Analysis of Parawing Canopy Behavior in Free-Flight Depolyment

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An analysis is made of certain parawing data obtained during the deployment of 400- and 4000-ft² parawing canopies in free flight at dynamic pressures to 100 psf and altitudes to 20,000 ft. Special attention is given to the first reefed stage of deployment because it constrains the minimum load that can be achieved at high dynamic pressure and because structural damage to the fabric was most prevalent in this stage. An improved reefing concept is described, and its flexibility, in terms of meeting various requirements, is discussed.

Introduction

PARACHUTES of various design have been used for many years to limit the touchdown velocity of both human and nonhuman cargoes after release from platforms at heights above the earth's surface. They have been designed mainly as aerodynamic "drag" devices where the horizontal motions have been governed primarily by the magnitude and direction of local winds. In recent years, there has emerged considerable interest in devices that have, in addition to the parachute features of low stowage volume and light weight, significant aerodynamic lift for the purpose of wind penetration and lateral control of the touchdown point. Several design concepts for satisfying these needs and interests have stemmed from "kite" and "wing" technology that embodies the principles of aerodynamic lift on the one hand and parachute technology that embodies the principles of aerodynamic drag, deployment simplicity, and structural integrity on the other. One family of devices that represent design features gleaned from both of these technologies is the NASA Langley Research Center's "parawing."[1]

During the 1967–1969 time period, one of the Langley "twin-keel" parawing concepts was designed, fabricated, and flight-tested at 400- and 4000-ft² canopy sizes.[2,3] The principal objective of the flight-test program was to investigate the deployment and glide characteristics of the canopy/payload system at large scale when deployed at altitudes to 20,000 ft and dynamic pressure to 100 psf. A goal for limiting the payload deceleration to 3 g's during canopy deployment at high dynamic pressure has identified the first reefed stage of deployment as the most difficult. In addition to the problems of reducing the deployment load to the 3-g limit, significant structural damage also was experienced during inflation of the first reefed stage. For these reasons, this paper will be addressed primarily to an analysis of deployment behavior during the first reefed stage and also will present a new reefing concept addressed to the deployment problems identified during the flight-test program.

The 4000-ft² canopies were deployed with payload weights to 6000 lb and attained lift-to-drag ratios $(L/D)_{\max}$ in the range 2.5–2.75, with corresponding resultant force coefficients of about 0.64. Wing loadings (W/S) were in the range 0.75–1.5. The gliding flight characteristics are discussed in detail elsewhere[3] and will not be discussed further in this paper.

Presented as Paper 70-1189 at the AIAA Aerodynamic Deceleration Systems Conference, Dayton, Ohio, September 14–16, 1970; submitted November 2, 1970; revision received May 11, 1971 Although several people of the NASA Langley Research Center staff contributed to this paper in one way or another, I would like especially to acknoweldge the efforts of A. D. McHatton and H. Morgan for their innovations and ideas precipitating the canopy reefing scheme reflected in Fig. 8, and their efforts in generating experimental data relative to the suspension line reefing concept reflected in Fig. 9.

Index categories: Aircraft Testing; Entry Vehicles and Landers; Aircraft Configuration Design.

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Parawing Description

The twin-keel parawing under consideration herein (Fig. 1) is of flat planform with a 45° leading-edge sweep. The center section is rectangular in shape, and the two outboard panels are of triangular shape with side lengths equal to the center panel length. Outboard panels are attached to the center panel along the "keels." Suspension lines located along the keels, leading edges, and trailing edges connect the parawing canopy to the payload.

Deployment Staging

The parawing was packed into a fabric bag for stowage on the aft end of its payload. The payload/parawing system was taken to the drop altitude by an airplane, where it was released by conventional means. Following clearance of the aircraft, a conventional parachute was deployed for the purpose of bringing the payload/parawing system to the desired near-vertical trajectory and proper velocity. Upon reaching the proper test condition, the conventional parachute extracted the parawing canopy from its place of stowage on the payload. At the instant of "line stretch," the parawing canopy was extracted from its bag in the wake of the payload. All suspension lines were rigged to equal length during the first three stages of reefing, with the excess length of each suspension line, used for gliding trim, stowed near the confluence. The final stage of disreef was implemented by releasing all suspension lines to their proper lengths for gliding trim.

The first three stages of canopy reefing (Fig. 2) were effected by the location of braided fabric lines around the canopy periphery and along the keels. The reefing lines were attached to the fabric by means of regularly spaced metal rings that were sewn to the canopy. During the first reefed stage, the canopy took the shape of three lobes (Fig. 2a) attached along the keels, hereafter referred to as "center lobe" and "outboard lobes." The reefing lines constrained the size of the air inlets to each of these three lobes and thereby were the principal means of controlling their inflation time. All disreefing was implemented by time-controlled pyrotechnic line cutters. Following inflation and near steady-state equilibrium of the three lobes during the first reefed stage, the two outboard lobes were disreefed along their leading edges, allowing a step growth in the parawing drag area (Fig. 2b), referred to as the second reefed stage. After near steady-state equilibrium was reached in the second reefed stage, the reefing lines along both keels were severed, allowing another step growth in the canopy drag (Fig. 2c), leaving the canopy reefed only along the trailing edges and nose in a "draw-string" fashion. Following near steady-state equilibrium of the third reefed stage, the reefing lines along the nose and trailing edges were severed simultaneously, leaving the canopy shape only slightly constrained by the equal-length suspension-line rigging (Fig. 2d). Finally, as mentioned earlier, the suspension lines were extended to gliding trim lengths, where control of only the aft tip lines on each leading edge and the aft line of each keel was maintained for trim maneuver and glide slope modulation.

