A Lifting Parachute for Very-Low-Altitude, Very-High-Speed Deliveries

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A two-stage lifting parachute system is being developed for very-low-altitude subsonic and transonic deliveries. This type of delivery had previously required a small, heavily constructed, single-stage parachute. The two-stage parachute system can decrease the impact energy of a payload to one-tenth that of a conventional single-stage system and increase the impact angle to nearly vertical. Development testing of the lifting parachute has included five drop tests at release velocities of Mach 0.64 to Mach 0.78. The payload was lifted 16 to 142 ft above the release altitude in these tests. A sixth test at Mach 1.2 resulted in a structural failure, thus demonstrating a requirement for a short-reefed stage for supersonic deliveries.

Introduction

A high-speed retarded payload delivery or spacecraft recovery is usually made by means of a staged parachute system. The first stage is a heavily constructed parachute, usually a ribbon parachute, designed to survive high dynamic pressure and to slow the payload to a velocity that a large, lightweight parachute can survive. A large, lightweight parachute or a cluster of parachutes is then deployed to slow the system to a low-impact velocity. When an application requires delivery from an altitude as low as 100 ft above ground level, there is insufficient time to deploy a second parachute prior to impact. With the added constraints of a high-delivery velocity and a limited parachute weight and volume, the optimum parachute system for low-altitude delivery has been a single, small, heavily constructed ribbon parachute.[1] The impact velocity of a payload has been very high and the impact angle very shallow. To survive this impact, the payload must be extremely shock resistant and well protected by shock mitigation materials.

In 1964, a two-stage lifting parachute system was proposed by the author as a more effective means of making high-speed, low-level deliveries. At that time an analysis of the trajectory of such a system indicated that with a very short lifting phase and a small lift-to-drag ratio it would have a great advantage over any other system envisioned in reducing impact severity; however, the program was discontinued before the concept could be developed.

In 1973, the study was revived and a program was begun to design the two-stage lifting parachute system. This paper describes the program objectives, a system analysis, the wind tunnel tests used in selecting the parachute design, and the design itself. A system roll analysis is included, as well as the results of full-scale tests of single- and two-stage lifting parachutes. An extensive program to develop this parachute system for subsonic and supersonic deliveries is continuing. An extensive analytical simulation and drop test program is in progress.

Objectives

The objectives of the exploratory development program have been first to develop a parachute with a lift-to-drag ratio of 0.4 or greater, suitable for the very high stresses imposed by the high-velocity delivery. The second objective is to develop suitable roll characteristics in the parachute so it will remain sufficiently upright, with the aid of a small roll control system if necessary, to lift the system enough to meet the impact requirements.

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System Analysis

Deployment of the first stage of the lifting parachute system was to lift the payload above its release altitude after it had fallen clear of the aircraft and slow the system to allow second-stage deployment. The large second-stage parachute would be deployed to slow the payload to a low terminal velocity and turn it to a steep impact angle (Fig. 1). An analytical simulation using the equations of motion for a point mass in a plane was performed for two 2400-lb systems. These systems were identical except that one used a two-stage lifting parachute and the other used a conventional single-stage ribbon parachute of the same weight.[2] The release altitude for this study was 100 ft above ground level, and the release velocity was Mach 0.45 to Mach 1.2. The impact energy of the payload with the two-stage system was one-tenth that with the conventional system. Table 1 provides a comparison of the results for the Mach 0.85 delivery velocity for the two systems.

System Design

On the basis of the computer analysis already described and the wind tunnel tests described in the following sections, a lifting parachute design was selected.

