Testing of a two-stage reefed 27m polyconical parachute for the Cirrus Jet
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The Cirrus SF-50 is a single-engine, low-wing, seven-seat, very light jet aircraft that is currently in development. Like other Cirrus Aircraft, the SF-50 will be equipped with a whole aircraft-parachute recovery system: the Cirrus Aircraft Parachute System (CAPS). Since the jet is heavier and will fly faster than the existing SR-20 and SR-22 aircraft, an improved CAPS system is required. To aid development of the parachute system, a series of nine tests was conducted from Kingman, Arizona using modified SR-20 parachutes decelerating masses of between 1500 and 3600 lbs. Two tests characterized the unreefed inflation profile of the parachute, thereby providing a baseline against which to compare the effects of reefing. Five tests maintained a reefed state for a relatively long duration, to allow accurate determination of the reefed drag area ratio, and the final two tests tested the parachute and reefing system in a use-case equivalent to an aircraft recovery.

I. Nomenclature

<table>
<thead>
<tr>
<th>CAPS</th>
<th>Cirrus Aircraft Parachute System</th>
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</thead>
<tbody>
<tr>
<td>D₀</td>
<td>Reference Diameter</td>
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<tr>
<td>DAS</td>
<td>Data Acquisition System</td>
</tr>
<tr>
<td>DTV</td>
<td>Drop Test Vehicle</td>
</tr>
<tr>
<td>GPS</td>
<td>Global; Positioning System</td>
</tr>
<tr>
<td>KEAS</td>
<td>Knots Equivalent Airspeed</td>
</tr>
<tr>
<td>KTAS</td>
<td>Knots True Airspeed</td>
</tr>
<tr>
<td>RDAR</td>
<td>Reefed drag area ratio. The ratio of drag area in reefed flight to the drag area after full inflation.</td>
</tr>
<tr>
<td>RLLR</td>
<td>Reefing line length ratio. The ratio of the reefing line length to the constructed circumference of the parachute (πD₀)</td>
</tr>
</tbody>
</table>

The term reefing ratio is not used, due to possible confusion between RDAR and RLLR.

II. Introduction

The Cirrus SF-50 is a single-engine, low-wing, seven-seat, very light jet aircraft that is currently in development. Like other Cirrus Aircraft, the SF-50 will be equipped with a whole aircraft-parachute recovery system: the Cirrus Aircraft Parachute System (CAPS). Since the jet is heavier and will fly faster than the existing SR-20 and SR-22 aircraft, an improved CAPS system is required.

The recovery parachute in this system is a low porosity 27 m (89 ft) poly-conical parachute similar, but larger, than that used on the SR-20 aircraft, with reefing lines cut by pyrotechnic reefing cutters rather than the slider reef system used on the earlier parachutes. Initially, the parachute bridle maintains a small aircraft pitch-up orientation while the aircraft velocity is reduced. Subsequently, the rear bridle is extended to allow the tail to drop and the aircraft to descend in an upright orientation. Earlier analysis has shown that reefed drag area ratios of 5% and 13% are required in order to manage inflation loads throughout the parachute deployment envelope.

1 CAPS Engineer, AIAA Member.
2 Principal Engineer, AIAA Senior Member
3 Senior Engineer. AIAA Member

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To aid development of the reefing system, a series of 9 tests was conducted out of Kingman, Arizona using 16.9 m D₀, modified SR-20 parachutes decelerating masses of between 1500 and 3600 lbs. Two tests characterized the unreelfed inflation profile of the parachute, thereby providing a baseline against which to compare the effects of reefing. Five tests maintained a reefed state for a relatively long duration, to allow accurate determination of the reefed drag area ratio, and the final two tests tested the parachute and reefing system in a use-case equivalent to an aircraft recovery, with the 3600 lb mass chosen to give a representative loads with the smaller test parachutes.

These tests were conducted in 3 sorties spread over a 5 day period, allowing analysis of earlier test results to influence later test configurations. To determine the parachute glide quantitatively, and to assess whether it glides at all, wind control vehicles were used with overall descent rates similar to the test payloads. Each control vehicle descended under a cluster of two parachutes to eliminate any gliding of the control vehicle.

This paper discusses the results of these tests, which includes interesting results with implications for reefing line length selection and steady-state drag of low porosity parachutes.

