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Radial Reefing Method for Accelerated and Controlled Parachute Opening

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Future Army airdrop systems will require aerial insertion of cargo and personnel from low altitudes to minimize ground-fire hazards. A radial reefing method was developed as a potential candidate to meet this requirement. The radial reefing method involves selecting equally spaced radials of a parachute canopy and reefing these radials near the skirt; concurrently, the canopy fabric adjacent to the reefed radials is puckered. Reefing the canopy this way creates large fabric pockets near the skirt during initial canopy inflation, resulting in an accelerated and controlled parachute opening. This was confirmed by full-scale airdrop testing using single Army personnel and cargo parachutes. In addition to demonstrating promises for single-canopy low-altitude airdrop applications, the radial reefing method also shows potential to improve clustered parachute opening by minimizing canopy enfolding and slumping.

Nomenclature

F_o = opening force, lbf
F_s = snatch force, lbf
n_g = number of gores between reefed radials
n_p = number of fabric pockets
n_t = total number of gores of canopy
R = canopy radius, ft
r = radial reefing ratio
t = time, s
t_p = time when upper canopy begins to inflate, s
t_s = time when snatch force occurs, s

Introduction

OPENING of a single parachute or a cluster of parachutes is a complicated phenomenon that involves flow and structural interaction between the surrounding air flowfield and the canopy fabric. As the parachute gets larger, the interaction becomes less manageable, resulting in opening difficulties.[1] To control the opening of a single parachute, the standard methods of skirt reefing, pulldown centerline, crown chute, and secondary chute at skirt have shown some success for certain airdrop applications. Future Army airdrop systems will require aerial insertion of heavy cargo and personnel from low altitudes to minimize ground-fire vulnerability.[1,2] The ultimate goal for airdrop altitude is 300 ft above ground level. Current standard Army parachutes are not capable for reliable and safe aerial delivery of payloads from such a low altitude. New methods and parachutes need to be developed to meet this requirement. A radial reefing method was developed for this purpose.[3] This article presents the concept, procedure, and full-scale test results of the method.

Method

Figure 1 shows the inflation sequence of a standard Army 100-ft-diam G-11 cargo parachute using skirt reefing. The sequential photographs show that the parachute is inflated by the incoming air flowing through the canopy mouth as it moves in a curvilinear trajectory. The growth of the canopy mouth is a slow process, beginning from the horizontal deployment position. If the mouth is large and well-formed early in the inflation process, preferably during canopy snatch when the canopy is in the horizontal position (canopy mainly in one-dimensional inlet airflow), the inflation should be accelerated and more positive. This is particularly important and desirable for clustered parachutes that often have irregular and uneven mouth shapes, resulting in the well-known lead- and lag-opening problem. In addition, for large cargo parachutes, such as the 137-ft-diam developmental Army cargo parachute, the large amounts of canopy fabric often cause canopy enfolding and slumping, resulting in inflation difficulties.[1] The radial reefing method was developed to establish a well-formed, stiff, large canopy mouth during canopy snatch and to solve the canopy fabric enfolding problem.

Skirt reefing is commonly used to control and stage canopy opening. It mainly restricts the skirt opening, but it offers no control of the upper canopy. It appears that if the canopy fabric is reefed during opening, the opening should be more manageable and controlled. This is the basic idea of radial reefing.

Figure 2a shows the radial reefing method using a 64-ft-diam and 64-gore standard Army G-12 cargo parachute to illustrate the method. Four equally spaced reefing rings (2 ft apart) are sewn inside the canopy on radial no. 1 from point

