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Continuous Disreefing Method for Parachute Opening

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Although round parachutes have been used for airdrop for over 60 years, damage to canopy fabric and suspension lines still occurs during parachute opening due to the rapid canopy opening and the associated high opening force. Continuous disreefing of round parachutes to slow down the opening and decrease the peak opening force has been discussed in the literature, but no viable continuous disreefing method has ever been developed. In this paper, we present a practical, effective, and low-cost continuous disreefing method that does not use any external electrical or power source, only the opening force and the weight of the payload. The method was successfully demonstrated in a full-scale test from an aircraft using a 10.7-m (35-ft) diameter round parachute. The kinetic energy of the payload at parachute deployment of that test was 11 times higher than that of the standard deployment that the parachute is designed for. In spite of the severe deployment condition, no damage to the parachute was observed after ground impact.

I. Introduction

ROUND parachutes have been used for aerial delivery of cargo and personnel for over six decades. However, damage to canopy fabric and suspension lines still occurs during parachute opening. Damages are mainly due to the high air pressure inside parachute canopies and the high opening force on suspension lines. For U.S. Army airdrop of cargos, it is estimated that 10% of the 10,000 G11 Army cargo parachutes [30.5-m-diam (100-ft)] used annually suffer canopy fabric and suspension line damage.

Current research and development effort of military parachutes and airdrop systems are focused on lowering the threats to delivery aircraft and ground soldiers, and lowering the costs of one-time use systems for operations in remote areas and for humanitarian relief operations. These requirements are being addressed through the development of precision airdrop using guided parafoils deployed from high altitudes over 7.62 km (25,000 ft) above ground level [1]. However, their high costs have prompted the investigation of lower cost, steerable round parachutes [2,3]. In addition, round parachutes are also being considered for low-altitude, high-speed cargo airdrop and for one-time use low-cost airdrop systems. Parachute deployment from an aircraft at high altitudes and/or high speeds generates much higher opening forces than those at normal deployment conditions. Therefore, effective methods and techniques are needed to slow down the opening process and decrease the opening force of round parachutes.

The current U.S. Army method to control parachute opening is the skirt reefing method. Skirt reefing mitigates opening shock by providing a stepped opening process through the use of a finite length of reefing line feeding through a series of reefing rings attached along the full circumference of the canopy skirt (bottom edge). During initial opening, the reefing line restricts full opening of the canopy skirt and it opens only to the circumference formed by the reefing line. After a finite amount of time, a pyrotechnic cutter at the canopy skirt cuts the reefing line to allow the canopy to continue to full opening. Current G11 cargo parachutes use either two or four pyrotechnic cutters on each canopy at a cost of $90 per cutter. Very often, single-stage reefing is insufficient and multistages of reefing and disreefing are required. Multistage reefing/disreefing is costly and complicated. Therefore, although the theoretically best opening process available would be one that continuously reefs and disreefs the canopy using a very large number of reefing lines and pyrotechnic cutters, it is simply too complex and expensive to be practical.

Continuous disreefing of round parachutes has been discussed and analyzed in the literature, and a cumbersome electromechanical system has been attempted [4,5]. To date, no practical methods for continuous disreefing have been developed [6]. In addition, although the energy from the opening process has been identified as being available for doing useful work (e.g., to slow down parachute opening), no concepts or methods to effectively use this energy have been demonstrated. In this paper, we present a simple low-cost, nonpowered continuous disreefing method that uses the opening force and the weight of the payload to execute the continuous disreefing. This method was successfully tested and demonstrated in a full-scale airdrop test using a 10.7-m-diam (35-ft) flat circular parachute.

II. Description of Method

As mentioned earlier, the gravitational force of a payload and the opening force are two available sources for doing useful work during parachute opening. It is realized that during opening, once the reefing line is fully extended, it will be under tension due to the opening force. Concurrently, suspension lines will also be under tension, supporting the payload. If the tension force from the reefing line is directed downward toward the payload, the tension force will be acting directly opposite the downward gravitational force of the payload. If a frictional braking device is positioned and integrated as a section of a suspension line and pulled by these two opposite forces, the frictional force generated by the frictional brake can be used to control the release of the reefing line. If the frictional brake is designed properly, it can thus continuously disreef the parachute. Typically, the opening force and the reefing force of a given parachute system can be estimated. This information can be effectively used to guide the design of the frictional brake. The frictional brake can be made of inexpensive materials like elastic cable, Kevlar, or Spectra lines, etc. This forms the principle of the present low-cost, nonpowered continuous disreefing method.