III. Test equipment and method

The testing program was conducted out of Kingman, AZ and used a drop zone nearby. The drop aircraft was a Fairchild C-123 and 3 sorties were flown. On each sortie, 3 test articles and two wind control vehicles were dropped, the latter were used to assess the wind conditions during the drop, and thereby allow calculation of the wind relative velocity.

On each sortie, the drop aircraft made 3 passes through the drop zone. On the first and third passes, test payloads followed by a wind control vehicle were released; on the second pass a test payload alone was released.

When the test article left the aircraft, a programmer parachute was deployed to stabilize it during free-fall and limit the payload free-fall speed to a predetermined velocity. After 15 seconds, the programmer parachute was cut away from the payload and deployed the test parachute, still in its deployment bag, away from the payload. The programmer then stripped the deployment bag from the test parachute, allowing the test parachute to inflate controlled by its reefing system and the test parachute and payload descend together to the ground. This sequence is shown in Figure 2.

The test payload consisted of two to four 55 gallon drums strapped together and ballasted for mass, as seen in Figure 1.

![Figure 1. 1500 lb (left) and 3600 lb (right) payloads being prepared for testing. Note the plywood base and lid on each payload, and the cardboard honeycomb section near the base to provide a measure of impact attenuation.](image-url)
The programmer was a 16.9 ft diameter ringslot parachute which produced a terminal velocity of 38 m/s for the 1500 lb payload. The programmer parachute was reefed to reach the 140 KEAS desired for test 7 and 8.

The control vehicles consisted of a DAS unit and battery suspended under a cluster of two disk-gap-band parachutes. The use of a cluster of parachutes ensured that the control vehicle would not glide. This is shown in Figure 3 and Figure 4.

The Vorticity-built DAS (Figure 5) had the ability to record GPS data, including global position and global velocity at 4 Hz, as well as body axis accelerometer and body-axis angular velocity at 1 kHz. These units were powered by an external battery, and weighed approximately 1 kg. They were mounted on the payload as shown in Figure 6. Note that this mounting location is a significant distance from the center of gravity of the payload.

Figure 2. Three pictures from various 1500lb tests; showing (a) parachute deployment by the programmer chute, (b) steady state reefed flight, (c) descent under fully inflated test parachute.
IV. Test articles and test plan

Two sizes of parachute were used for the test. Type 1 was a 16.9 m modified version of the SR-20 parachute to be used for inflation profile characterization and long duration reefed flight. Type 2 had a nominal diameter of 18.6 m and was built out of stronger materials to allow testing at higher payload mass and higher dynamic pressure conditions. Both of these parachutes had a similar extended skirt triconical construction and were reefed by a reefing line around the mouth of the parachute, connected to the parachute by rings mounted on the parachute’s hem tape.

The test program had three aims. Firstly, to assess the glide characteristics of the test parachute in steady descent, as there was uncertainty before the test about the glide angle, and indeed whether the parachute would glide at all. To determine this, the wind relative parachute velocity had to be determined.

The second aim was to discover the relationship between reefed drag area ratio and reefing line length ratio to this particular parachute, as a step toward the final test aim, of conducting a test with a 3600 lb payload and a reefing system configured in a manner that is scaled for an aircraft recovery. Simulations conducted beforehand determined that a two stage reefing system with reefed drag area ratios of 5% and 13% and durations of 2.5 and 5 seconds would meet this goal.
However the reefing line lengths required to produce these reefed drag area ratios was not known before the test campaign, as this parachute type had not yet been flown with this type of reefing system, and so the initial reefing line lengths were based on analysis of the data published by Knacke\(^1,2\), as seen in Figure 7.

![Figure 7. Relationship between reefed drag area ratio and reefing line length from Knacke\(^1,2\), for a solid circular parachute.](image)

In order to achieve these objectives, five of the tests had a 10 second duration reefed flight to allow the payload to approach steady descent under the reefed flight and to provide a meaningful amount of data in reefed flight – these tests were conducted using an Analysis In Loop method, where the results were be analyzed overnight, and the reefing configurations for the next test produced by the next morning in Arizona.

Two tests were conducted to measure the unreefed inflation of the parachute, to allow calculation of the unreefed inflation profile and allow prediction of the opening profile for the reefed cases.