Wind Tunnel Tests

Wind tunnel tests of scale models were used extensively to evaluate potential lifting parachute designs and to optimize and evaluate the characteristics of the slanted-ribbon lifting parachute after it had been selected. Lift and drag characteristics were measured during inflation and at steady state. These measurements were made for many designs, for reefed parachutes and for parachutes during inflation and disreefing. The lift angle of incipient collapse was measured by forcing the parachute to increasingly higher lift angles until it collapsed. The loads in the suspension lines were measured simultaneously during inflation and at steady state. The roll torque with combinations of pitch and yaw were measured for many lifting chute designs. The aerodynamic coefficients of model lifting parachutes were measured, and models were tested behind aircraft models to evaluate the effect of the aircraft wake on the parachute. Results of these tests are reported separately.[3]

Lifting Parachute Design

The parachute which was developed is a 24-gore ribbon type with slanted ribbons in the five gores at the back.[4] The leading edge is lined with a low-porosity material (Fig. 2). Its measured lift-to-drag ratio is 0.45 to 0.50, and its pitch oscillation is less than 1 deg from its stable lift position. Its oscillation in yaw varied from less than 2 deg for some models to up to 10 deg.

Table 1 Impact comparison for Mach 0.85 delivery from an altitude of 100 ft

	1st stage diam, ft	2nd stage diam, ft	Range, ft	Impact time, sec	Impact velocity, fps	Impact angle, deg	Impact energy, kft-lb
Lifting	13	36	2200	9.1	60	85	134
Conventional	19	None	1630	3.2	187	15	1300

Table 2 Effect of various roll histories on the performance of the lifting parachute system.

Roll characteristics	Impact velocity, fps	Impact angle, deg	Dispersion, ft	Altitude gain, ft
No roll	53	88	0	175
No lift above release altitude	53	75	0	51
45 deg roll throughout	53	83	295	75
45 deg/sec roll rate	53	86	188	120

Table 3 Full-scale test results

Test no.	Payload wt, lb	Lifting chute diam, ft	Ringsail chute diam, ft	Release velocity, Mach	Max decel., gs	Deployment delay, sec	Altitude loss before lift, ft	Altitude gain, ft
1	695	10	—	0.64	—	0.6	32	48
2	695	10	—	0.78	—	0.6	23	165
3	695	10	—	1.15	—	0.6	Susp. lines failed	
4	2400	13	36	0.67	45	1.0	52	94
5	2400	13	36	0.72	42	1.0	36	131
6	2400	13 (reefed)	36	0.72	22	1.0	95	85
7	2400	13 (reefed)	36	0.69	22	1.0	95	5

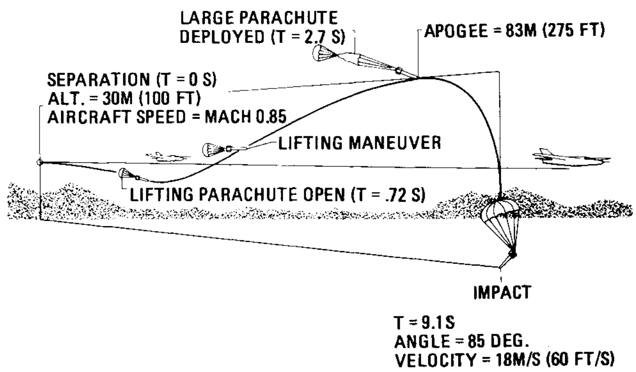

Fig. 1 Two-stage lifting parachute delivery.

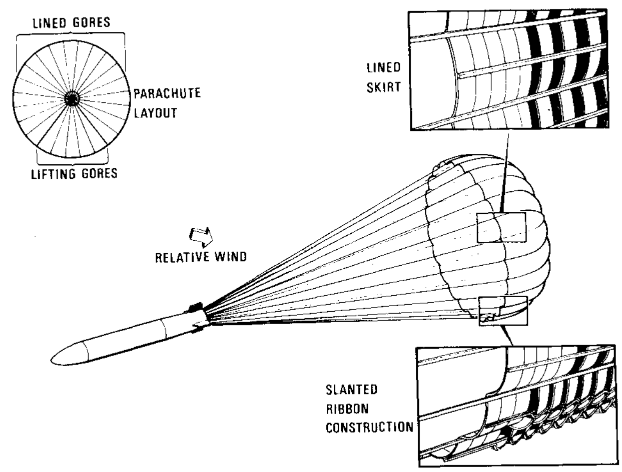

Fig. 2 Slanted-ribbon lifting parachute.

