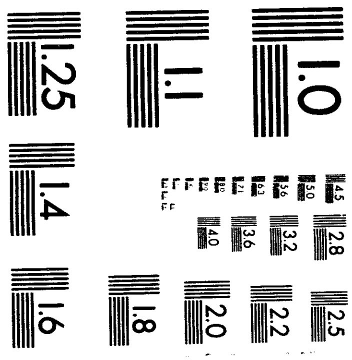

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Load limiting parachute inflation control

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ABSTRACT

Excessive deceleration forces experienced during high speed deployment of parachute systems can cause damage to the payload and the canopy fabric. Conventional reefing lines offer limited relief by temporarily restricting canopy inflation and limiting the peak deceleration load. However, the open-loop control provided by existing reefing devices restrict their use to a specific set of deployment conditions. In this paper, the sensing, processing, and actuation that are characteristic of adaptive structures form the basis of three concepts for active control of parachute inflation. These active control concepts are incorporated into a computer simulation of parachute inflation. Initial investigations indicate that these concepts promise enhanced performance as compared to conventional techniques for a nominal release. Furthermore, the ability of each controller to adapt to off-nominal release conditions is examined.

1. INTRODUCTION

Modern parachute systems are used in a variety of important applications including troop deployment, emergency air-drops, high speed vehicle braking systems, lay-down weapon systems, and aircraft personnel escape systems. Both the parachute fabric and the payload can be damaged due to excessive deceleration forces that result from high speed deployment. Traditionally, one or two reefing lines are employed to limit peak force level by temporarily constraining the canopy opening. Explosive cutting devices discard the reefing lines at predetermined times, eventually permitting full inflation of the canopy. However, these systems provide sub-optimal deceleration profiles and cannot easily adapt to varying deployment conditions. Consequently, excessive deceleration loads or an increased inflation time results from off-nominal deployment conditions.

An early approach to remedy this situation was developed in the 1950s at the University of Kentucky and centered on a mechanical clutch reefing device.[1] Mounted at the junction of a suspension line and the canopy, this device permitted continuous reefing line deployment while the tension in the suspension line remained at an acceptably low level. If the tension exceeded the critical load designated by the size of the spring separating the clutch faces, the clutch teeth engaged and reefing line deployment was immediately halted. Further deployment was permitted after the tension dropped to an acceptable level and the clutch disengaged. Although early test flights demonstrated great potential for this approach, the device suffered from limited line length and occasional line breakages.

Recently, a number of alternative load-limiting concepts have emerged. Webb introduced the use of stretch fabrics and auxiliary parachutes to effectively modulate inflation rates.[2-4] The stretch fabric provides the canopy with variable permeability while the auxiliary parachute restrains the opening of the main canopy. Hennings introduced a novel reefing concept that increases inflation rate for low speed deployment and decreases the inflation rate during high-speed deployment.[5] This concept is particularly useful for low altitude deployments at variable speeds, such as the conditions encountered in emergency escape systems. Lee introduced an alternative radial reefing technique useful for large canopies which are subject to enfolding and slumping, making traditional reefing concepts impractical.[6]

Although each of the previously mentioned concepts have demonstrated their utility in certain applications, they have limited adaptability due to their passive nature. Therefore, variations in the deployment conditions relative to the nominal can significantly degrade the system performance. However, application of the emerging adaptive structures technologies to parachute inflation control promises improved performance over a wide range of release conditions. In this paper, the use of active control for modulating parachute inflation is explored using three approaches. In the first approach, a conventional reefing line is incrementally extended by severing shunts that limit the effective reefing line length. The second approach uses a disk brake to slow the continuous deployment of a reefing line from a rotating spindle. The third technique differs markedly from the first two in that it utilizes a sliding ring to limit the effective suspension line length. This approach indirectly limits parachute inflation by altering the canopy full-open configuration.

A previously developed single-degree-of-freedom model of parachute inflation is the platform for this current study of active inflation control.[7] Section 2 of this paper discusses the parachute inflation model which includes provisions for a single reefing line operated in an open-loop fashion. In section 3, the load-limiting inflation control concepts are integrated into the computer model. In section 4, the active controllers are used to limit the peak deceleration loads experienced by a payload during a high speed deployment. These simulations demonstrate the superior deceleration profiles provided by active control as compared to the traditional approach. Furthermore, the performance advantages of active control are summarized through two performance metrics that represent a desire for a soft, vertical impact of the payload. A range of drop altitudes is revealed in which active disreef control predicts improved performance as compared to traditional reefing techniques. Some concluding remarks are given in section 5.