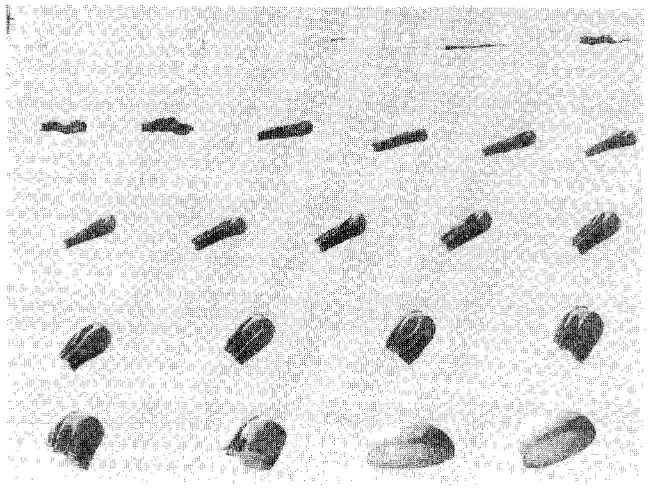

Fig. 1 Photographs showing the opening sequence of a standard 100-ft-diam G-11 cargo parachute.

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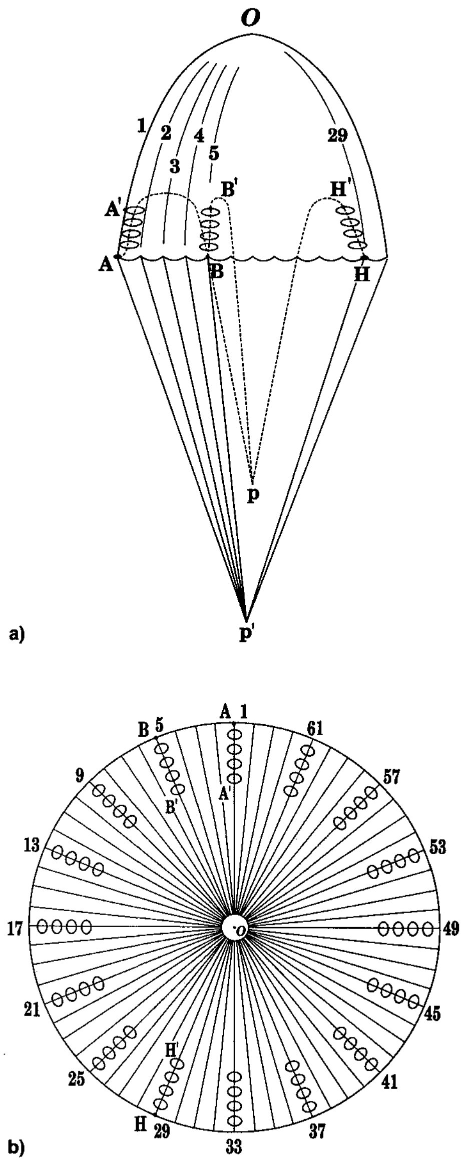

Fig. 2 Schematics showing the radial reefing method: a) side view showing the radial reefing rings and radial reefing lines of a G-12 canopy and b) plan view of the G-12 canopy showing the radial reefing rings.

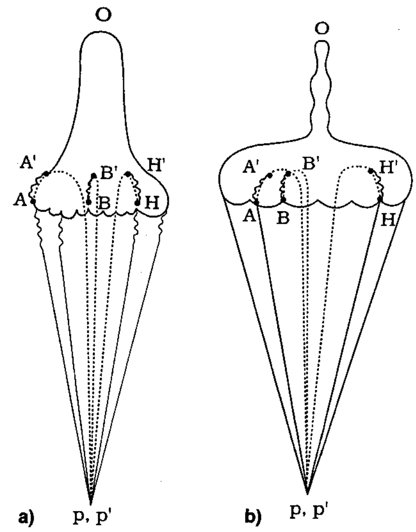

Fig. 3 Schematic showing the effects of the radial reefing method: a) G-12 canopy after radial reefing and b) radial reefed G-12 canopy at canopy snatch.

