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New Technique for Parafoil Inflation Control

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A new cell pull-down method for parafoil openings is being developed at the Natick Soldier Center. Rigging procedures of the method involve pulling down either the end cells or the center cells of a parafoil toward the payload by reefing the suspension lines. Flight tests on a 220- and a 500-ft^2 parafoil show that this new method provides a controlled, staged inflation of the parafoils and is a viable parafoil inflation method that will provide simple rigging procedures and low opening forces.

Introduction

THE technology of ram-air flexible gliding wings (parafoils) is currently being pursued actively for future Army precision aerial delivery of personnel and cargo.[1] The opening process of a parachute, either a round parachute or a rectangular parafoil, is a critical phase for its successful performance. Various techniques for inflation control during canopy opening is well documented by Knacke.[2] More recent inflation control methods for round parachutes are presented by Butler and Crowe[3] and Lee.[4]

The opening of a parafoil is a rapid and chaotic process that often results in high and unacceptable opening forces. Some studies[5,6] are currently being conducted to investigate the opening process and to model the fabric/flow interaction. Because of the rapid opening process, some devices are needed to control the cell inflation and canopy opening processes to decrease the opening force to an acceptable level. Currently sliders[7] are used to regulate the inflation of personnel parafoils, and a staged reefing deployment method[1,8] is used to control the inflation of large cargo parafoils. These two inflation control methods for parafoils are shown in Figs. 1 and 2, respectively, by using a seven-cell parafoil. Figure 1a shows the slider beneath the closed cells immediately after canopy deployment. As the cells start to inflate and the canopy expands, a downward force acts through the suspension lines and pushes the slider downward. This downward force is counteracted by the upward drag force on the slider. Through this force interaction, a properly designed slider restrains the parafoil from rapid opening and slides down the suspension lines at a proper speed (Figs. 1b–1d), thereby decreasing the opening force. However, the slider is a passive device that does not provide active inflation control. Details of slider performance are currently being investigated by Potvin[7] (also see Ref. 1).

The staged reefing deployment method uses a large number of line loops on the canopy to reef the cells in the canopy chord and span directions. Many pyrotechnic cutters are also required to disreef and stage the opening process, as shown in the simplified schematics in Fig. 2. The complicated packing procedure of this method is labor intensive and time consuming.[1,8] However, this is the only available opening method for large cargo parafoils. It is constructive to develop a new alternative opening method that will provide simple rigging procedures and low opening forces. This paper presents a new parafoil opening method[9] currently being developed at the Natick Soldier Center.

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Method Description

It is common knowledge that the cells of a parafoil have to be inflated in stages to minimize the opening force and to avoid canopy damage. The proposed opening method is based on this same requirement. However, the way staged inflation is accomplished in this new method is different from the two methods just mentioned. Here, the end cells of the canopy are naturally closed by pulling them down toward the payload using the suspension lines. The result of this simple rigging procedure is a streamlined teardrop canopy shape (Fig. 3b) that has low drag forces (opening forces) during initial canopy opening. Alternatively, the center cells of the canopy can also be pulled down for staged inflation (Fig. 4). Hence, the name of this new method is called the cell pull-down method. Details of the method are presented in the following paragraphs.

The cell pull-down method is shown in Fig. 3 using a seven full-cell parafoil as an example. Figure 3a shows the front view of a fully inflated seven full-cell parafoil. The seven cells are designated C1–C7. There are eight groups of suspension lines shown, L1–L8. Each group has two sets of lines, one supporting the front and one supporting the back of the cell in the chord direction (Fig. 3c). Point I is the end of the cascaded part of the suspension line group L1 at the left end. Lines JK and LM are the risers. Again, there are two risers in JK, one for the front set of suspension lines and one for the back set, and similarly for LM.