2. PARACHUTE INFLATION MODEL

Typical parachute designs consist of a number of suspension lines connecting the payload to the canopy which generates deceleration forces by presenting a substantial drag area to the airflow. During deployment, the total deceleration force increases until the canopy is fully inflated. Then the deceleration force steadily decreases as a consequence of the reduction of system velocity along the flight path. As shown in Figure 1, the peak load can be limited by employing a reefing line in an open-loop fashion. The reefing line is threaded through eyelets which run the circumference of the canopy leading edge and controls the loading by limiting the canopy drag area presented to the airstream. After sufficient deceleration has occurred, the reefing line is discarded by means of explosive cutters, and the parachute is permitted to inflate to its full-open configuration. In the absence of accurate numerical prediction capabilities, the appropriate reefing line length and cutting time are quite often determined through a considerable amount of testing. However, these quantities depend on specific deployment conditions and can produce poor performance in service where exact release conditions cannot be specified.

In an effort to reduce the dependency of parachute design on extensive flight testing, Macha recently developed a simple, single degree-of-freedom computer model of parachute inflation that is applicable to ribbon and ringslot canopies over a wide-range of release conditions.[7] Recognizing the limitations of CFD methods, Macha based his model on the principle of conservation of momentum as applied to canopy radial motion. Neglecting the relative motion between the canopy and the payload as well as the drag induced by the payload, the radial motion of the canopy is described by

$$(m_p + m'_r)\frac{d^2R_c}{dt^2} = \frac{1}{2}\rho C_r S\left(U^2 - \left|\frac{dR_c}{dt}\right|\frac{dR_c}{dt}\right) - \rho k_r \frac{dR_c}{dt}\frac{dV}{dt} - F_x\frac{1+\sin\theta}{\cos\theta} - 2\pi T_{rl} \qquad \text{(EQ 1)}$$

in which m_p is the parachute mass, m'_r is the added radial mass, R_c is the canopy radius, ρ is the air density, C_r is the radial force coefficient, S is the reference area, U is the velocity along the flight path, k_r is the radial added mass coefficient, V is the enclosed canopy volume, F_x is the aerodynamic force along the flight path, θ is the suspension line angle relative to the flight path, and T_{rl} is the reefing line tension. The above inflation equation is coupled to the trajectory through the flight path equations given by

$$(m_b + m_p + m'_x)\frac{dU}{dt} = (m_b + m_p)g\sin\gamma - \frac{1}{2}\rho C_x S U^2 - \rho k_x U\frac{dV}{dt} \qquad \text{(EQ 2)}$$

$$U\frac{d\gamma}{dt} = g\cos\gamma \qquad \text{(EQ 3)}$$

where m_b is the payload mass, m'_x is the axial added mass, g is the gravitational acceleration, γ is the flight path angle measured downward from the horizon, C_x is the axial force coefficient, and k_x is the axial added mass coefficient.

In the previous equations, the added mass terms account for the nonsteady portion of the drag forces and are related to the inertia of the air in the canopy. These terms depend on the instantaneous canopy shape as well as the inflation history and are evaluated on the basis of flight test data that has been included in the computer program. The axial and radial force coefficients are smooth functions of the canopy radius and were derived from wind tunnel data. Finally, the reefing line tension depends on the elasticity of the reefing line and the instantaneous canopy radius according to

$$T_{rl} = \left(\frac{2\pi R_c - L_{rl}}{L_{rl}}\right)\frac{P_u}{\varepsilon_u} \qquad \text{(EQ 4)}$$

in which L_{rl} is the unstretched reefing line length, P_u is the ultimate breaking strength of the reefing line, and ε_u is the strain at failure. A detailed development of the entire inflation model is contained in reference 8.

3. LOAD-LIMITING INFLATION CONTROL

A fixed length reefing line combined with a time delay cutter can successfully limit peak payload deceleration force under ideal deployment conditions. The length of the reefing line limits the peak load experienced during reefed inflation while the cutting time affects the peak load experienced during full inflation. Using this single line approach, the most rapid deceleration is achieved by matching the peak loads to the constraint load. However, this open-loop control cannot easily adapt to variable deployment conditions. In addition, the time between the completion of the reefed inflation and reefing line cutting represents a loss of system performance since the peak load drops below the maximum permitted load as the system decelerates. Ideally, the reefing line length would continuously increase in response to the payload deceleration to maintain the load at the maximum permissible load. In this way, the deceleration rate is maximized without causing harm to the payload. A disreefing system based on deceleration feedback control has the potential for providing near-optimal performance as well as an ability to adapt to varying deployment conditions.