First Reefed Stage

A design goal of limiting the deceleration loads imposed on the payload to 3 g's during deployment and the structural damage encountered have pointed up the first reefed stage of parawing deployment as the most challenging. The characteristic of low fabric porosity required for efficient glide performance of a canopy leaves, primarily, the *rate* of drag growth and the *extent* of drag growth as variables for controlling the deceleration loads during inflation of the first reefed stage. Generally, the minimum steady-state C_DS that can be achieved in the first reefed stage with this skirt reefing concept will result when the reefing lines about the inlets are of minimal length. The rate of C_DS growth is also dependent upon the reefing line length by virtue of the volumetric rate of airflow into the canopy which is governed by the inlet areas. On the basis of small-scale wind-tunnel tests and estimated scale relationships, it was determined early in the test program that first-stage reefing lines would have to be less than about 20% of the keel length ($L_{RL}/L_K < 0.2$). Wind-tunnel data also indicated that steady-state C_DS values of the canopy were rather insensitive to reefing line lengths in the interval $0.10 < L_{RL}/L_K < 0.20$, leaving, primarily, the growth rate, controlled by inlet size, as the load-controlling factor. Reefing to L_{RL}/L_K values smaller than 0.10 during tunnel tests also indicated that steady-state C_DS was becoming quite sensitive to reefing line length, and the results were unpredictable (i.e., nonrepeatable). It is believed that this phenomenon resulted from the onset of significant pressure drop across the inlet as the canopy shape approached equilibrium because of the finite porosity of the canopy fabric (i.e., $P \approx 10$ ft^3/min/ft^2-0.5-in. H_2O). During flight tests of the 400-ft^2 models, it appeared that first-stage reefing line lengths in the 0.10–0.14 range would meet the 3-g load limit based on the existing scale theories, using (L_{RL}/L_K) as the scale parameter for inlet control; however, test data from some of the early 4000-ft^2 canopies indicated that smaller reefing ratios would be required. Some of the 4000-ft^2 canopies were reefed to L_{RL}/L_K values of 0.08 in attempts to meet the 3-g requirement without success. Smaller values of L_{RL}/L_K were not attempted because of risks that the canopy would not inflate fully during first stage and thereby introduce excessive second-stage loads and because the significant canopy buffeting over the longer inflation periods was believed to be the main source of canopy damage during first stage. The lack of scale agreement between the 400- and 4000-ft^2 tests and the canopy damage sustained during first-stage inflation of the 4000-ft^2 canopies have led to the analysis contained herein. The main thrust of this analysis will be to evaluate the effectiveness of the parameter L_{RL}/L_K for controlling the fill time (t_f) of these canopies and to examine its scalability by comparing results of the 400- and 4000-ft^2 data analyses.

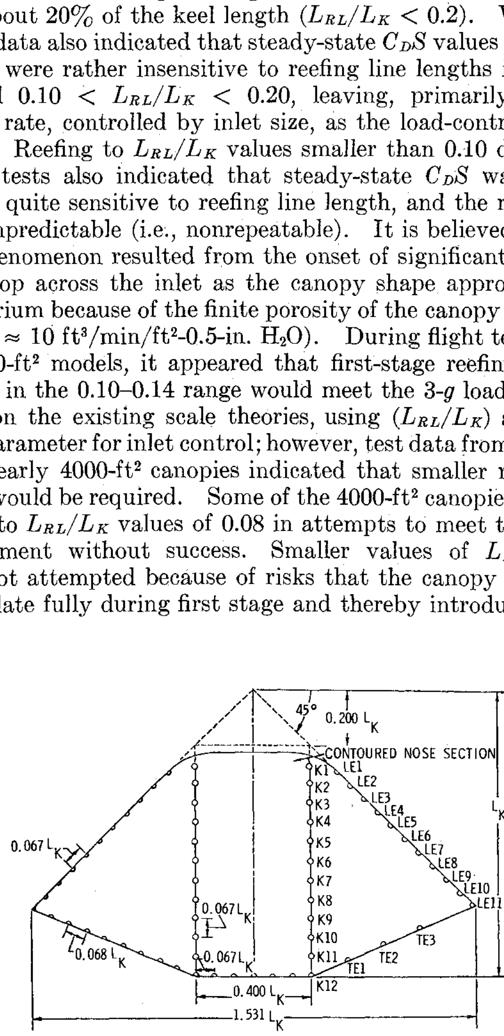

Fig. 1 Planform of twin-keel parawing including suspension-line attachment points.

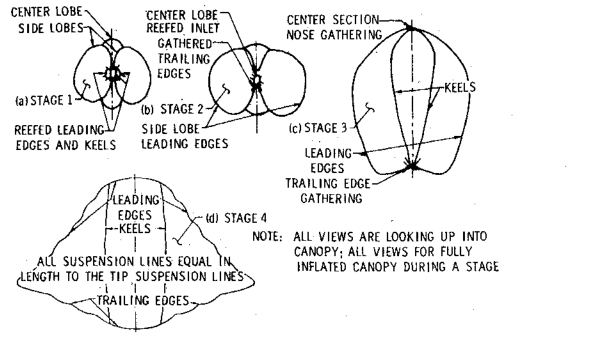

Fig. 2 Typical planforms during reefing sequence for twin-keel parawing.