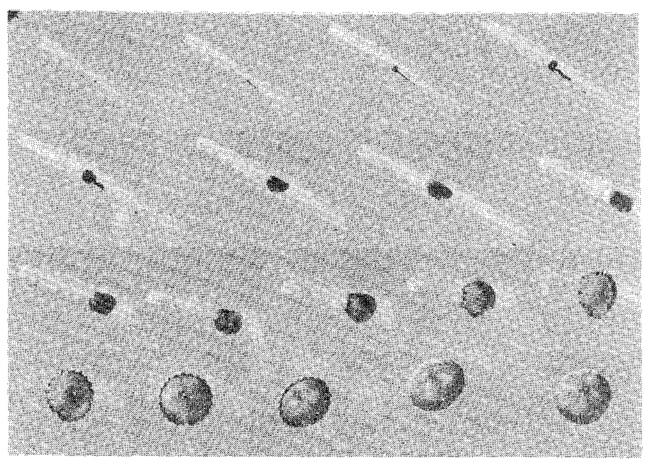

Fig. 4 Photographs showing the opening sequence of a 100-ft-diam G-11 cargo parachute radial reefed at $r = 25\%$.

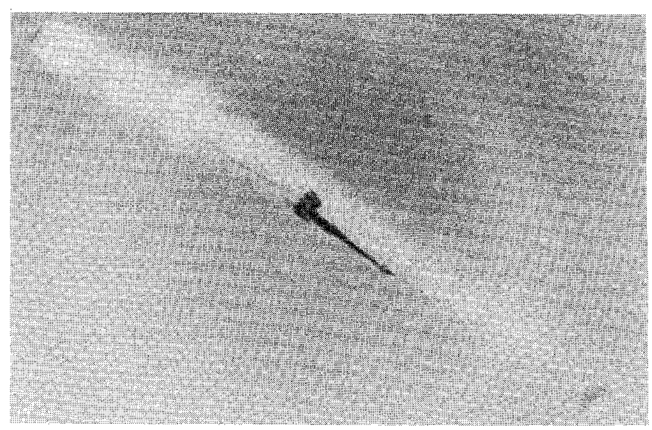

Fig. 5 Photograph showing the large, stiff mouth of a 25% radial reefed G-11 at canopy snatch.

A at the skirt to point A′, 8 ft from the skirt. Radial reefing line AA′P, sewn and anchored at point A at the skirt, runs through the four reefing rings and bends downward at A′ toward the parachute confluence point P′. Skipping every four gores, the identical arrangement of reefing rings and radial reefing line for radial no. 1 is also constructed on radials no. 5, 9, 13, . . . and 61 as shown in Figs. 2a and 2b. The final result is 16 equally spaced radial reefing lines anchored at the skirt, bent at 8 ft from the skirt and joined at point P. The canopy is now ready for radial reefing.

The radial reefing procedure involves pulling point P of the 16 radial reefing lines downward to point P′ so that along gore no. 1 point A is pulled next to point A′, resulting in puckering the canopy fabric between points A and A′. Similarly, along gore no. 5, point B is pulled next to point B′, resulting in puckering the canopy fabric between points B and B′, etc., for gores no. 9, 13, 17, . . . and 61. The net result of this packing procedure is the 8-ft reefing of canopy fabric near the skirt at 16 equally spaced radials as shown in Fig. 3a. The amount of radial reefing is expressed by r, which is defined as the ratio of the original gore length AA′ before reefing (Fig. 2a) to R, i.e., $r = AA'/R = AA'/AO$. For the current G-12, $r = 8/32$ ft $= 25\%$. As AA′ increases, r increases, meaning more canopy fabric is reefed.

After the G-12 parachute has been radial reefed, the 16 radial reefing lines are grouped together at the center as shown in Fig. 3a. Because of the radial reefing, the suspension lines connected to the nonradial-reefed radials are slightly loose; the looseness is kept near the skirt as shown in Fig. 3a. A