One of the keys to the success of the slanted-ribbon lifting parachute is its resistance to collapse. Previous attempts to make a lifting parachute for deployment at very high velocity failed because the parachute collapsed as it began to take an angle of attack. Characteristics that enhanced the parachute's resistance to collapse were a relatively low geometric porosity for a ribbon parachute, the slanted-ribbon design, and the leading-edge liner.

Even when released at velocities of Mach 1.2, the system is slowed to a subsonic velocity prior to full inflation. In fact, it is slowed to a subsonic velocity 0.2 sec after inflation is initiated. It is not necessary that the parachute provide lift supersonically; it must inflate and retard the system and it must not roll excessively during that fraction of a second before lifting is effective.

Every attempt has been made to produce a parachute that has a low roll torque. Very low tolerances have been specified, with particular attention paid to making a parachute that is perfectly symmetrical about its vertical axis. A wind tunnel test series to evaluate modifications that would minimize any tendency of the lifting parachute to roll was recently completed. As a result of these tests, slight modifications may be made to the sides of the parachute to enhance its resistance to roll.

System Roll Analysis

Large roll rates of the system during the early part of the lifting phase adversely affect both the impact conditions and the lateral dispersion. Since the velocity, and thus the energy available for lifting, is reduced very rapidly, roll must occur during the first fraction of a second after parachute deployment to be detrimental. To illustrate the effect of various types of roll behavior, four possible types of roll histories are considered for a Mach 0.85 delivery (Table 2). The trajectories were computed using the equation of motion for a point mass. The first is an ideal trajectory without roll; the second lifts only until it climbs back up to the release altitude; the third is rolled back 45 deg at parachute deployment and maintains that roll orientation throughout the lifting phase; the fourth rolls at a rate of 45 deg/sec from parachute deployment throughout the lifting phase.

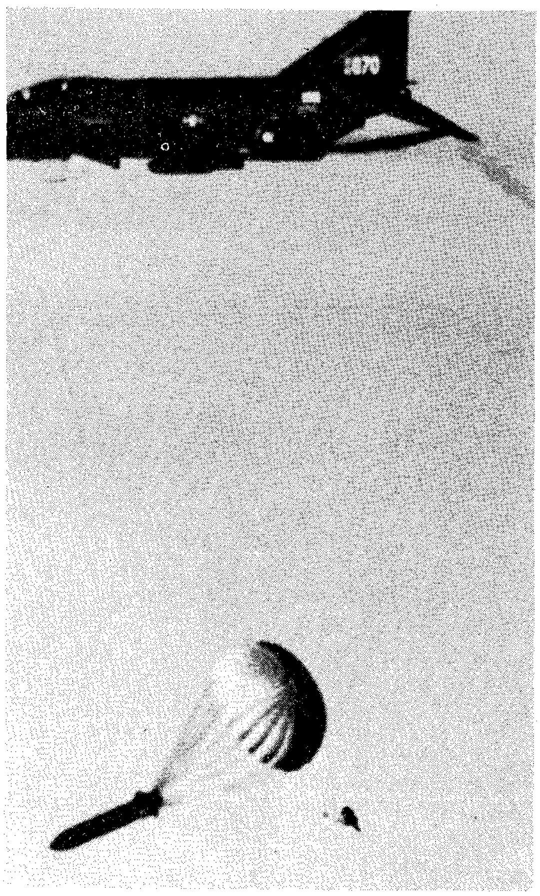

Fig. 3 After deployment, the lifting parachute quickly pitches and begins to lift the system.