Flight-Test Data

Flight-test data used in this analysis are summarized in Table 1. Column 1 numbers the various sets of data available with respect to reefed inlet size. The nondimensional length of reefing lines around each of the three lobe inlets is shown in column 2. Column 3 contains the flight-test number relatable to Refs. 2 and 3. Canopy fill times located in column 4 were determined from analysis of time-coded motion pictures. Freestream velocity, time-averaged over the fill period, determined from space positioning cinetheodolite data is shown in column 5. Canopy drag at first-stage fill as determined from onboard total force measured between payload and parawing and freestream dynamic pressure is shown in column 6. The other parameters in Table 1 are derived from values in the first six columns or will be explained as they are introduced in subsequent portions of this analysis.

Data Analysis

The measured fill times contained in Table 1 were determined by experienced motion-picture film-reading technicians instructed to measure the increment of time from line stretch, when the canopy was exposed to the payload wake, until the canopy ceased to grow in size. Accurate determination of the fill time of a highly reefed parawing canopy has proved more difficult than, for example, the fill time determination of a conventional parachute. This is because the rate of growth of a highly reefed parawing peaks early in the inflation process because of airflow restrictions imposed by the small reefed inlets, where the rate of growth of a "normally deployed" parachute peaks very near the time of full inflation. An individual accustomed to measuring the fill time of a parachute from time-coded high-speed motion-picture film is therefore more apt to make an error in deciding when a parawing canopy is filled in the absence of an abrupt cessation of canopy growth such as that to which they are accustomed in the determination of parachute fill times. For this reason, caution must be exercised in the analysis and use of experimentally determined fill times of highly reefed devices until the film readers have learned to cope with this problem. This point is illustrated by several "sets" of fill-time data (Table 2) for the flight tests under consideration herein which have evolved from various attempts to establish the fill times during the data-reduction phases of the program.

Table 1 Flight test data and related values used in analyzing the first reefed stage of inflation

(1) Data set	(2) L_{RL}/L_K	(3) Flt. no.	(4) t_f	(5) v	(6) C_DS	(7) $(C_DS)^{3/2}$	(8) $(C_DS)^{3/2}/vt_f$	(9) A_R	(10) A_0/K_a	(11) K_v	(12) K_a	(13) $t_fvS/(C_DS)^{3/2}$	(14) A_R/S	(15) $(K_v/K_a)_{av}$	(16) $(A_0/K_a)_{av}\cdot 1/S$
							400-ft² canopy data								
1	0.141	105-T	1.14	195	25	125	0.562	0.815	0.414	0.197	0.277	711	0.00204	0.47	0.00168
2	0.172	101-T	1.37	189	35	207	0.799	1.21	0.662	0.197	0.288	500	0.00303	0.47	0.00168
	0.172	106-T	0.92	302	40	253	0.911	1.21	0.662	0.197	0.327	439	0.00303	0.47	0.00168
	0.172	107-T	0.69	368	45	302	1.189	1.21	0.662	0.197	0.428	336	0.00303	0.47	0.00168
					40[a]	254[a]	0.966[a]				0.314[a]	425[a]			
3	0.178	103-T	0.87	205	35	207	1.161	1.30	0.714	0.197	0.390	338	0.00325	0.47	0.00168
4	0.212	102-T	0.57	170	42	272	2.81	1.84	0.893	0.197	0.582	143	0.00460	0.47	0.00168
	0.212	104-T	0.43	208	50	354	3.96	1.84	0.893	0.197	0.825	101	0.00460	0.47	0.00168
					46[a]	313[a]	3.39[a]		0.671[a]		0.700[a]	122[a]			
							4000-ft² canopy data								
1	0.08	209-T	5.58	234	300	5196	3.98	2.64	−0.858	0.197	0.224	1005	0.000660	0.94	−0.00037
	0.08	210-T	4.50	261	290	4939	4.20	2.64	−0.858	0.197	0.236	951	0.000660	0.94	−0.00037
					295[a]	5068[a]	4.09[a]				0.230[a]	978[a]			
2	0.10	201-T	5.34	179	350	6548	6.85	4.12	−1.558	0.197	0.235	584	0.00103	0.94	−0.00037
	0.10	202-T	4.25	287	400	8000	6.56	4.12	−1.558	0.197	0.228	610	0.00103	0.94	−0.00037
	0.10	205-T	4.42	288	375	7262	5.70	4.12	−1.558	0.197	0.198	701	0.00103	0.94	−0.00037
	0.10	207-T	4.47	215	300	5196	5.40	4.12	−1.558	0.197	0.187	740	0.00103	0.94	−0.00037
					356[a]	6752[a]	6.13[a]				0.212[a]	659[a]			
3	0.139	200-T	3.77	160	299	5170	8.57	7.97	−2.07	0.197	0.170	467	0.00199	0.94	−0.00037
	0.139	203-T	3.50	261	450	9546	10.45	7.97	−2.07	0.197	0.205	383	0.00199	0.94	−0.00037
					375[a]	7358[a]	9.51[a]		−1.49[a]		0.188[a]	425[a]			

[a] Average values.