A continuous disreefing design based on the aforementioned principle is shown in Figs. 1 and 2. In Fig. 1, the skirt of the canopy is reefed by the reefing line (RL). To direct its tension force toward the payload when the RL is fully expanded, the RL is extended

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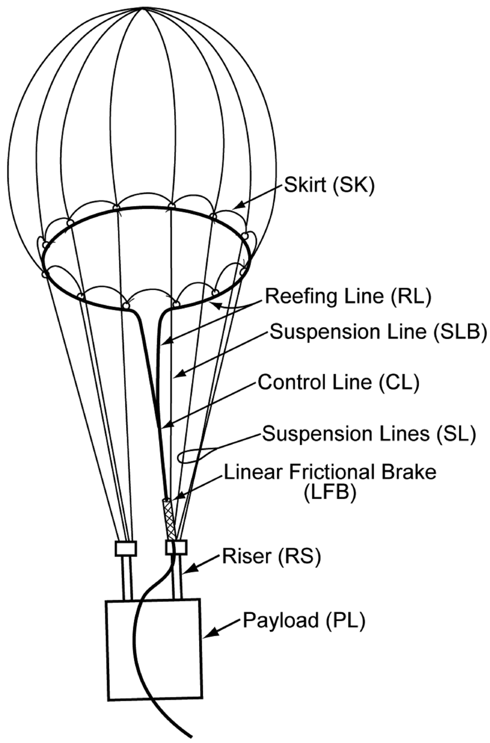


Fig. 1 Schematic showing the implementation of a continuous disreefing system on a round parachute.

downward and its two ends join together to form a single control line (CL). A self-releasing linear frictional brake (LFB) is positioned on suspension line (SLB) and becomes an integral part of SLB (see Fig. 2 for details). As shown in Fig. 2, the control line is fed into the LFB to form a simple sensing and control mechanism for the continuous disreefing of the parachute. As the canopy opens, the reefing line at the skirt expands and exerts an upward force and pulls the CL upward from the LFB. Simultaneously, the weight of the payload exerts a downward force through the riser and tightens the LFB. The frictional force generated by the LFB on the CL retards the release of the CL and the RL. A properly designed LFB will then be able to continuously disreef the canopy. Therefore, the frictional force generated by using the opening force and the weight of the payload are used to continuously disreef the canopy. This automatic feedback loop type of control exploits the available energy of the parachute system by means of a very simple mechanism and no external power is used. Although only one LFB is shown in Fig. 1, for a more uniform opening of a cargo parachute, two or more LFBs positioned in parallel can be used. Referring to Fig. 1, for a two LFB system, this simply means adding a second LFB to a suspension line that connects to the riser on the left-hand side. In addition, the reefing line will be divided into two equal halves and a second control line will be introduced to go through the second LFB. For the full-scale test of the 10.7-m-diam parachute, such a two LFB system was used.

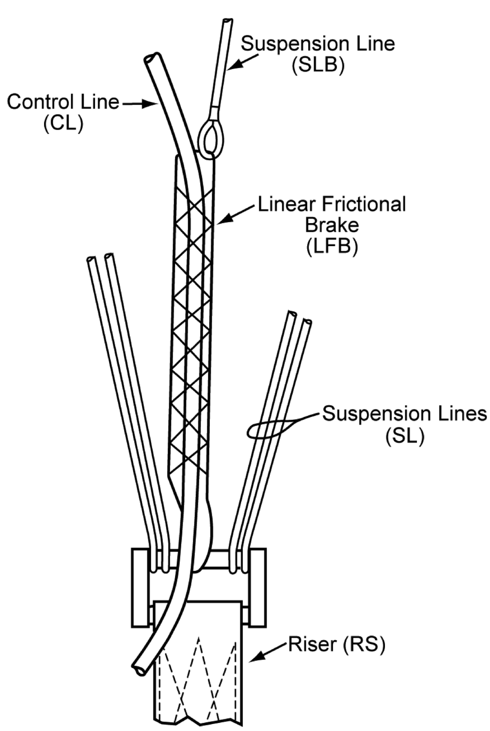


Fig. 2 Enlargement of the frictional brake device in Fig. 1.