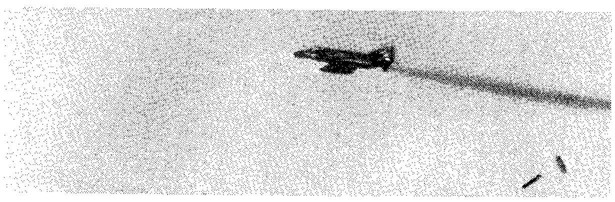

Fig. 4 The system is slowed as it begins to lift.

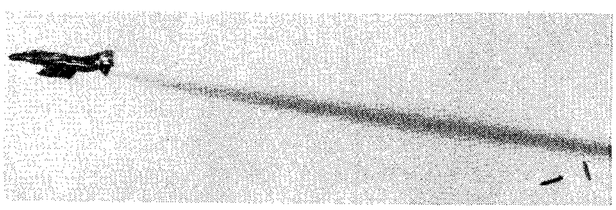

Fig. 5 It is lifted through the wake and continues to climb up to 150 ft above the release altitude.

The most probable type of roll behavior, the fourth, has the least effect on the impact conditions and a small effect on dispersion. This study demonstrates that the lifting performances of the lifting parachute system are acceptable for the roll rates considered. However, differences in parachute roll characteristics and a variety of carriers that impose different initial conditions may require a roll control system to assure acceptable impact conditions and minimize dispersion.

The trajectory time with the lifting parachute is short (1.5 sec) and, with the low rolling characteristics of the lifting chute, minimizes the roll and the effects of the roll on dispersion. In addition, a roll control system has been designed to control body roll orientation before parachute deployment

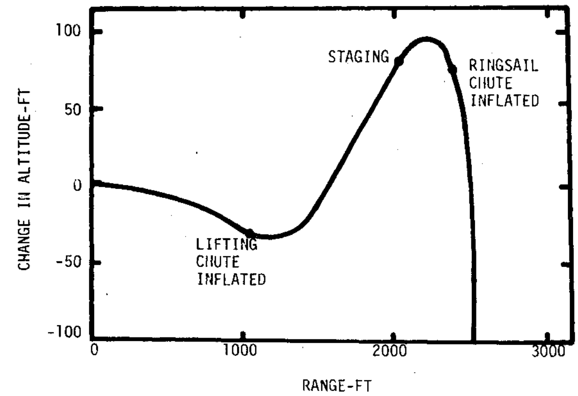

Fig. 6 Trajectory and sequence of events for Test 5.

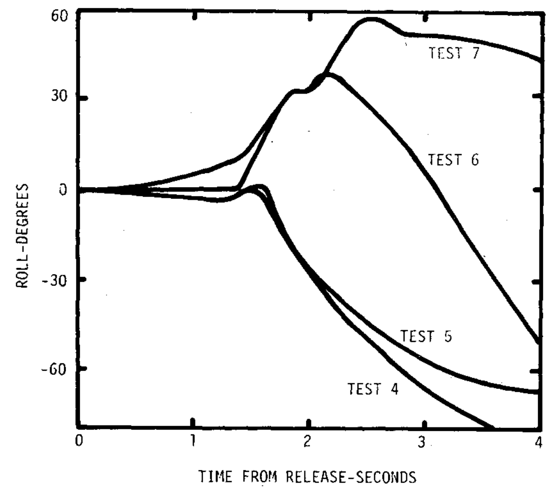

Fig. 7 Roll histories of the instrumented drop tests.

and to continue roll control into the early part of the lifting phase. The system under development is a reaction jet system; it was found that even in the case of a very high torque, control of the body roll orientation can effectively control the parachute orientation without twisting the parachute suspension lines.

Full-Scale Tests

Two successful drop tests of single-stage lifting parachutes with 700-lb payloads were conducted in 1974. Four successful drop tests of a two-stage lifting parachute with a 2400-lb payload have been made during the exploratory development phase and a development test program is continuing. The payloads in all of these tests (except the last, which had a severely reefed parachute) were lifted above the release altitude by from 16 to 142 ft. In addition, a supersonic test was made with an overinflated condition and the suspension lines failed. Although the suspension lines could be strengthened to meet the stress requirements, a short reefed stage (approximately 0.25 sec) for supersonic delivery will meet the same objective with a lighter weight parachute. The results of the seven tests are summarized in Table 3.