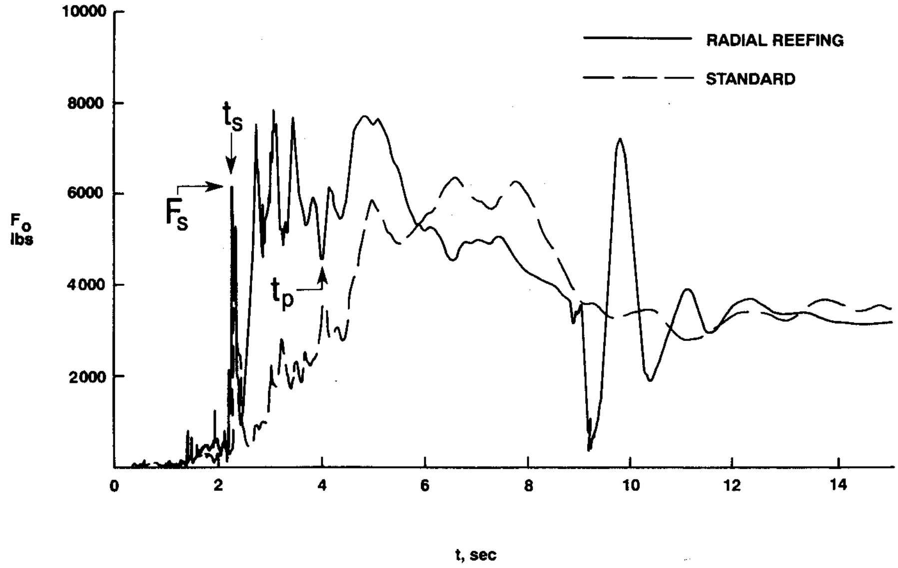

Fig. 6 Comparison of the opening force between a standard G-11 and a radial reefed G-11 (r = 25%).

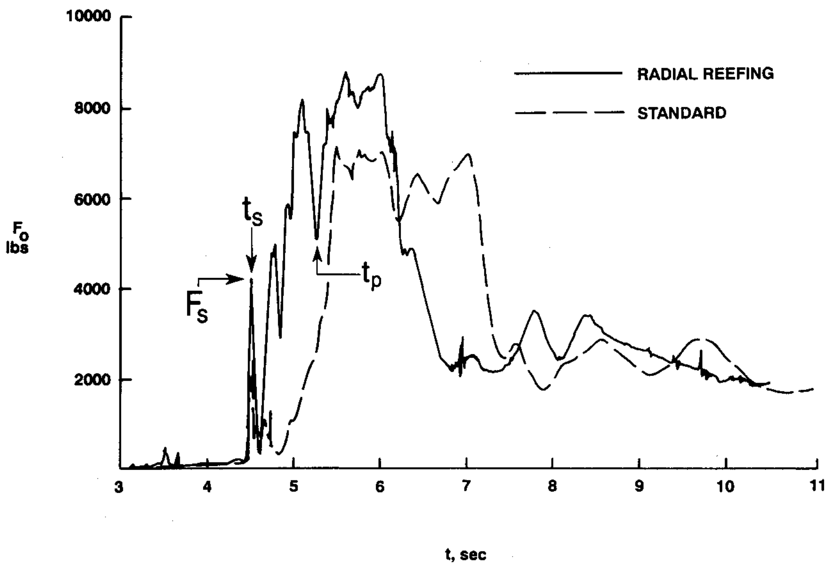

Fig. 7 Comparison of the opening force between a standard G-12 and a radial reefed G-12 (r = 25%).

pyrotechnic cutter is installed at point P to tie points P and P′ together so that the canopy remains radial reefed during early opening. To enhance the effect of radial reefing, an 80-lb breaking strength line is used to tie the canopy at 3 ft above point A′ (Fig. 3a). The radial reefing procedure is now completed. The parachute is then packed in a G-12 deployment bag using standard procedures.

As mentioned earlier, the main purpose of radial reefing is to form a large stiff canopy mouth during canopy snatch and to avoid canopy enfolding. By radial reefing the selected gores, a considerable amount of canopy fabric is puckered, thereby decreasing the excess fabric during early inflation and avoiding canopy enfolding. Between each two adjacent reefed radials, e.g., radials no. 1 and 5 in Fig. 2, the three radials and the four associated gores are not reefed. Therefore, during canopy snatch, as soon as the lower part of canopy is exposed to the incoming airstream in the horizontal position, a fabric pocket near the skirt is formed by the four gores between radials no. 1 and 5. Similarly, 15 other fabric pockets are also formed simultaneously between the adjacent reefed radials. The looseness of the suspension lines near the skirt and the 80-lb line tie at the canopy (Fig. 3a) further enhance the formation of these pockets. The 16 fabric pockets together form a large stiff mouth for efficient airflow and early positive canopy inflation. This is depicted in Fig. 3b. By increasing r, the size of the mouth opening and its formation rate can be increased, thereby decreasing the canopy inflation time. Once the large stiff mouth is formed and the canopy is well inflated, the canopy can be disreefed by firing the pyrotechnic cutter at point P (Fig. 3a).