The data set taken as the most accurate and used in this analysis (Table 1, column 4) is that which was published in the contractor's final reports.[2,3] Because of the inherent difficulty in reading the fill-time data accurately, however, caution must be exercised even with this data set.

This analysis is begun by taking the generally accepted equation for the fill time of nonporous parachutes or other lightweight ram-air inflated, flexible devices

$$t_f = V/Av \tag{1}$$

as representative of the relationship between fill time t_f, canopy volume V, inlet area A, and inlet airflow velocity v. At first examination of this equation, one wonders how to account for the fact that the twin-keel parawing consists of three lobes, each with its own reefed inlet and all lobes inflating simultaneously. Upon examination of the physical configuration of the parawing during the first reefed stage, it is seen that the inflated volume of the center lobe is considerably larger than either of the two outboard lobes, whereas the reefing lines constraining each of the three inlets are of equal length. It is, therefore, concluded that the center lobe should be last to complete inflation and, hence, the lobe for which the measured fill-time data are applicable. The fill-time portion of this analysis will, therefore, be related primarily to that of the center lobe.

The inlet flow velocities will be assumed equal to the free-stream velocities and taken as the time-average velocity during the fill process, as determined from space-positioning cinetheodolite data (Table 1, column 5).

The center lobe volume is not easily determined. It cannot be measured in flight directly without significant effort in reconstructing a three-dimensional shape of the asymmetric configuration from simultaneous triangulation photographs and, therefore, will be accounted for indirectly by assuming that it is proportional to the drag area to the three-halves power such as the volume of a sphere is proportional to its cross-sectional area to the three-halves power. The constant of proportionality relating the center lobe volume and $(C_DS)^{3/2}$ for a 400-ft² canopy was estimated from wind-tunnel photography for a representative steady-state inflation as

$$K_V = V/(C_DS)^{3/2} = 50/(40)^{3/2} = 0.197 \tag{2}$$

Using the same constant of proportionality, a 4000-ft² model with the same drag coefficient is predicted to have a center lobe volume of 1580 ft³. This prediction is compared with the center lobe volume of flight 203T, a 4000-ft² model, estimated to be 1700 ft³ from a detailed three-dimensional reconstruction of the canopy volume using motion-picture data. The proportionality constant value of 0.197 will, therefore, be taken as equally applicable to 400- and 4000-ft² canopies.

The inlet area will be referenced to the length of reefing line placed around the inlet to the center lobe. If the reefing line length is L_{RL} and the line forms the circumference of a circle, the area contained within the circle will be

$$A_R = L_{RL}^2/4\pi \tag{3}$$

This area (A_R) will be called the "reference area" for convenience. The next question is that of relating the well-controlled reference area to the actual area A needed to satisfy Eq. (1). The reefing line might be expected to remain in a reasonably well-defined plane normal to the airflow during inflation because the suspension lines attaching the inlet to the payload are all of equal length; however, the in-plane forces developed during inflation and the balance of forces between the outboard lobes and the center lobe may alter the reefing line contour significantly from that of a circle, such as that illustrated in Fig. 3. A correction for this type of inlet distortion is taken as a constant shape parameter, K_a, which is assumed to be the same for all reference areas within the finite range of reefing line length variances under consideration herein. Multiplying the correction factor times the reference inlet area (K_aA_R) gives the area within the confines of the distorted reefing line.

Consideration of physical materials in the vicinity of the inlet, such as reefing rings, the length and width of the fabric edge terminating at adjacent reefing rings, and the suspension lines that attach to the canopy at the reefed inlets, makes it seem reasonable to assume that there will be a portion of the area within the circumferential confines of the reefing line which will be occupied by materials. The area occupied by these materials should also remain fairly constant as the reefing line length is varied over the finite range of lengths under consideration herein. In addition to the presence of materials in the vicinity of the inlet, there is still another factor that may affect the actual inlet area significantly, and that is the arrangement of the fabric edges to which the reefing rings and, hence, the reefing lines are attached. Since the fabric edge being constrained by the reefing line is much longer than the line itself (Figs. 3 and 4), there is an excess of fabric edge which must be located either inside or outside the circumferential boundary of the reefing line. Fabric edge segments that are packaged inside the reefing line confines will tend physically to block the inlet as mentioned previously and, in addition, may "shunt" a portion of the air flowing across the area bounded by the reefing line such that it does not flow into the center lobe. By the same token, fabric edge segments located outside the reefing line confines may shunt air that is flowing outside the reefing line boundary into the center lobe. The relative lengths of fabric edge and reefing lines do not change significantly when the reefing line lengths are varied over finite ranges, such as that under consideration herein (Fig. 4), and, therefore, these effects, along with the effects of physical materials present, can be defined as area blockage (A_0). In view of the preceding considerations, it is believed that an equation of the form

$$A = K_a A_R - A_0 \tag{4}$$

may express the actual inlet area in terms of the reference area reasonably well. It is noted that the foregoing definition of A_0 makes it possible for A_0 to be either positive or negative, depending on the way the fabric edge is arranged around the inlets. (Note that, unfortunately, no specific procedures for arranging the inlet fabric were followed during this flight-test program.) For example, if the segments of fabric edge about the inlet are arranged predominantly outside the area bounded by the reefing line, the actual inlet could be greater than $K_a A_R$, where, on the other hand, predominant arrangement of the fabric edge segments inside the reefing line confines could completely block the inlet to the center lobe ($A_0 = K_a A_R$) when the reefing line is sufficiently short.

