $V_r = 130.6$ fps, $V_{e_r} = 68$ KEAS. If the total recovery weight were carried by the lead parachute, the unit canopy loading would be

$$\left(\frac{W^*}{C_{D_o}S_o}\right)_L = \frac{11{,}000 \text{ lb}}{4000 \text{ ft}^2} \qquad \left(\frac{W^*}{C_{D_o}S_o}\right)_L = 2.75 \text{ psf}$$

Therefore, the actual lead-parachute unit canopy loading is some value less than 2.75 psf. Try

$$(W^*/C_{D_o}S_o)_L = 2.42 \text{ psf}$$

From Fig. 5, for a unit canopy loading of 2.42,

$$(C_DS_F)_L = 6400 \text{ ft}^2$$

The mass rate of inflow on the lead parachute at disreef is

$$\dot{m}_L = (\rho V C_D S)_r$$
$$= (18.52 \times 10^{-4} \text{ slugs/ft}^3)(130.6 \text{ fps})\ (350 \text{ ft}^2)$$
$$\dot{m}_L = 85 \text{ slugs/sec}$$

From Fig. 6 for $\dot{m}_L = 85$ slugs/sec and $W^*/C_{D_o}S_o = 2.42$ psf, $t_{f_L} = 1.8$ sec. Then, $\Delta t_r/t_{f_L} = 1.20/1.8 = 0.66$. From Fig. 7 for $\Delta t_r/t_{f_L} = 0.66$, $(C_DS_F/C_DS_r)_l = 3.05$. Summarizing,

$$(C_DS_F)_L = 6400 \text{ ft}^2$$
$$(C_DS_F)_l = (3.05)(280 \text{ ft}^2) = \underline{855}$$
$$(C_DS_F)_{\text{total}} = 7255 \text{ ft}^2$$

Recomputing,

$$\left(\frac{W^*}{C_{D_o}S_o}\right)_L = \frac{\frac{6400}{7255} \times 11{,}000 \text{ lb}}{4000 \text{ ft}^2}$$

$(W^*/C_{D_o}S_o)_L = 2.42$ (compares with 2.42 initially assumed)

Entering Fig. 4 with the foregoing value and a V_{e_r} of 68 KEAS,

$$X_L = 0.41$$

Finally,

$$F_{F_L} = X_L\ q_{r_L}\ C_{D_o}S_o = (0.41)(15.8 \text{ psf})(4000 \text{ ft}^2)$$
$$F_{F_L} = 25{,}900 \text{ lb}$$

If redundant reefing lines and reefing cutters are used, the maximum disreef time differential can be reduced to approximately 0.5 sec with a corresponding peak disreef load of 24,000 lb. Use of advanced-design reefing cutters to provide truly synchronous disreefing would further reduce the peak disreef load to 22,300 lb, all other factors remaining the same.

5. Conclusions

The method of shock-factor load analysis provides a convenient method for predicting peak disreef loads for individual parachutes in cluster. Comparison of predicted loads with actual peak loads measured in numerous drop tests with the 83.5-ft D_o Ringsail parachute in cluster shows that the average accuracy of the predicted loads is ±10%. The method has proven itself to be a useful tool, not only in establishing peak parachute disreef loads for a variety of different recovery-system deployment conditions, but also in providing additional insight as to the relative importance of the various factors affecting individual parachute peak loads. It is, of course, apparent that use of this method requires a considerable amount of test data in order to establish the shock-factor curves and other operational characteristics for the specific parachutes employed. These data are traditionally expensive and time-consuming to obtain.

Reference

[1] "Performance of and design criteria for deployable aerodynamic decelerators," Aeronautical Systems Div., ASD-TR-61-579 (December 1963).