3.1 Reefing Line Shunts

The simplest approach to developing a feedback controller for disreefing involves closing the loop of the existing open-loop system. Sensing and processing hardware can be implemented to command a cutting of a fixed length reefing line when the deceleration load drops below a predetermined set load. Such a control introduces a degree of adaptability for a modest increase in complexity, however it offers no improvement in system performance for nominal deployment conditions. The performance of this closed loop system can be enhanced by using multiple reefing lines or a single line with multiple shunt-type line limiters as shown in Figure 2. Sequential severing of the shunts permits incremental increases in the effective reefing line length, offering enhanced control over the single length case. A simplified control algorithm can be employed to signal a cut when the deceleration force drops below a designated level.

When only a few shunts are employed, preliminary experiments may be necessary in order to determine the lengths of the reefing line and the cut load needed to satisfy the peak deceleration constraint for a given deployment. Consequently, adaptability is limited to a region about the operating condition and depends on the number of shunts used. For example, application of a given design to a lower speed deployment can result in uncut reefing lines and partial inflation due to low deceleration forces. A higher order controller can mitigate this difficulty by sending a cut signal when the deceleration load peaks regardless of its magnitude. In contrast, an excessive deployment speed can result in deceleration forces that surpass the allowable limit. Since this is caused by excessive reefing line lengths, the controller cannot be designed to compensate for this difficulty. Instead, the solution to this problem requires the use of shorter reefing lines. This approach can be extended to the limiting case in which the finite number of shunts is replaced by a shunting web. A knife edge is permitted to continuously sever the webbing and extend the reefing line while the deceleration load remains below the acceptable limit. Exceeding the set point would initiate the movement of a sheath to cover the knife edge, thus preventing further reefing line deployment. When the load drops below the set point, the sheath is removed and the reefing line is again deployed. Such a system does not require advanced determination of reefing line lengths and could therefore be used over a wide range of release conditions without excessive preliminary analysis. However, only a finite number of shunts are considered in this paper.

3.2 Disk brake

In this section, a conceptual design for a canopy-mounted braking device is presented. The brake system contemplated herein is driven by a piezoelectric actuator with stroke magnification, an electrical/mechanical solenoid, a hydraulic fluid, or a pneumatic system as shown in Figure 3. Feedback control is used to modulate reefing line deployment from the attached spindle, producing results similar to the mechanical clutch described in reference 1. As in the previous concept, payload deceleration is monitored using an accelerometer or a suspension line mounted load cell and is fed into a digital processor. Instead of the single switch line control algorithm described in the previous section, dual switch line logic modulates reefing line payout by demanding full braking authority when the deceleration load exceeds a high switch point. The brake remains engaged until the deceleration falls below the low switch point. To minimize the needed breaking authority, capstans are used to frictionally reduce the reefing line tension at the spindle. An initial slack in the reefing line is included in the simulation to permit unimpeded inflation during the initial phase of deployment.

Two equations are used to describe the interaction of the parachute inflation and the disk brake controller. The rotational motion of the reefing line spindle is described by

$$I\dot{\omega} + d_b\omega + M_b \operatorname{sgn}\omega = rT_r e^{\mu\beta} - M \qquad \text{(EQ 5)}$$

where I is the disk mass moment of inertia, ω is the disk angular speed, d_b is the bearing damping coefficient, M_b is the constant bearing frictional moment, r is the radius of the disk, T_r is the tension in the reefing line, μ is the capstan coefficient of friction, β is the capstan angle of wrap, and M is the control moment supplied by the brake. A critically damped second order transfer function is used to model the transition of the brake moment when a switch command is signaled. This simple model is described as

$$\frac{M(s)}{M_c(s)} = \frac{\omega_n^2}{s^2 + 2\omega_n s + \omega_n^2} \qquad \text{(EQ 6)}$$

in which M_c is the commanded brake moment, ω_n is the natural frequency of the brake system, and s is the Laplace operator.

Weight constraints may require that the reefing line be extended so that the brake hardware can be mounted on the payload. However, the inflation code calculates the stiffness of the reefing line based on the amount of line deployed from the spindle plus the initial slack. Therefore, payload mounting requires a minor code modification to include the effects of increased line length and additional tension induced from the reefing lines acting as suspension lines. For this study, canopy mounting is assumed and the effect of the brake mass on the canopy configuration is neglected.