On the basis of the various considerations and assumptions discussed previously, Eq. (1) can be rewritten as

$$t_f = K_v (C_D S)^{3/2} / (K_a A_R - A_0) v \tag{5}$$

To calculate the actual inlet size A corresponding to the various reefing line controls A_R, it is necessary to determine

Table 2 Various sets of first-stage canopy fill-time data reflecting difficulty in fill-time determination

Reefing ratio (L_{RL}/L_K)	Flight no.	First stage fill time t_f, sec: First documentation	Second documentation	Final documentation
		400-ft² canopies		
0.141	105-T	0.475	0.58	1.14[a]
0.172	101-T	0.588	1.14	1.37[a]
	106-T	0.262	1.21	0.92[a]
	107-T	0.671	0.48	0.69[a]
0.178	103-T	0.510	0.87	0.87[a]
0.212	102-T	0.250	0.44	0.57[a]
	104-T	0.466	0.37	0.43[a]
		4000-ft² canopies		
0.08	209-T	1.050	3.42	5.58[b]
	210-T	1.520	3.07	4.50[b]
0.10	201-T	1.131	2.26	5.34[b]
	202-T	0.907	1.10	4.25[b]
	205-T	0.963	1.80	4.42[b]
	207-T	0.760	2.28	4.47[b]
0.139	200-T	0.670	1.50	3.77[b]
	203-T	0.884; 0.836	1.15	3.50[b]

[a] Ref. 2.
[b] Ref. 3.

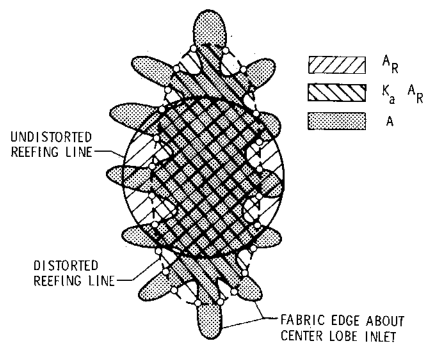

Fig. 3 Conceivable distortions of center lobe inlet during first-stage inflation.

the values for K_a and A_0. Equation (5) is rewritten to give

$$K_a(A_R - A_0/K_a) = K_v(C_D S)^{3/2}/vt_f \tag{6}$$

This equation says that all factors $(C_D S)^{3/2}/vt_f$ using a specific reference area A_R should be constant. These factors have been calculated for each flight and are located in column 8 of Table 1. In cases where more than one flight test was conducted with the same reefing line length L_{RL}/L_K (hence the same reference area A_R), it will be noted from Table 1 that there is some variance in the values for $(C_D S)^{3/2}/vt_f$. These values are averaged to give a single value corresponding to each reference area. Using two sets of A_R and $(C_D S)^{3/2}/vt_f$ data denoted by subscripts 1 and 2 and dividing one equation by the other gives

$$\frac{K_a[A_{R_1} - (A_0/K_a)]}{K_a[A_{R_2} - (A_0/K_a)]K} = \frac{K_v[(C_D S)^{3/2}/vt_f]_1}{K_v[(C_D S)^{3/2}/vt_f]_2} \tag{7}$$

Simplifying Eq. (7) gives

$$\left[\frac{A_0}{K_a}\right]_{1\text{-}2} = \frac{A_{R_2}[(C_D S)^{3/2}/vt_f]_1 - A_{R_1}[(C_D S)^{3/2}/vt_f]_2}{[(C_D S)^{3/2}/vt_f]_1 - [(C_D S)^{3/2}/vt_f]_2} \tag{8}$$

The subscript 1-2 on the left side of Eq. (8) denotes the values of A_0/K_a calculated for data set 1 with respect to data set 2. This procedure can be continued until values for A_0/K_a are calculated for all other data sets, applicable to the same size of canopy, with respect to data set 1 and averaged to give a single value of A_0/K_a for data set 1 with respect to all of the other data sets. Mathematical expression of this procedure is

$$\left[\frac{A_0}{K_a}\right]_1 = \frac{1}{N-1} \sum_{n=1}^{n=N} \left(\frac{A_0}{K_a}\right)_{1-n} \tag{9}$$

This procedure can be used in a similar fashion to provide single values of $[A_0/K_a]_2$, $[A_0/K_a]_3, \ldots [A_0/K_a]_N$ for testing

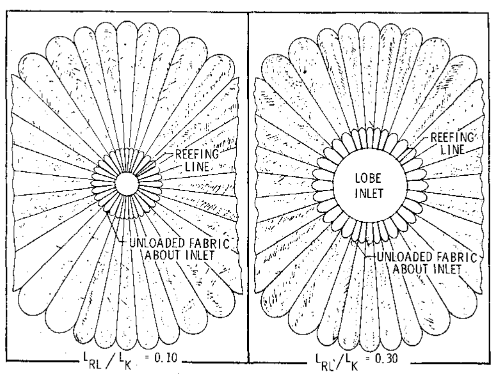

Fig. 4 Scaled sketches of fabric materials around an idealized parawing inlet with reefing line lengths of 0.10 L_K and 0.30 L_K, respectively.