The rigging of the present inflation method simply involves pulling down point I toward point J to reef line IJ, thereby pulling the right-side cells C5, C6, and C7 down, as shown in Fig. 3b. The reefing of IJ is secured by reefing line 1 that connects I and J. The same rigging procedures (reefing line 2) is also applied to point N to pull down the left side cells C1, C2, and C3. Line loop Q is used to secure the two end loops of reefing lines 1 and 2 (J and M). Line loop Q is threaded through a pyrotechnic cutter R. Figure 1b shows the front view for clarity and Fig. 1c shows the right-side view of the canopy. Identical rigging procedures are also applied to the back suspension line I′J′ (and M′N′ on the left side). The same line loop Q and cutter R are used to secure the reefing of I′J′ and M′N′. Therefore, IJ, I′J′, MN, and M′N′ are reefed and released by the same line loop Q and cutter R, respectively.

The result of this cell pull-down procedure is that when the rigged parafoil comes out from the deployment bag, the shape and movement of the canopy fabric are well controlled, which leads to the formation of a streamlined teardrop shape, as shown in Fig. 3b. Concurrently, the top cells, C3, C4, and C5, begin to inflate while the end cells remain closed. This process and shape produce low drag forces and result in low opening forces. Once the top cells are well inflated and the teardrop shape is formed, cutter R is fired to release points I and N and the end cells. The end cells subsequently rise toward the center cells and inflate to complete the opening process. The canopy finally becomes fully inflated, as shown in Fig. 3a.

A proper amount of suspension line reefing or amount of end-cell pull-down is required to form an optimum streamlined teardrop shape for the canopy. An insufficient amount renders the method

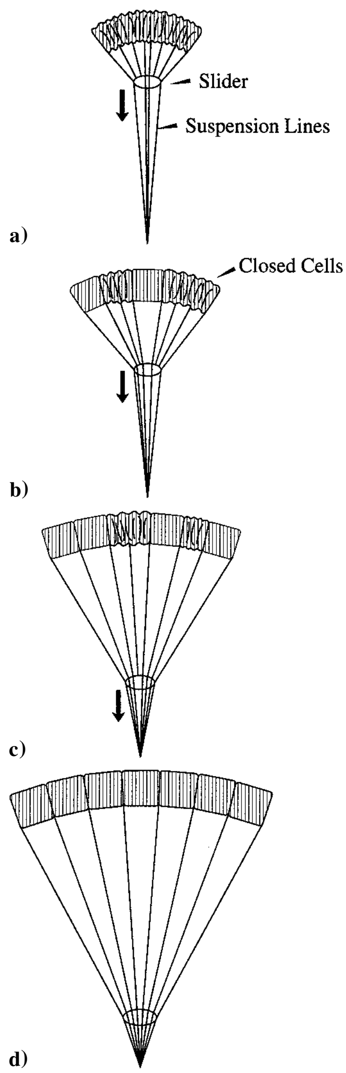


Fig. 1 Schematics of slider method.

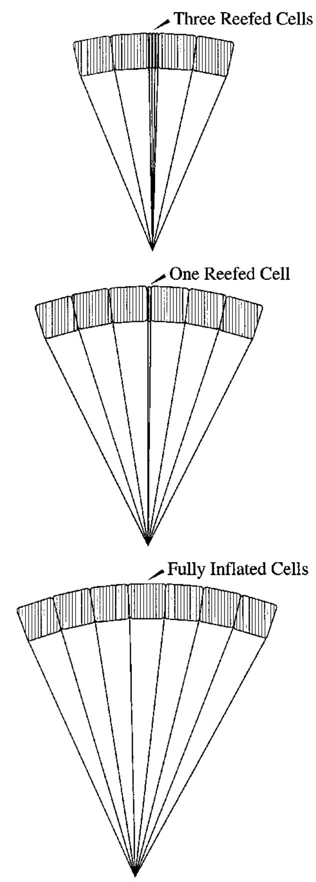


Fig. 2 Schematics of staged reefing method.