3.3 Sliding ring suspension line limiter

In this section, an indirect approach is proposed for controlling parachute inflation. Unlike the previous concepts which employ reefing lines to constrain canopy diameter, this concept uses a sliding ring suspension line limiter to alter the system geometry as shown in Figure 4. Although less effective than reefing, limiting the suspension line produces an effect similar to reefing by temporarily adjusting the steady state canopy configuration. Furthermore, this approach circumvents the complications introduced by large reefing line tensions that result from high speed deployments. The single-degree-of-freedom inflation model treats the payload and parachute as a single point mass. Consequently, there is no provision for the motion of the payload relative to the canopy and the suspension line tensions are assumed to be uniform. An accurate model of the interaction between the ring and the parachute requires a more sophisticated inflation simulation. However, a simplified model is developed here in order to highlight the general features of this approach. This model is based on the simplifying assumption that the tensions above and below the ring are identical. Neglecting frictional effects at the ring-suspension line interface, the inertia of the ring and the imbalance of the axial components of the suspension line tension drive the ring toward the payload according to

$$m_r\ddot{x} = (\ddot{R} - g\sin\gamma)\,(m_r + m_b(1 - \cos\theta)) \qquad \text{(EQ 7)}$$

in which m_r is the mass of the ring, x is the distance measured from the payload to the ring, and $\ddot{R}$ is the payload inertial acceleration.

Although dual switch line logic is again used to intermittently halt the advance of the ring, the suspension line limiter does not directly restrain the opening of the canopy as is the case when reefing lines are employed. Rather, its control authority is derived from its ability to temporarily alter the steady state angle theta. With this approach, the translation of the limiter must be interrupted well in advance of the set load to accommodate the additional inflation that occurs after the control is applied. This limitation will become evident in the following examples.

4. EXAMPLE DEPLOYMENT

To demonstrate the utility of load controlled reefing, we consider the high speed deployment described in Table 1 and simulated using the enhanced version of the code developed by Macha.[7] The objective of the control system is to limit the peak deceleration forces acting on the payload to 65,000 pounds using a kevlar reefing line with an ultimate

Table 1: Baseline Deployment Parameters

Deployment Parameter	Input
Full Open Canopy Drag Area	285.0 ft^2
Canopy Constructed Diameter	26.0 ft
Suspension Line Length	26.0 ft
Parachute Weight	47.0 lbs
Payload Weight	1500.0 lb
Initial Dynamic Pressure	937.0 lb/ft^2
Initial Airstream Velocity	1025.0 ft/s
Initial Canopy Diameter	0.0
Initial Flight Path Angle	8.0°

strength of 6500 pounds and a strain at failure of 0.03. First we consider the traditional single line open-loop approach where the required reefing line length and cutting time are determined by trial and error. After several iterations, it was determined that a reefing line length of 14.9 feet and a cutting time of 0.55 seconds satisfy the load constraint while optimizing the deceleration profile. The payload force time history for this case as well as the uncontrolled case are shown in Figure 5. The uncontrolled deceleration profile clearly indicates the need for reefing in order to maintain acceptable deceleration loads. For the controlled case, the parachute inflates unimpeded and the load increases until the circumference of the canopy opening is equal to the reefing line length. After the transient dynamics associated with reefing line stretch settle out, the deceleration force steadily decreases as the velocity drops and the drag area is held constant. After the reefing line is discarded at 0.53 seconds, the deceleration force again increases as the canopy inflates. Eventually, the canopy reaches its steady state configuration, and the load again decreases. As indicated, the controlled case successfully limits the peak deceleration to 65,000 pounds as compared to 128,000 pounds for the uncontrolled inflation. However, the decrease in deceleration force between the two peaks of the reefed inflation indicates a potential for significant improvements in performance.

To enhance the parachute performance, the simulation program was modified to incorporate the previously described control strategies. The parameters for the shunt, brake, and ring concepts are described in Tables 2,3, and 4, respectively. The modified code also requires input describing the controller hardware. For this example, the controller is based on a sixteen bit digital signal processor with a 200 micro-second input to output delay. The sampling rate of the processor is set at 2500 Hz with load information supplied by the signal from high frequency accelerometer in combination with the known payload mass. Assuming a full scale load of 100,000 pounds, the sixteen bit processor provides approximately 1.5 pounds of resolution. The simulated deceleration histories for these cases are shown in Figure 6. For the shunt case, the canopy inflates freely until the first reefing line length is engaged. When the controller

Table 2: Shunt Controller Parameters

Deployment Parameter	Input
Shunt Severing Load	50,000 lb
Incremental Reefing Line Lengths	14.9, 18.3, 22.9, 28.9, 33.5, 39 ft

Table 3: Disk Brake Controller Parameters

Deployment Parameter	Input
Brake Application Load	63,500 lb
Brake Release Load	63,000 lb
Spindle Radius	2 in
Disk Mass Moment of Inertia	0.12422 slugs-in^2
Full Brake Torque	50.0 ft-lb^2
Bearing Frictional Torque	1.0 ft-lb
Bearing Damping	0.01 ft-lb-s/rad
Initial Reef Line Slack	13.0 ft
Brake Natural Frequency	100 Hz
Capstan Coefficient of Friction	0.2
Capstan Angle of Wrap	540°