For the continuous disreefing mechanism to be effective, the linear frictional brake has to be designed properly to be able to continuously disreef the parachute. The frictional braking force generated by the frictional brake has to be at an appropriate level to slowly and continuously disreef the control line and the reefing line. This frictional force is a function of the physical properties and dimensions of the materials for the outer brake liner and the inner control line. An experimental setup shown in Fig. 3 was used to investigate the line release characteristics of an LFB as a function of the materials of the LFB. In the setup, an LFB is hung from the ceiling by a line that simulates the suspension line. The other end of the LFB is connected to a line that connects to a brake force applicator. The brake force applicator provides a force that simulates a fraction (1/number of suspension lines if one LFB is used) of the payload weight to the linear frictional brake. A line that simulates the control line goes through the linear frictional brake. One end of the control line is connected to a weight that simulates the reefing force, and the other end is free to move.

Various combinations of control line materials (Dacron, Kevlar, and Spectra) and brake materials of the LFB (steel wire mesh, Kevlar, and Spectra), and different lengths of LFB [12.2, 15.2, and 20.3 cm (4, 6, 8 in., respectively)] were examined in this setup. A typical test involved applying a fixed force on the brake force applicator and slowly increasing the weight pulling the control line until the control line began to release from the LFB. Although this is a static test and does not exactly simulate the dynamic parachute opening process, some useful quantitative measurements were obtained to guide the design of the LFB. Based on some preliminary test results, a combination of Dacron control line and a 15.2-cm-long steel mesh LFB was chosen for the full-scale test of the 10.7 m parachute. The

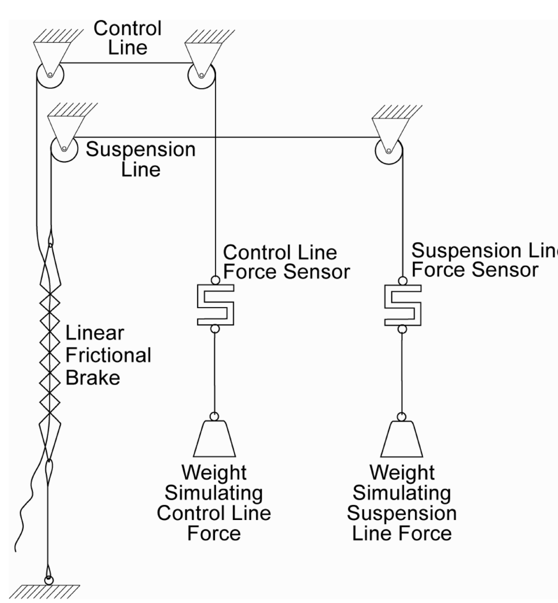


Fig. 3 Schematic of the laboratory test setup for testing of a linear frictional brake.