Table 1 Properties of parafoils[a]

Parafoils, ft^2	Number of cells	Wing span, ft	Chord length, ft	Suspension line, length, ft
200	7	18	9	11
500	9	34	13	21

[a]Low porosity fabric.

ineffective, and an excessive amount results in center-cell collapse. Full-scale tests of a seven-cell personnel canopy show that 45% reefing of the suspension line (11 ft long) produces good inflation results, that is,

$$1 - [\mathrm{IJ\ (reefed)} + \mathrm{HI}]/[\mathrm{IJ\ (unreefed)} + \mathrm{HI}] = 45\%$$

Because it takes time for the canopy to form the teardrop shape, time delay of the cutter is also important. For the seven-cell personnel parafoil, a 4-s cutter is shown to be ample.

Instead of pulling the end cells down, the center cells can also be pulled down to form a T-shaped canopy, as shown in Fig. 4a. The center cells can be conveniently pulled down by pulling points P and O (Fig. 4a) of the center suspension lines toward points J and M, respectively, to reef the suspensions lines. The result of center-cell pull down is that the canopy forms a T shape after the canopy comes out from the deployment bag. The end cells now inflate first (Fig. 4a). On the release of the reefed suspension lines by the cutter, the center cells will then rise and inflate to complete the opening process. Because a T shape has a higher drag force than a teardrop shape, the center-cell pull-down method produces higher opening forces than those of the end-cell pull-down method. However, the shape and the movement of the canopy fabric after canopy snatch are also well controlled to form the T shape.

For a larger parafoil with more cells, the pull-down cells in either end-cell pull down or center-cell pull down can be released in steps to control the inflation in an orderly manner. This can be done conveniently by releasing the reefed suspension lines in steps with two or more pyrotechnic cutters. Another approach is to combine the end-cell and center-cell pull-down methods to form an M-shaped canopy. In this geometry, two groups of top cells will be inflated first. Then the center cells and end cells can be released simultaneously or in steps to complete the opening process.

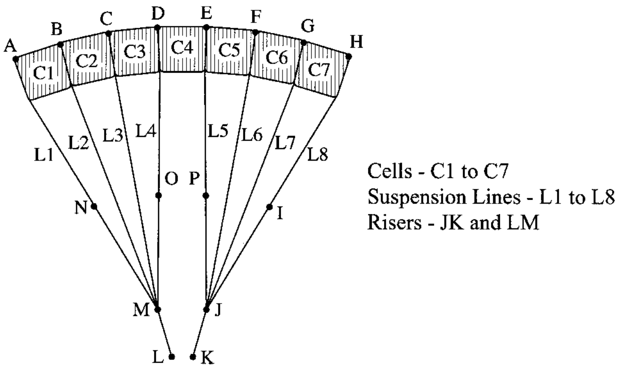
Test Results

The concept of center-cell pull down was first examined in a wind tunnel at Natick using a 100-ft^2 parafoil. The wind tunnel was too small for inflation study on the parafoil. Only the feasibility of forming a T-shaped canopy was examined. Using the center-cell pull-down procedure, an inflated T-shaped canopy as shown in Fig. 5 was achieved. Once the feasibility was demonstrated, outdoor testing followed.

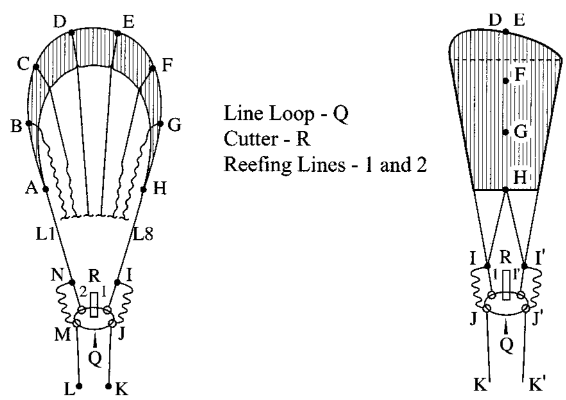
A remote-control ultralight aircraft with a payload capacity of 500 lb was used for the testing at the Sudbury drop zone near the Natick Soldier Center. A 220-ft^2 personnel parafoil with a 150-lb payload and a 500-ft^2 lightweight cargo parafoil with a 200-lb payload were used for the testing. Properties of these two parafoils are shown in Table 1.