After the parachute has been deployed, it quickly lifts and turns the payload into its lifting position (Figs. 3 and 4). The payload is lifted through the wake (Fig. 5), and its upward momentum and a small amount of additional lift carry it well above the release altitude. The trajectory from this test, from release to 100 ft below the release altitude of fall (Fig. 6), illustrates the sequence of events. The unit continues to fall for a short time after the lifting parachute has been deployed. After the second stage has been deployed, the unit is quickly slowed to its terminal velocity and turned to a nearly vertical position.

The 13-ft lifting parachute inflates in approximately 0.12 sec and pitches to its lifting position 0.07 sec later. The parachute reaches its stable pitch position of approximately 28 deg and maintains that orientation relative to the wind. The body oscillates in pitch throughout its 1.7-sec lifting phase. The high pitch acceleration of the body (approximately 130 rad/sec^2 max) is driven by a load component in the vertical direction of approximately 12,000 lb at the back end of the test vehicle. A strong afterbody and good structural integrity of the vehicle's joints are required to survive these loads. The lifting parachute is cut free 1.7 sec after it is deployed and acts as a large pilot chute to deploy the second parachute.

Roll of the four two-stage systems 1.5 sec after parachute deployment was in the range of +55 to −65 deg (Fig. 7). Although the systems had higher transient roll rates, their average roll rates did not exceed 45 deg/sec. With the roll histories of these drops, the system would, with operational timing, have had acceptable impact velocity and impact angle. Other initial conditions or higher roll rates could require a roll control system to meet the impact requirements.

To evaluate the effect of the flowfield on the system's roll, the drops were made from different stations of the delivery aircraft. Tests 4 and 5 were dropped from the left inboard wing station; Test 6 was dropped from the right inboard wing station; and Test 7 was dropped from the centerline station. No roll behavior pattern developed that could be attributed to the aircraft flowfield.

Conclusions

On the basis of the tests and analyses conducted to date, the two-stage lifting parachute system developed at Sandia Laboratories has been shown to be a feasible system for low-altitude subsonic and transonic delivery. Its use can reduce the impact energy of the low-altitude delivery of a store by an order of magnitude when compared to a conventional retardation system. A parachute with adequate lifting characteristics and good roll characteristics has been developed. The supersonic test demonstrated a requirement for stronger suspension lines or reefing to reduce the maximum stress in the suspension lines. Although roll of the systems tested was acceptable without roll control, different delivery velocities, different carriers, and different parachute roll characteristics require a roll control to assure acceptable impact conditions.

Future Programs

Development of the two-stage lifting parachute system is continuing with a program of wind tunnel tests and full-scale tests to measure aerodynamic characteristics and coefficients and to optimize the lifting parachute's characteristics. An extensive analytical program is being conducted to analyze and model parachute stresses, trajectory and dispersion, and two-body dynamics. Methods to minimize roll motion of the parachute are being emphasized in both the parachute development and the analytical part of the program. A roll control system is under development.

Acknowledgment

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References

[1] Maydew, R. C. and Johnson, D. W., "Supersonic and Transonic Deployment of Ribbon Parachutes at Low Altitudes," *Journal of Aircraft*, Vol. 9, July 1972, pp. 497-502.

[2] Rychnovsky, R. E. and Everett, R. N., "Optimization of a Lifting Parachute System for Laydown Delivery of a Bomb," Sandia Laboratories, Livermore, Calif., SLL73-0295, Jan. 1974.

[3] Rychnovsky, R. E. and Everett, R. N., "Wind Tunnel Tests to Evaluate a Lifting Transonic Parachute," AIAA Paper 75-1365, Albuquerque, N.Mex., Nov. 1975.

[4] Patent No. 537,810 for "A Lifting Parachute," issued December 1975.