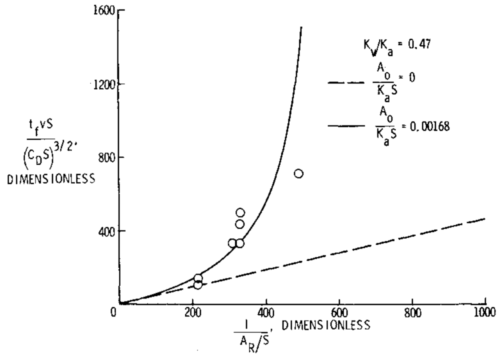

Fig. 5 Nondimensional variation of canopy fill time with reference inlet area for 400-ft² canopies during first reefed stage.

and studying the assumption that A_0 and K_a are constant. The values have been calculated for all reference areas tested on both the 400- and 4000-ft² models (Table 1, column 10).

Two very interesting observations are made at this point; first, all values of A_0/K_a for the 400-ft² data are positive, indicating that A_0 is positive (i.e., K_a is positive by definition), and hence the inlet areas are consistently smaller than the area bounded by the reefing line, and, second, all values of A_0/K_a for the 4000-ft² data are consistently negative, indicating that A_0 is negative, and hence the inlet areas are consistently larger than the area bounded by the reefing line. A third observation is that the magnitude of A_0/K_a increases toward more positive values with increasing reefing line length for 400-ft² canopy data, and the magnitude of A_0/K_a increases toward more negative values with increasing reefing line lengths for 4000-ft² canopy data. These variances could result from either A_0 or K_a trends; however, no significance has been attached to this phenomenon. Continuing on the basis of the assumption that A_0 and K_a are constant over the range of inlet reefing investigated, the average value for 400-ft² A_0/K_a data is 0.67, and for 4000-ft² data it is -1.49.

The values for K_a can now be calculated from Eq. (6) by substituting the appropriate test data and A_0/K_a values from Table 1. Averaging these values for 400- and 4000-ft² canopy data gives K_a values of 0.42 and 0.21, respectively (Table 1, column 12). It is noted at this point that differences in the inlet geometric shape factor (K_a) of this magnitude do not seem reasonable in view of the apparent geometric similitude of the 400- and 4000-ft² canopies during first stage, as evidenced by good agreement in C_DS and volumetric data comparison.

With values for each of the parameters appearing in Eq. (5) now in hand, the trend analysis of fill time with respect to reference area A_R can be continued for both the 400- and 4000-ft² canopy flight tests.

Equation (5) can be written in nondimensional form, equating a function of t_f with a function of A_R for analyzing the behavior of flight-test data. Such a form is

$$t_f vS/(C_DS)^{3/2} = (K_v/K_a)/(A_R/S) - A_0/K_aS \qquad (10)$$

Equation (10) generates a curve that fits the 400-ft² canopy data rather well when using the calculated values for K_v/K_a and A_0/K_aS (Fig. 5). The time required for filling a particular volume tends to become rather long as the reference area becomes small, approaching a state of complete inlet blockage near $1/A_R/S$ values of 500–600. On the other hand, as the reference inlet areas become large, it appears that a less sensitive and linear relationship between fill time and $1/(A_R/S)$ is approached. This indicates that the physical blockage and fabric orientation about the inlet are becoming less important.

The relationship between fill time and reference inlet area during tests of 4000-ft² canopies appears quite different from that observed with the 400-ft² canopy data (Fig. 6). Again, Eq. (10) generates a curve that fits the data quite well using calculated values of K_v/K_a and A_0/K_aS. It will be noted, however, that the fill time becomes less sensitive to reference inlet area as reference inlet area decreases, in contrast to the increased sensitivity observed with the 400-ft² data. At large reference inlet sizes, the fill time approaches a linear relationship with $1/(A_R/S)$ (as was the case for the 400-ft² canopy data), again suggesting that physical blockage and fabric orientation become less important when reefing to large reference areas.

Direct comparison of all 400- and 4000-ft² canopy data is made on Fig. 7. The linear (dashed) curve has been constructed using a K_v/K_a value of 0.47 corresponding to the value calculated for the 400-ft² canopy data. In view of the unreasonable comparison of K_v/K_a values calculated for the two canopy sizes, the 4000-ft² canopy value for K_v/K_a has been arbitrarily set equal to that of the 400-ft² canopy data and justified by somewhat arbitrarily assuming that the reported fill times for each of the 4000-ft² canopy tests are twice ($0.94/0.47 = 2$) what they should be. These arbitrarily corrected data are also plotted on Fig. 7 (dashed symbols). Correction of the 4000-ft² canopy fill-time data is not entirely arbitrary, because the fill times are difficult to determine accurately, and the variances of fill-time data for 4000-ft² canopies reflected in Table 2 are well within this range. Correction of fill time for either the 400-ft² canopy data or the 4000-ft² canopy data will in no way invalidate the preceding calculations of A_0/K_a, as long as each fill time is multiplied by the same correction factor [see Eq. (8)].