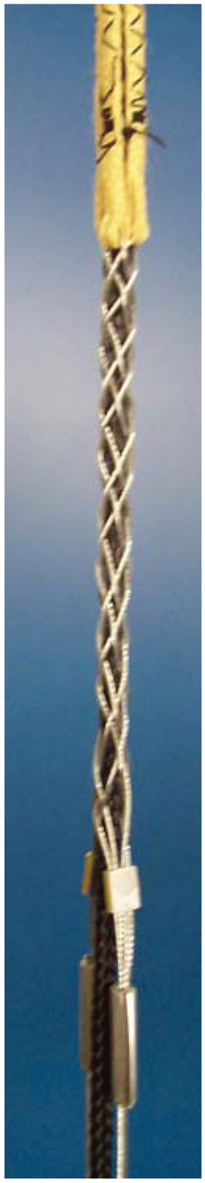
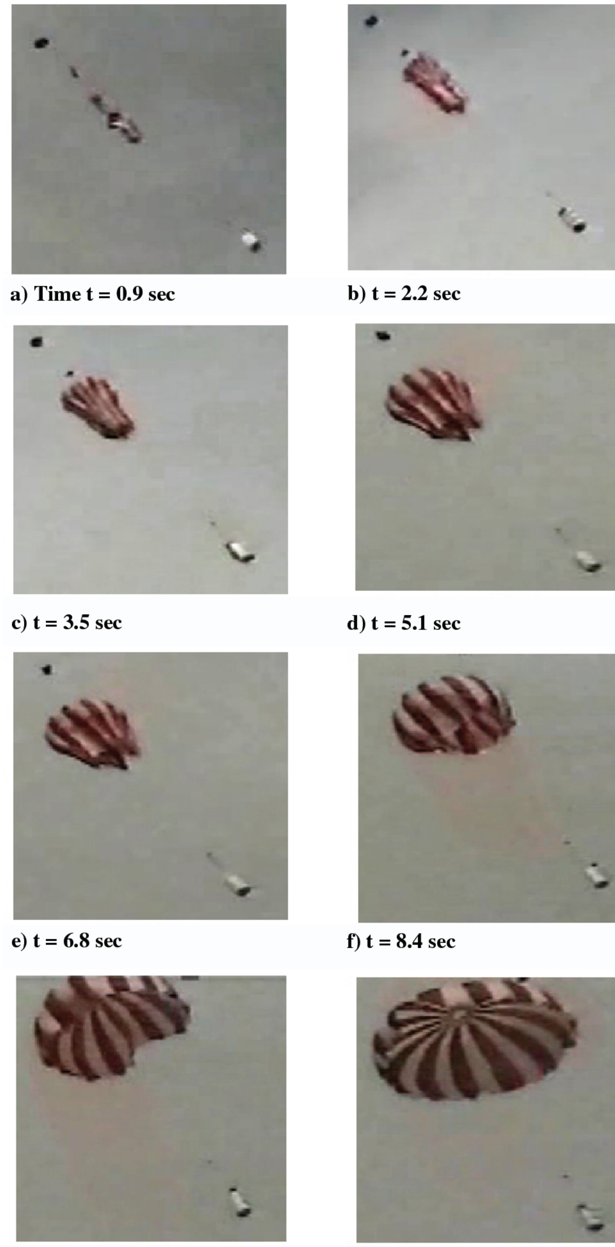


Fig. 4 Photograph showing the steel mesh/Dacron-control-line linear frictional brake used on the 10.7-m parachute flight test.



a) Time t = 0.9 sec **b) t = 2.2 sec** **c) t = 3.5 sec** **d) t = 5.1 sec** **e) t = 6.8 sec** **f) t = 8.4 sec** **g) t = 9.6 sec** **h) t = 10.5 sec**

Fig. 5 Opening sequence of the 10.7-m parachute using the continuous disreefing method.

cost of the LFB was only \$10. A picture of the Dacron/steel LFB is shown in Fig. 4.

III. Test Results

The 10.7-m-round parachute is designed to airdrop a 136-kg (300-lb) payload at a deployment speed of 100 kt. To demonstrate the exceptional capability and effectiveness of the present continuous disreefing method, an airdrop test with a much more severe deployment condition of a 283-kg (625-lb) load and 230-kt deployment speed was executed. The associated energy of this deployment condition was 11 times higher than that of the normal deployment condition that the 10.7-m parachute is designed for. The test result is described as follows.

The full-scale airdrop test was entirely satisfactory and demonstrated the capability and effectiveness of the continuous disreefing method. The opening sequence of the parachute is shown in the eight still photographs in Fig. 5, extracted from the video coverage of the test. The time t in Fig. 5 is the time measured from the instant, time zero, when the parachute was just extracted from the deployment bag. The opening sequence shows that the canopy was opened in a slow, orderly fashion without any damage. The expansion of the skirt area (beginning from Fig. 5d) after the top area of the canopy has been inflated is particularly slow as compared to the opening of other similarly sized round parachutes. This is clearly an indication of the result of the continuous disreefing mechanism. This slow opening and the successful test result expressed in terms of the measured opening force time profile is shown in Fig. 6.