In addition to r, the formation of the fabric pockets is also influenced by n_g. This number is determined by n_t and n_p desired. These three variables are related as follows. For the current G-12, $n_p = n_t/n_g = 64/4 = 16$. Although n_g and r are independent, they are related through the desired requirement that the skirt length of n_g (AB in Fig. 2a) and the reefed radial distance (AA′ in Fig. 2a) to be in the same order of magnitude. This desired requirement ensures well-formed pockets. For the current G-12 parachute, AB = 12.6 ft and AA′ = 8 ft.

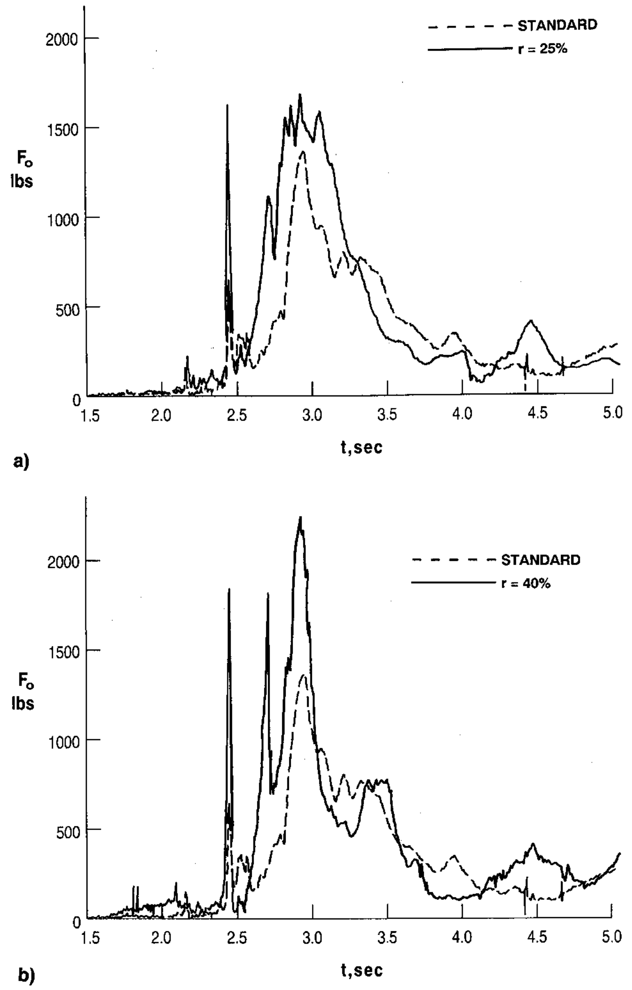

Fig. 8 Comparison of the opening force between a standard T-10 and a) a T-10 radial reefed at r = 25% and b) a T-10 radial reefed at r = 40% (payload weight = 220 lb).