In all of the tests, the aircraft speed was about 40 mph at load release from an altitude between 500 and 800 ft above ground level. An 8-ft static line was used to deploy a 40-in.-diam pilot chute, which deployed the parafoil at about 50 fps.

A series of inflation tests were conducted on the 220-ft^2 parafoil to investigate the cell pull-down method. Additionally, tests with a slider provided by the parafoil manufacturer and tests without the



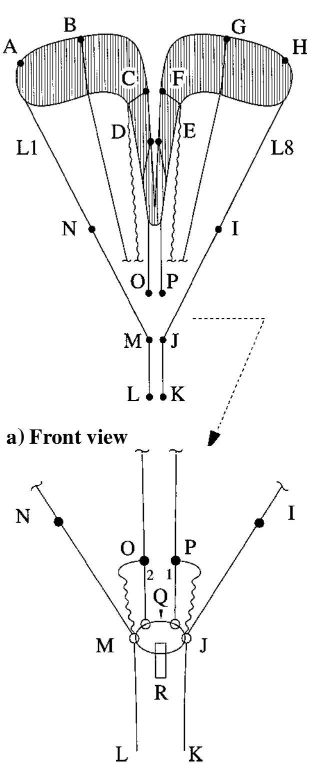
a) Front view of a fully inflated seven full-cell parafoil



a) Front view of cell pull-down method

b) Side view of cell pull-down method

Fig. 3 Schematics of end-cell pull-down method.



a) Front view

b) Side view

Fig. 4 Schematics of center-cell pull-down method.

Fig. 5 Photograph of T-shaped canopy using center-cell pull-down method.

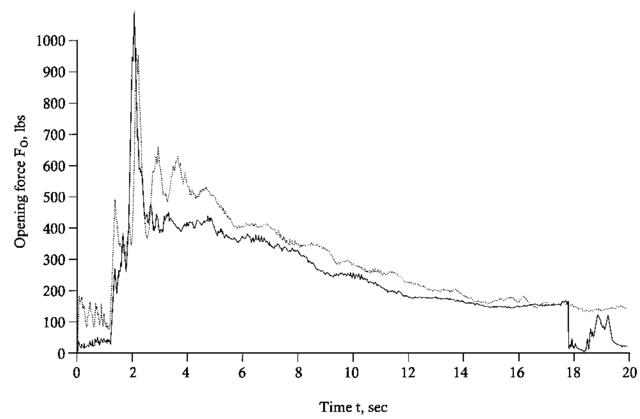


Fig. 6 Opening force from two tests of seven-cell parafoil without the slider.

slider were also conducted for comparison. A load cell was used on the main riser of each parafoil to measure the total opening force. The force was measured and recorded on a data recording system on the payload, and the data were down loaded on a personal computer after each test. Figure 6 shows the opening forces of two tests without the slider. Without the inflation control provided by the slider, the opening was extremely rapid and resulted in a sharp peak opening force of about 2000 lb (13 g). When the slider was used to restrain the cell inflation and canopy opening, the opening force was less rapid, and its peak value was reduced to 700 and 880 lb (4.7 and 5.5 g) as shown in Fig. 7 from two tests.

The end-cell pull-down method as described earlier was applied to the 220-ft^2 parafoil. Various amounts of end-cell pull down were obtained and tested by varying the amount of suspension line reefing. As mentioned earlier, 45% of suspension line reefing was the optimum value that resulted in a well-formed teardrop shape during initial cell inflation. Three tests were conducted with 45% suspension line reefing. Opening forces from the three tests are shown in Fig. 8. Time t =5.5 s was the instant when the pyrotechnic cutters were activated. During the opening process, a moderate amount of fabric fluttering was observed (see Fig. 9), most likely due to the low deployment speed. The fluttering is reflected in the fluctuation of the opening force profiles. It is expected that the degree of fabric fluttering will be decreased at higher deployment speeds (current tests on a 750-ft^2 parafoil deployed at 130 kn tend to support this).