If there were no inlet blockage, either positive or negative, and the values of K_v/K_a were the same and equal to 0.47 for both canopy sizes, all data should lie on the straight line (Fig. 7) and would scale with respect to A_R. The lack of scale agreement between 400- and 4000-ft² canopy data is obvious. Particularly, it can be seen that extrapolation of 400-ft² canopy data to smaller values of A_R for predicting 4000-ft² canopy inflation behavior is grossly misleading.

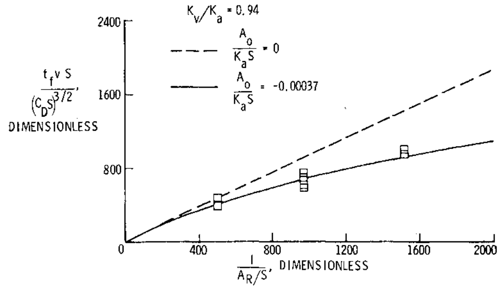

Fig. 6 Nondimensional variation of canopy fill time with reference inlet area for 4000-ft² canopies during first reefed stage.

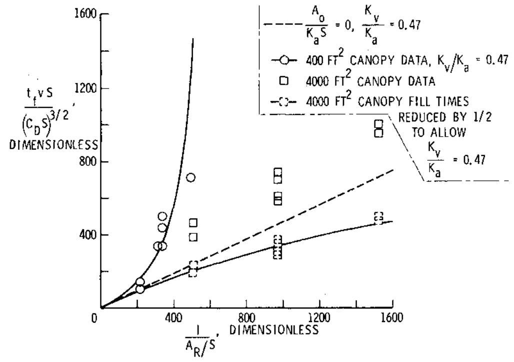

Fig. 7 Comparison of scale relationship between 400-ft² canopy data and 4000-ft² canopy data during first reefed stage of inflation.

Curves fit to data of each canopy size appear to converge toward a fairly good scale relationship with respect to A_R as $1/(A_R/S)$ decreases to values in the range 100 to 200 and less. For flight-test operations where specific procedures were used consistently for arranging the fabric about the inlet during the folding and packaging of each canopy for flight, it would seem reasonable to assume that more favorable scale relationships and better repeatability could be achieved for $1/(A_R/S)$ values larger than 200.

In summary, this inlet behavior analysis has indicated that 1) the center lobe reefing line encompasses only about 20–30% of the reference area, probably because of asymmetric loading around the periphery of the line, 2) the inlets of 400- and 4000-ft² canopies did not scale because of the presence and random arrangement of large quantities of materials about the inlet, and 3) larger inlets and more care in arranging the fabric about the inlets during flight preparation should provide more favorable scale relationships and better repeatability.

Structural Damage

Structural damage to the 4000-ft² canopies occurred repeatedly during the first reefed stage. Fabric tape sewn to the canopy in a grid pattern was effective in limiting the extent of damage; however, the initiation of rips in the fabric was numerous and, in most cases, confined to the outboard lobes. The inlet behavior analysis has pointed up some interesting possibilities that could have been the source of this damage. The fact that the inlet blockage was negative for the series of 4000-ft² canopy tests suggests that the excess fabric edge around the center lobe reefing line was located predominantly outside the reefing line boundary and hence outside the center lobe and inside the outboard lobes. The rather stiff and unloaded fabric edge located between each pair of reefing rings is quite long compared to the distance between reefing rings for the reefing line lengths used (Fig. 4). High-velocity airflow across the inlets would generate some rather significant motions of the unloaded fabric edge. The length of the unloaded edge would allow it to impact the inside surface of the outboard lobes throughout most of the inflation period, which could cause sufficient local damage from which a rip could propagate because of normal fabric loading during the inflation process. Increasing the reefing line length and/or loading the fabric edge during inflation should tend to allevaite this source of structural damage.

Modified Reefing Concept

Canopy Reefing

Having expended all means of reliable control for the first reefed stage of inflation before achieving the 3-g payload deceleration goal, a new canopy reefing concept was investigated where only a portion of the canopy is released from its bag during the first reefed stage. This reduces the steady-state C_DS and hence the first reefed stage deceleration loads imposed on the payload at high dynamic pressures. This concept opens up a new range of steady-state C_DS values that can be acquired with the parawing canopy. The control is accomplished by "drawstring" reefing completely across the canopy in the span direction parallel to the trailing edges, where all of the canopy forward of the drawstring reefing line remains in a bag during the first reefed stage. Steady-state C_DS values throughout the range of 0.03–0.10 can be achieved by location of the drawstring at the proper chord, as evidenced by a series of wind-tunnel tests (Fig. 8) utilizing 400-ft² canopies. The small C_DS values obtainable with this concept allow increased opening of the inlets to aid in overcoming scale relationship problems, repeatability problems, and structural problems caused by long inflation-time buffeting.

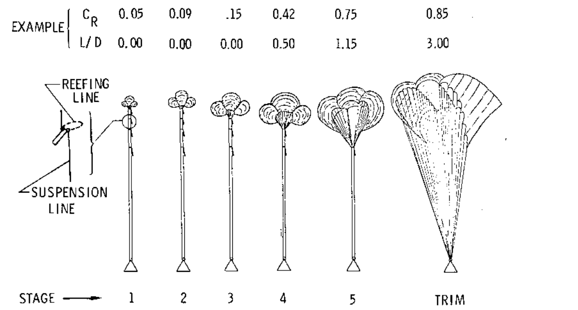

Fig. 9 Typical sequence of deployment staging featuring new canopy reefing concept in first stage, with suspension line reefing used exclusively in all subsequent stages.