Table 4: Sliding Ring Suspension Line Limiter Controller Parameters

Deployment Parameter	Input
Initial Location Relative to Payload	23 ft
Ring Weight	1.0 lb
Ring Stopping Load	26,250 lb
Ring Releasing Load	54,500 lb

senses that the load has dropped below 50,000 pounds, the first shunt is cut and the canopy is permitted to inflate to the next level. This process repeats until the last shunt is severed and full inflation is achieved. Although the stated load-limiting objective is fulfilled, the sharp variation of the deceleration load between shunts represents a loss of performance. Conversely, a near-optimal deceleration profile is provided by the disk brake which modulates reefing line deployment to maintain the deceleration forces between 63,000 and 65,00 pounds while the control is in effect. In comparison, the sliding ring is less effective than the brake since inflation is impeded much earlier in the deployment. As the load exceeds the stopping load, the ring is halted 9.5 feet from the payload, causing a more gradual rise to the peak load than the previous cases. This configuration is maintained until the deceleration drops below the release load at approximately 0.5 seconds, and the ring proceeds toward the payload. Although this approach causes a delay in the impulse provided to the payload, the sliding ring may be the preferred technique for extremely delicate payloads because it minimizes the jerk associated with reefing line snatch.

The relative performances of these techniques are judged on their ability to provide a low-speed vertical (90° flight path angle) impact of the payload. The flight path angle versus drop distance for the various controlled cases is shown in Figure 7 while the system airspeed versus drop distance is shown in Figure 8. Although all feedback cases provide a significant improvement over the open-loop case, the disk brake consistently outperforms the ring and shunt cases. The improvement is especially significant for drop altitudes of 50 to 200 feet. In this range, the brake provides an increase of as much as 15° of flight path angle and a decrease in airspeed of 200 feet per second over the open-loop case.

The major benefit of the closed-loop concepts is their adaptability to off-nominal release conditions. The deceleration force profiles for the uncontrolled and the open-loop controlled case are shown in Figure 9. The controlled case shows a peak deceleration force of approximately 60,000 pounds and a secondary peak after disreef of approximately 45,000 pounds. To optimize the deceleration profile for this case, the reefing line length and the cutting time must be tailored to the exact release conditions. Thus, the performance of the open-loop control suffers greatly due to the change in initial velocity. As shown in Figure 10, the closed-loop cases adapt to the new deployment conditions to varying degrees. Considering the shunt case, the deceleration force initially peaks at approximately 60,000 pounds, indicating that the initial line length is too short for the new release conditions. Although some subsequent peaks reach the 65,000 pound limit, the peaks are generally lower than the maximum permissible load. The performance of the sliding ring also suffers in the presence of off-nominal release conditions. The deceleration load peaks at approximately 63,000 pounds with a secondary peak of 55,000 pounds. Although it consistently provides the smoothest deceleration profile, this indirect method of inflation is overly sensitive to the choice of switching loads. Conversely, the deceleration history associated with the disk brake closely resembles its profile from the nominal deployment example. The brake regulates the peak load between the 63,000 and 65,000 pounds until full inflation is achieved. The superior performance of this system is demonstrated in Figures 11 and 12. For this off nominal deployment, significant performance enhancements are again realized for drop altitudes of 50 to 200 feet. In this range, the disk brake provides as much as a 15° increase in flight path angle and a 250 feet per second reduction in airspeed as compared to the open-loop case.

In the previous examples, we have considered only a decrease in the severity of the deployment conditions in judging the adaptability of the controllers. Note that an increase in the initial airspeed would cause an increase in the deceleration loads, exceeding the maximum permissible load for the open-loop control. In addition the shunt and ring closed-loop control cases will likely produce excessive deceleration loads due to their sensitivity to the release conditions. However, the disk brake would function well over a wider range of release conditions due to its precise control over the canopy opening. In some cases however, the initial slack in the reefing line will need to be reduced to avoid excessive loads prior to reefing line snatch.