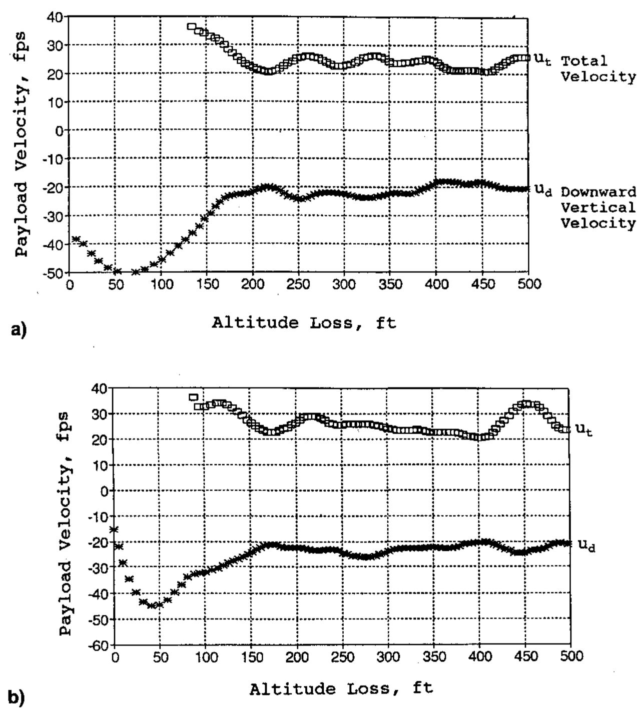

Fig. 9 Comparison of the altitude loss between a) a standard T-10 and b) a radial reefed T-10 (r = 25%).

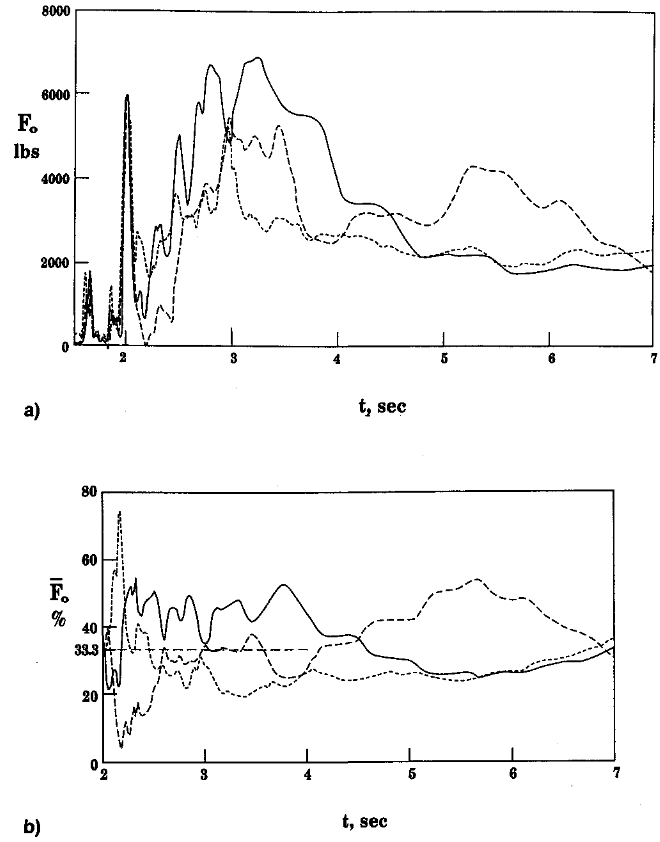

Fig. 10 Measured opening forces of a three G-12 cluster using both radial reefing and line reefing methods: a) opening force measurements and b) opening force distribution among the three parachutes (r = 25%).

Although a G-12 parachute has been used to illustrate the details of the radial reefing method, it is a generic method that can be applied to all circular parachutes.

Full-Scale Tests

The radial reefing method was investigated first using scale model parachutes in a wind tunnel, and ultimately verified by full-scale testing using Army G-12 and G-11 cargo parachutes, and T-10 personnel parachutes.

Figure 4 shows the opening sequence of a G-11 parachute radial reefed at r = 25%. As designed by the radial reefing method, at canopy snatch (photograph no. 3 from left in the top row), a large, stiff mouth is already formed for early and positive canopy inflation. This is more clearly shown in Fig. 5, which shows an enlargement of that picture. The resemblance between Fig. 5 and Fig. 3b is evident. On the other hand, at canopy snatch, the standard G-11 parachute is hardly inflated (picture no. 3 from the left in the top row of Fig. 1). After the large stiff mouth is formed for the radial reefed G-11, the canopy continues to inflate rapidly and positively. The large pockets at the skirt are clearly shown in the last two rows of the pictures in Fig. 4. Comparison of the opening between the two G-11s is quantitatively shown by the measured F_o in Fig. 6. The fast and early opening of the radial reefed G-11 is clearly shown by the rapid rise in F_o immediately after F_s, whereas the rise in F_o of the standard G-11 is much slower. The decrease and increase of F_o between t = 9 and 10 s correspond to the disreef of the canopy (pictures no. 3 and 4 in the bottom row of Fig. 3). For this test, the reefing time was too long. Disreefing at four seconds should further shorten the opening time of the radial reefed G-11.