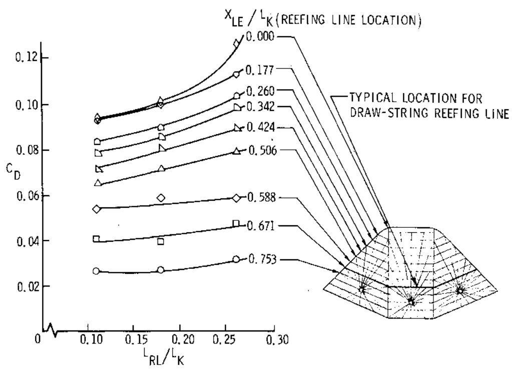

Fig. 8 Steady-state C_D of a twin-keel parawing with various forward portions of the canopy reefed.

Radial lines emanating from points located in the aft portion of each canopy section (Fig. 8 inset) represent load tapes that connect to each suspension-line attachment point. Once the chord station for drawstring reefing is determined for a particular application, it is suggested that load tapes passing through the geometric center (crown) of the fabric to be inflated in the first reefed stage of each lobe will enhance the structural efficiency of the canopy. The radial tapes, in conjunction with those tapes located parallel to the trailing edges of each section of canopy, also will provide a gridwork for stopping rips that might occur even after all known design precautions have been taken. Radial load tape locations on the insert of Fig. 8 correspond to a drawstring reefing line location at chord station 0.671. This concept for locating load tapes has been tested on 400-ft² canopies in free flight with respect to its effect on gliding performance, with no discernible effects detected.

Suspension-Line Reefing

In conjunction with the concept described previously for reducing first reefed stage deceleration loads imposed on the suspended payload when deployed at high dynamic pressure, all canopy reefing (except the single drawstring used in the first stage) has been moved from the canopy skirt onto the suspension lines (Fig. 9). This concept allows all three lobes of the canopy to develop simultaneously as the various stages of disreef are activated. The relative motion of reefing line and fabric which might cause structural damage is minimal because of short sections of reefing line. The configuration can be rigged for progressively larger lift-over-drag ratios with each stage of disreef. Figure 9 shows a typical sequence of deployment staging successfully tested several times in free flight with 400-ft² canopies. On the basis of wind-tunnel tests, the resultant force coefficients for this particular example varied from 0.05 with no lift in the first stage to 0.85 with a lift-over-drag ratio of 3 in the final stage of deployment. The first reefed stage featured all of the canopy forward of chord station 0.671 remaining inside a bag. The second reefed stage allowed inflation of the forward portion of the canopy. During the first and second reefed stages, all suspension lines connecting canopy and payload were essentially of equal length. In subsequent stages of disreef, the various suspension lines are extended in differing amounts in a fashion that controls the canopy shape and size during each stage while simultaneously transitioning from equal line lengths during first and second stages to trim gliding line lengths in the final stage. This distributes the required extension of each suspension line among several stages, providing a smoother transition than the case where all of the extension, going from equal line length configuration to gliding trim, is made in one step.

Flexibility is inherent in this new reefing concept. Discrete steady-state resultant force coefficients are attainable over a continuous range, varying from less than 0.03 to completely disreefed values near 0.85. Wind-tunnel and free-flight tests with 400-ft^2 canopies have indicated good canopy stability throughout this range of configurations.

This new concept of canopy and suspension-line reefing appears applicable 2ver a wide range of deployment load requirements. With multiple stages of reefing, the payload can be decelerated from initial conditions of high dynamic pressure to gliding trim at low dynamic pressure while maintaining the same maximum deceleration load during each stage in the interest of minimal staging time.

Conclusions

It is concluded that an equation derived herein for analyzing the fill time with respect to other related variables of a highly reefed parawing works reasonably well. Simple mathematical procedures developed to bring all related data to bear simultaneously on a single analysis give strength and confidence to the argument. Some discrepancy between the scale relationship of 400- and 4000-ft^2 canopy data, in the view of observed geometric similitudes, points up inherent difficulties and possible errors in measuring canopy fill times. The analysis has indicated the need for careful arrangement of all fabric located about the canopy air inlets during preflight folding and packaging as a means for improving fill-time repeatability and scale relationships. First-stage reefing ratios larger than 0.25 should provide improved fill-time repeatability and scaleability. Excessive loose fabric about the inlets of highly reefed devices are a source of potential structural damage during canopy inflation.

A new first-stage canopy reefing concept described herein holds promise for limiting payload deceleration to 3 g's when deployed at dynamic pressures to 100 psf. The concept also provides for wide flexibility in the selection of steady-state C_DS. It uses larger inlets to alleviate canopy damage from loose fabric buffeting and to improve the repeatability and scaleability of first-stage inflation.

The suspension line reefing concept offers wide flexibility in the selection of steady-state resultant force coefficient and lift-over-drag ratio for each stage of deployment. It also allows the entire canopy to expand during each stage of disreef and provides a smoother transition in going from equal length suspension lines at first stage to trim line lengths at final stage through incremental payout of line extensions during each stage of disreef.

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