5. CONCLUDING REMARKS

The need to limit payload deceleration while optimizing performance has renewed interest in developing techniques for controlling parachute inflation. Although the conventional approach which uses a reefing line with a time delay cutter can successfully limit deceleration under ideal deployment conditions, the poor performance and the lack of adaptive capability associated with this approach indicate the need for closed-loop control strategies. In this paper, three closed-loop control strategies were developed to enhance the system performance over a range of release conditions. The first concept extended the conventional reefing technology by incrementally extending the reefing line through load-controlled shunt severing. Although this technique demonstrated an improved performance for nominal release conditions, it suffered from a lack of adaptability due to the need to precisely determine the proper reefing line lengths for a given deployment. The second approach utilizes a disk brake to modulate reefing line deployment from a rotating spindle. This technique provided the largest performance enhancement as compared to the open-loop control and showed excellent adaptive capabilities in the presence of off-nominal release conditions. The final approach considered provides indirect inflation control through a sliding ring suspension line limiter. Payload jerk is minimized with this technique since the canopy opening is not directly constrained. For the nominal release, the ring provided an enhanced performance, but the performance suffered in the off nominal release demonstration due to the sensitivity of the designed switch loads to the release conditions.

6. ACKNOWLEDGMENTS

This work performed at Sandia National Laboratories is supported by the U.S. Department of Energy under contract DE-AC04-94AL85000. The authors wish to thank Chris Hailey (1552) who initiated this project. Also, the helpful suggestions of Don McBride (1552), Michael Nusser (2761), Michael Macha (9723), and Ernie Stech (Frost Engineering) are greatly appreciated.

7. REFERENCES

1. Lafferty, J.F. and Lange, K.O., "The University of Kentucky Continuous Disreefing Device," Wright Air Development Center Technical Note 58-177, May 1959.

2. Webb, D.B., "Development and Initial Test Results of Parachutes with Automatic Inflation Modulation," AIAA Paper 79-0467, March, 1979.

3. Webb, D.B., "Further Test Results of Parachutes with Automatic Inflation Modulation," *Proceedings of the 18th Annual Symposium of the Survival and Flight Equipment Association*, October 1981, pp. 116-123.

4. Webb, D.B., "Automatic Inflation Modulation Parachute Up-Date," *Survival and Flight Equipment Journal*, Vol. 16, No. 2, 1986, pp. 38-45.

5. Hennings, L.J., "RAPID - The Design of a Low-Altitude Parachute," *Proceedings of the 11th Aerodynamic Decelerator Systems Technology Conference*, April 1991, pp. 408-420.

6. Lee, C.K., "Radial Reefing Method for Accelerated and Controlled Parachute Opening," *Proceedings of the 12th Aerodynamic Decelerator Systems Technology Conference*, May 1993, pp. 62-71.

7. Macha, J. M., “A Simple Approximate Model of Parachute Inflation,” *Proceedings of the 12th Aerodynamic Decelerator Systems Technology Conference*, May 1993, pp. 44-53.

8. Macha, J.M., “Development and Experimental Verification of a Single-Degree-of-Freedom Inflation Model for Ribbon and Ringslot Parachutes” Sandia National Laboratories Report SAND92-1378, Albuquerque, NM, October 1992.

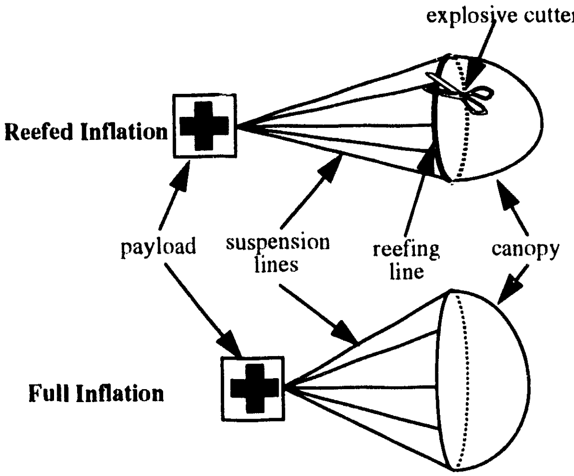

Figure 1. - Typical Parachute Configuration.

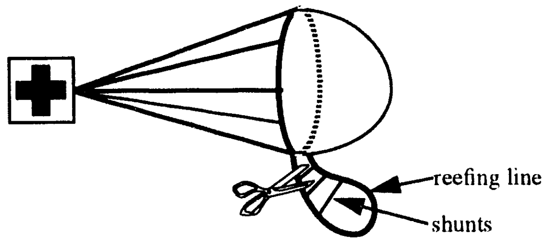

Figure 2. - Using Shunts to Incrementally Extend Reefing Line.