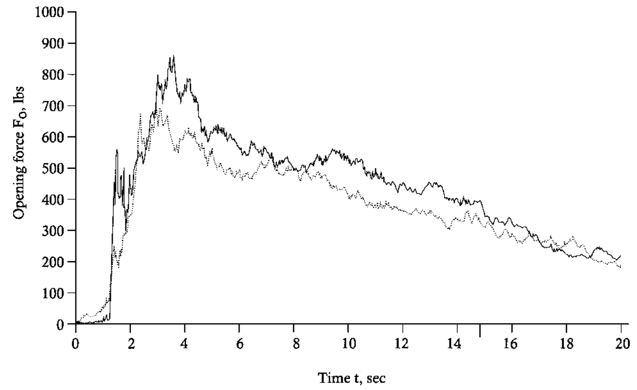


Fig. 7 Opening force from two tests of seven-cell parafoil with the slider.

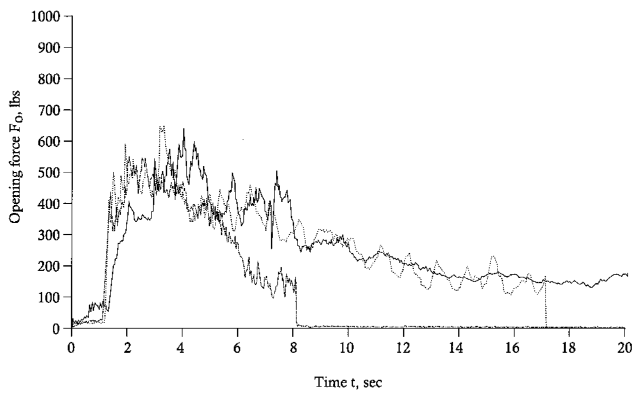


Fig. 8 Opening force from three tests of seven-cell parafoil with end-cell pull-down method.

In all of the tests, after canopy snatch, the parafoil went through a transitional phase to form a streamlined teardrop shape. At higher deployment speeds, this transitional phase is expected to be quicker and more positive (current 750-ft^2 parafoil tests also tend to confirm this). When this shape was formed, the three center cells were inflated first, while the remaining four end cells were closed. Immediately after the pyrotechnic cutter was activated, the end cells were released quickly, moved upward, and inflated. This second-stage inflation was relatively slow and did not result in a significant rise in the opening force. Because of the small size of the line loop Q (Fig. 3) and the opposite tension forces acting on it (canopy drag vs gravity), the end cells were released positively on activation of the pyrotechnic cutter. Through this controlled and orderly deployment and inflation process, time average of the opening force profile is relatively flat and low in magnitude. Comparison between Figs. 7 and 8 shows that the current new method provides lower opening forces, 30% on the average.

The center-cell pull-down method was also tested using the same parafoil. As designed, the canopy formed a T shape after deployment. Two end cells on each side were inflated, while the three center cells were closed, as shown in Fig. 4a. On firing the cutter, the center cells rose and inflated to complete the opening process. Because the T shape is not as streamlined as the teardrop shape, the opening forces of the center-cell pull-down method were higher than those of the end pull-down method, but comparable to those of the slider method.

The end-cell pull-down method was also successfully tested on the 500-ft^2 lightweight cargo parafoil. The opening sequence is shown in the series of photographs shown in Fig. 9. A 4-s cutter was also sufficient for a teardrop-shaped canopy to form. The transitional phase mentioned earlier is shown in the first two photographs of the top row. The third photograph shows the teardrop-shaped canopy. The fourth photograph shows the onset of the end-cell release after activation of the pyrotechnic cutter. The remaining photographs show the end-cell inflation and final complete opening of the parafoil.