The time in Fig. 6 is the real time of the test. The initial force rise at time $= 147$ s is the snatch force when the parachute was deployed from the parachute deployment bag. For a standard deployment, the snatch force would decrease sharply and then the opening force would rise rapidly when the canopy opens. The force behavior here is entirely different. Because of the continuous disreefing, the opening force drops slowly and continuously after deployment until full opening at steady descent without any sharp rises. It is noted that the opening time spans from 147 to 158 s, which corresponds to an opening time of 11 s. The extended long opening time results in a decreasing and low opening force profile without the high peak opening force normally observed. As a result, the entire system landed safely on the ground without any damage. For the 283-kg/230-kt deployment condition without this continuous disreefing mechanism, the opening force would be so severe that it

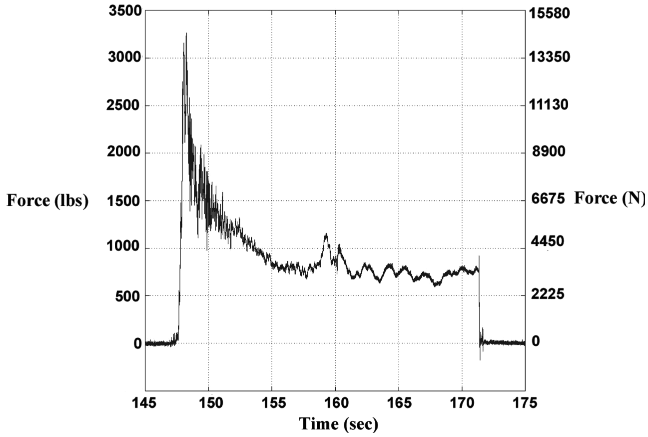


Fig. 6 Opening force of the 10.7-m parachute using the continuous disreefing method.

would cause catastrophic failure of the entire system in fractions of a second. In place of conducting such an airdrop test without the continuous disreefing mechanism, this opening force was estimated using the momentum-impulse theorem presented in [7,8]. The maximum opening force was calculated to be $\sim$66,800 N (15,000 lbs), or $24g$ for the 285-kg (625-lb) payload, a force that would definitely destroy the parachute. If the parachute were to survive, using the nondimensional inflation time ratio estimate [7,8], the opening time for such a test was calculated to be $\sim$1.1 s. Thus, the 10.5 s opening time using the continuous disreefing mechanisms is about 10 times longer. Alternatively, the nondimensional opening time $n = t_0 V_s / D_0$ ($t_0 =$ opening time, $V_s =$ snatch velocity, and $D_0 =$ constructed canopy diameter) can be calculated. The n values for the tests without and with the continuous disreefing mechanism are 10 and 95, respectively. The $n = 95$ is the highest in the history of parachute development and testing, to the best of the knowledge of the authors and a parachute expert in the field. These results have unequivocally demonstrated the superb capability of this simple, affordable, yet effective, continuous disreefing parachute opening method. A patent was awarded to this innovative method [9].

IV. Conclusions

For the first time, a simple, effective, and nonpowered continuous disreefing method for parachute opening has been developed and successfully demonstrated in a full-scale airdrop test. Because no external power is required and no significant weight and cost are added, this method is very practical and appealing to general parachute application. This continuous disreefing method is currently being considered for use on the U.S. Army's G12 (19.5-m-diam) and G11 round cargo parachutes, as well as with a number of parafoils. Other possible applications for this method include parachutes used for high-speed and high-altitude emergency egress from disabled aircraft in flight. These parachutes are part of an emergency ejection system and also reefed with pyrotechnic cutters. In addition, the method has application beyond the military because parachutes are also used by the firefighters of the U.S. Forest Service, other federal agencies, commercial companies in space exploration, and the general public in recreation and sport jumping.

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