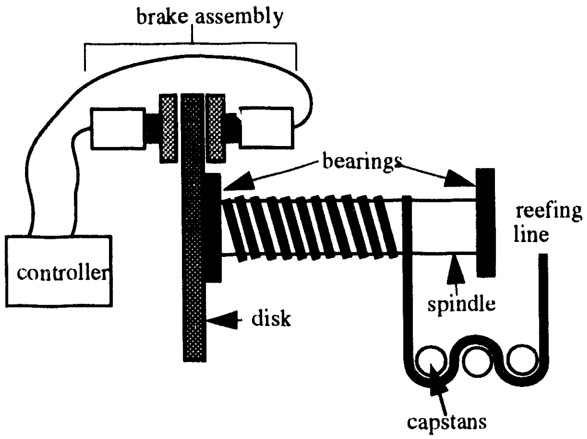

Figure 3. - Disk Brake Reefing Line Deployment.

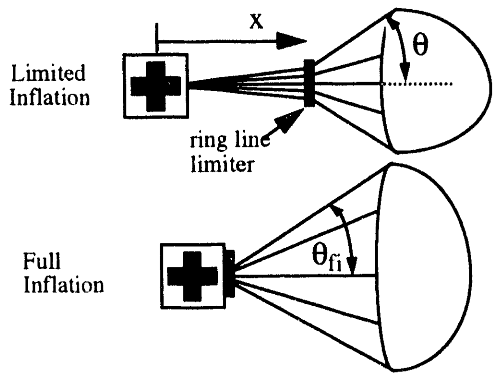

Figure 4. - Sliding Ring Suspension Line Limiter.

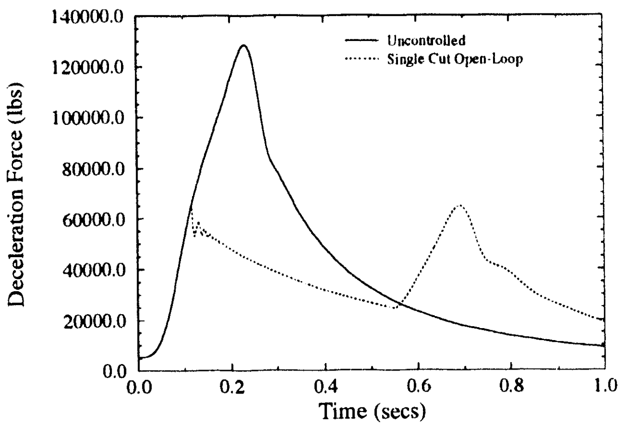

Figure 5. - Deceleration Force History For Uncontrolled and Reefed Inflation.

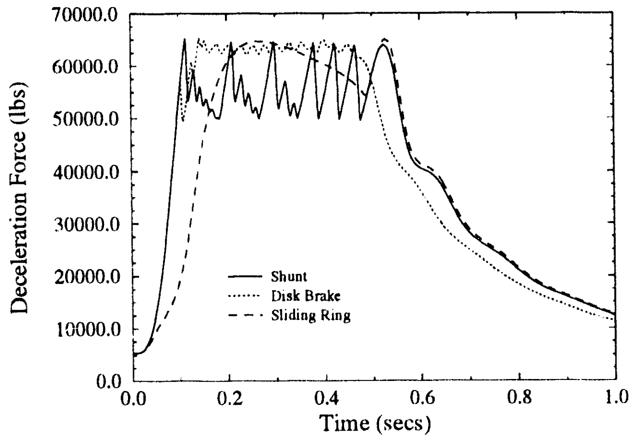

Figure 6. - Deceleration Force History For Load Controlled Cases.

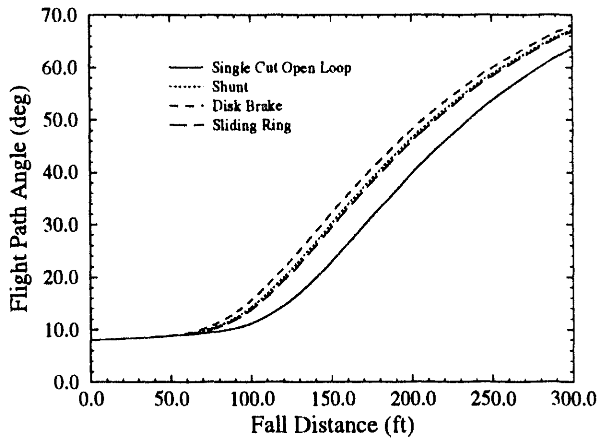

Figure 7. - Flight Path Angle Performance Comparison.