The radial reefing method was also applied to G-12 cargo parachutes and 35-ft-diam T-10 personnel parachutes. Similar to the radial reefed G-11 parachute, a large stiff mouth was

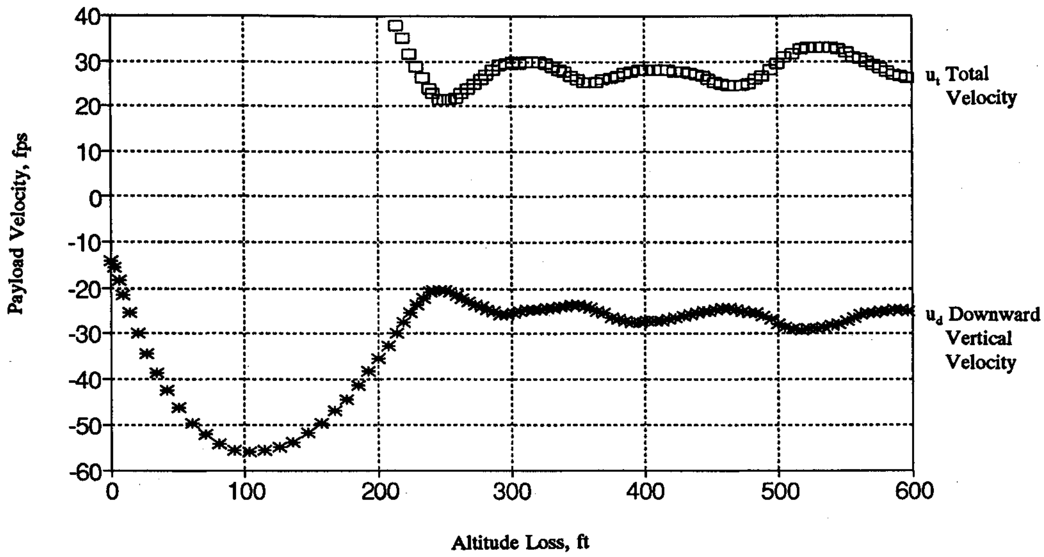

Fig. 11 Measured altitude loss for safe landing of a three G-12 cluster using both radial reefing and line reefing methods.

also formed at canopy snatch for both the G-12 and T-10. Figure 7 shows the comparison in F_o between a standard G-12 and a G-12 radial reefed at $r = 25\%$. The accelerated opening and shorter inflation time of the radial reefed G-12 are evident. Figure 8 shows the comparison in F_o between a standard T-10, and two radial reefed T-10s. The comparison shows that as r increases, the opening becomes more accelerated. At $r = 40\%$, the opening force and its rise rates are excessively high, resulting in canopy fabric damage. Test results show that r values between 25–30% are maximum radial reefing ratios without causing canopy fabric damage (unless fabrics stronger than the T-10 1.1 oz/yd^2 nylon and the G-12 2.25 oz/yd^2 nylon are used).

As expected, because of the early skirt opening formation at canopy snatch, the snatch forces of the radial reefed canopies are higher than those of the standard canopies (Figs. 6–8). The radial reefed canopies also have higher peak opening forces than the standard canopies. Examination of the measured opening force profiles and the high-speed movies of the tests show that the opening of the radial reefed parachutes is in two stages. The formation of the fabric pockets and the time duration of the large stiff mouth correspond to the time interval between t_s and t_p in Figs. 6 and 7. After t_p, the pockets begin to separate from each other, allowing the upper part of the canopy to inflate. This is indicated by the rise in F_o after t_p. The overall opening is thus an accelerated and controlled two-stage opening, avoiding an undesirable single sharp peak opening force. The avoidance of a sharp peak opening force is particularly important for personnel parachutes.