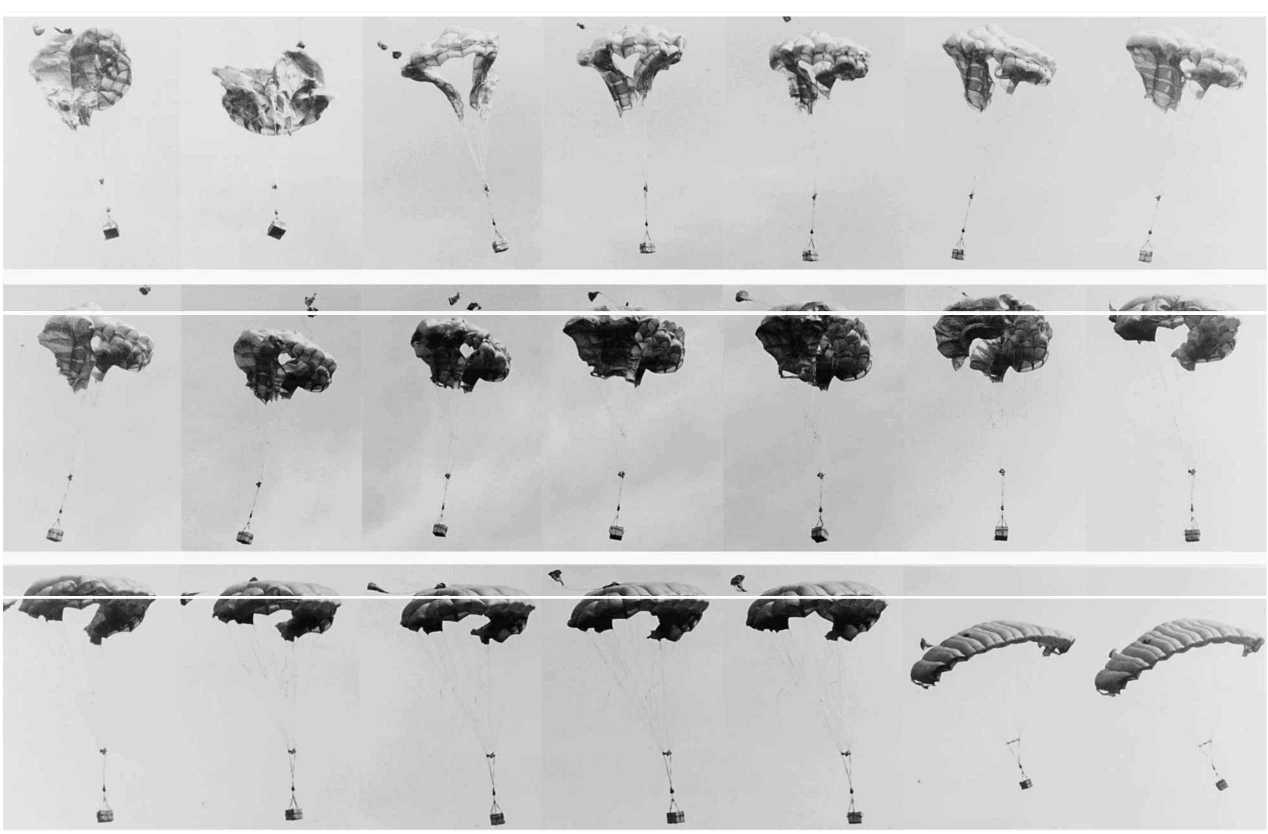


Fig. 9 Series of photographs of sequence of the 500-ft^2 canopy using end-cell pull-down method.

Although the end-cell pull down worked well, because of the larger canopy size, the combined end-cell and center-cell pull down to form an M-shaped canopy as described earlier may further improve the opening. Positive results are being achieved from current testing of the 750-ft^2 cargo parafoil using this combined end-cell and center-cell pull-down method.

Conclusion

A new cell pull-down method for parafoil inflation has been developed. The method consists of pulling down either the end cells or the center cells, or the combination of both groups of cells, depending on the canopy size, toward the payload by reefing the suspension lines. Flight tests have shown that this method is a viable method that will simplify parafoil rigging, canopy construction, and decrease opening forces. Testing of this new method on cargo parafoils is currently ongoing at Natick to further develop the method.

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