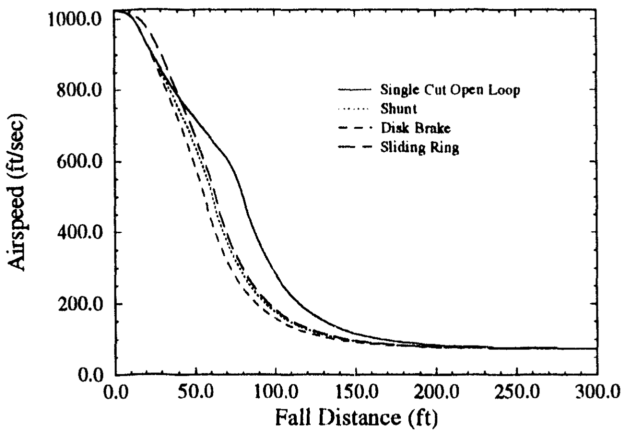

Figure 8. - Airspeed Performance Comparison.

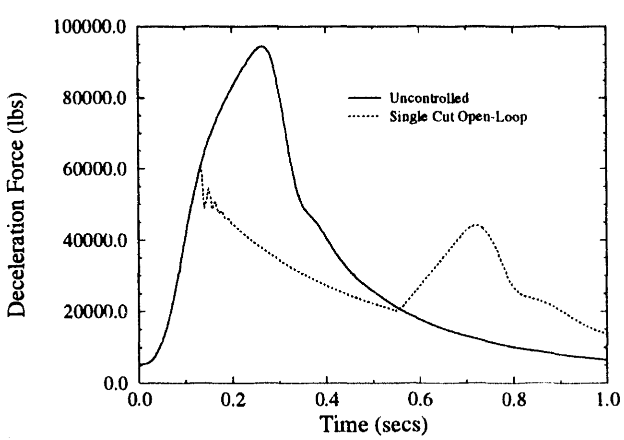

Figure 9. - Deceleration Force History For Off-Nominal Release Conditions.

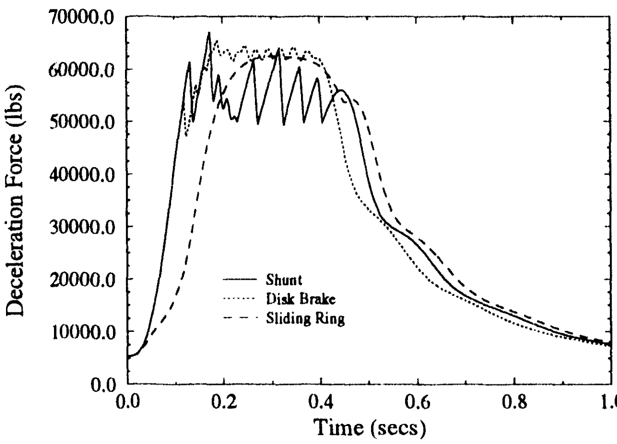

Figure 10. - Controlled Deceleration for Off-Nominal Release Conditions.

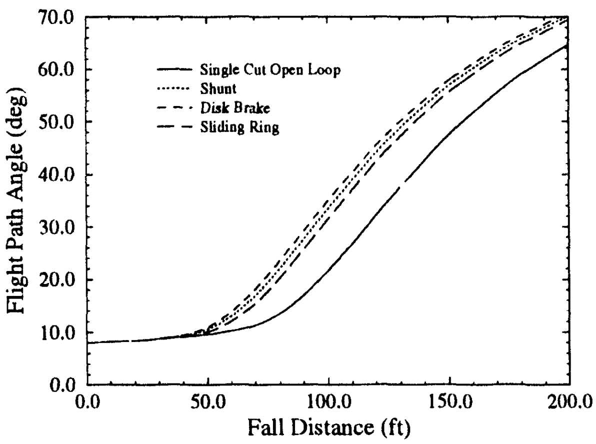

Figure 11. - Flight Path Angle Performance for Off-Nominal Release Conditions.

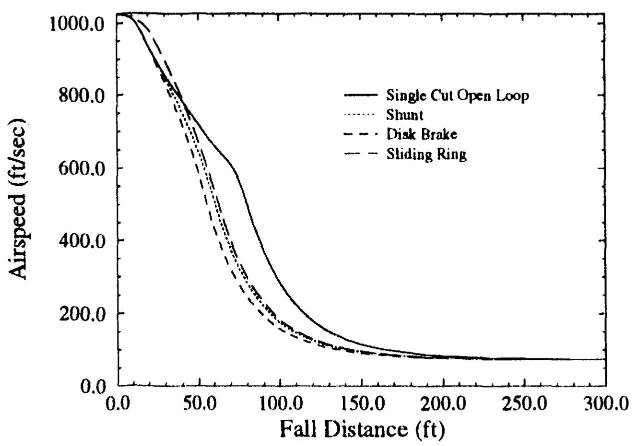

Figure 12. - Airspeed Performance for Off-Nominal Release Conditions

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