As a result of the accelerated opening provided by the radial reefing method, the altitude loss for full opening of a radial reefed parachute is smaller than that of a standard parachute. Figure 9 shows the altitude losses (measured from the airplane vertically downward) of a standard T-10, and a T-10 radial reefed at $r = 25\%$ (both pilot-chute deployed). It is seen that the radial reefed T-10 first reaches the 20-ft/s vertical downward velocity (an acceptable criterion for payload landing[4]) after an altitude loss of 170 ft, whereas a larger altitude loss of 220 ft is required for the standard T-10. Therefore, radial reefing enables aerial delivery of a payload from a lower altitude above ground level.

The radial reefing method was also tested on clustered parachutes. Tests were conducted with a cluster of three 25% radial reefed G-12 parachutes carrying a 5500-lb payload. The tests were not as extensive as those for single parachutes, but test results were sufficient to show the merits of the radial reefing method. For the radial reefing method, because of the close proximity of the canopies during canopy snatch, the airspace in the skirt area for fabric pockets to form is not unlimited. If r is too high, the air pockets might be too large and interfere with each other among the canopies. Video coverage of the three 25% radial reefed G-12 cluster opening tests showed the 25% radial reefing ratio was slightly high; a smaller ratio of 20% might have been better. Nevertheless, fabric pockets were formed on all three canopies immediately after canopy snatch, although they were not as well formed as in a single canopy. Opening was positive for all three canopies. Typical random opening of a cluster, and excessive lead and lag opening were not observed. The overall opening is thus satisfactory, although it is not as excellent as that provided by the control opening method.[5]

To further improve and control the formation of the fabric pockets, the line reefing method[6] was found to be effective. This method involves tightly holding all the radial reefing lines together at 5 ft below the canopy skirt by a pyrotechnic cutter for 1 s after canopy snatch. This additional control synchronizes the formation of the fabric pockets among the three canopies, thereby resulting in a more uniform initial opening. Typical opening forces for the three G-12 cluster using the radial reefing and line reefing methods together are shown in Figs. 10a and 10b. In Fig. 10a, canopy snatch occurs at about $t = 2$ s. The radial reefing lines are tied and constrained from spreading by line reefing for 1 s from $t = 2$–3 s. During this time period, the two reefing methods combined together result in F_o, approaching the ideal distribution of 33.3% as shown in Fig. 10b. At the end of the line reefing, $t = 3$ s, the radial reefing lines are free to spread and further inflation continues. Thus, the initial opening, which is the critical time period for cluster opening, is well controlled. The net result is a controlled two-step opening as in the case of a single parachute discussed earlier. However, two methods are used simultaneously to achieve this result. This multiple method requirement is often necessary for clustered parachutes, particularly for clusters of large cargo parachutes.

As a result of the positive individual parachute opening in the three 25% radial reefed G-12 cluster, its altitude loss for landing[4] was consistent at about 250 ft as shown in Fig. 11. For a cluster of three standard Army G-12 parachutes using vent pull-down lines, its altitude loss was inconsistent around 300 ft.[7] These test results of the three G-12 cluster show that the radial reefing method has considerable promise for improved cluster opening and low-altitude airdrop application.

Conclusions

A radial reefing method has been developed and successfully tested using single and clustered full-scale parachutes. The method involves reefing of selected equally spaced radials using reefing rings and radial reefing lines. Test results of the method show the following:

1) Canopy excess fabric is puckered during early opening, thereby eliminating canopy fabric enfolding.

2) A large and stiff canopy mouth is formed during canopy snatch, thereby allowing early and positive canopy inflation.

3) As a consequence, the lead and lag opening problem of clustered parachutes is greatly reduced.

4) As a result of the accelerated canopy inflation, the altitude loss for payload landing is smaller than that of the same parachute without radial reefing.

5) Radial reefing ratio of 25% is a good starting point for applying the method to either a single parachute or a cluster of parachutes. The reefing ratio can be refined as testing progresses.

Based on the above results, the radial reefing method shows promises for low-altitude airdrop applications and clustered parachutes for heavy cargo delivery.

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