The results of Sortie 1 showed that actual reefed drag area ratio for a given line length ratio was much higher than expected. Because of this, Sortie 2 was used to further explore the relationship between DRAR and reefing line length ratio for this parachute. These results allowed two tests of a two stage system at representative mass on Sortie 3. The final test matrix is shown below.

<table>
<thead>
<tr>
<th>Sortie No</th>
<th>Test No.</th>
<th>Parachute Type</th>
<th>DTV Drop Mass (lb)</th>
<th>Start of Inflation Vel (KTAS)</th>
<th>1st Stage Target RDAR</th>
<th>2nd Stage Target RDAR</th>
<th>1st Stage Actual RDAR</th>
<th>2nd Stage Actual RDAR</th>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Type 2</td>
<td>1500</td>
<td>85</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>Type 1</td>
<td>1500</td>
<td>85</td>
<td>15%</td>
<td>N/A</td>
<td>23.70%</td>
<td>N/A</td>
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<tr>
<td>1</td>
<td>3</td>
<td>Type 1</td>
<td>1500</td>
<td>81</td>
<td>4%</td>
<td>N/A</td>
<td>12.70%</td>
<td>N/A</td>
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<tr>
<td>2</td>
<td>4</td>
<td>Type 1</td>
<td>1500</td>
<td>86</td>
<td>11%</td>
<td>N/A</td>
<td>12.70%</td>
<td>N/A</td>
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<tr>
<td>2</td>
<td>5</td>
<td>Type 1</td>
<td>1500</td>
<td>86</td>
<td>13%</td>
<td>N/A</td>
<td>7.50%</td>
<td>N/A</td>
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<tr>
<td>2</td>
<td>6</td>
<td>Type 2</td>
<td>1500</td>
<td>82</td>
<td>5%</td>
<td>N/A</td>
<td>1.30%</td>
<td>N/A</td>
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<tr>
<td>3</td>
<td>7</td>
<td>Type 2</td>
<td>3600</td>
<td>Unknown</td>
<td>5%</td>
<td>13%</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>Type 2</td>
<td>1500</td>
<td>111</td>
<td>5%</td>
<td>13%</td>
<td>2.40%</td>
<td>11.40%</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>Type 1</td>
<td>1500</td>
<td>84</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 1. Final Test Matrix
V. Analysis and discussion

A. Data analysis

Figure 8. GPS tracks from the Sortie 1 (left) and Sortie 2 (right). The figure for sortie one shows the turning motion of some test parachutes (blue and cyan), the relatively straight glide of the third test vehicle, and the no-glide descent of the control vehicles.

Figure 9. Uncorrected, corrected and GPS derived acceleration for test 1. Time is from the start of the GPS week.

The measured accelerations were first corrected for the centripetal acceleration caused by the offset between the DAS accelerometers and payload center of gravity. Figure 9 illustrates the importance of removing these rotational components from the data when discerning the vertical acceleration of the vehicle. The inflation force shown by the uncorrected trace has roughly twice the magnitude and half the duration of the corrected trace. Note the good correlation between the corrected trace and GPS data.

After rate correction the accelerometers were calibrated against the recorded GPS velocities from the tests. This ensures that the change in velocity from integrating the accelerometer data is the same as that observed by the GPS. The rationale behind this was discussed in detail at the previous AIAA ADS conference.

Figure 10 shows velocity vs time for test 5. Note the acceleration after the programmer is released, while the test parachute is stripping, and how the resultant and vertical GPS velocities diverge immediately after full inflation, as the parachute starts to glide.

B. Steady Descent

Since we require the system airspeed, as opposed to the GPS measured ground speed, in order to calculate the parachute drag coefficient, the wind-relative velocity must be calculated by subtracting the lateral velocities seen on the wind control vehicles.

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Figure 11. Wind speed, test vehicle resultant ground velocity, and test vehicle resultant air velocity, for a turning parachute during steady descent (test 4).

Figure 11 shows the importance of calculating air-velocity instead of using uncorrected ground velocity. The air velocity of the parachute has a small oscillation around 8 m/s during descent steady descent, but the ground-relative velocity of the parachute varies between 6 and 12 m/s.

From Figure 12, the glide angle of the parachute is seen to be approximately 45°. Note that the parachute glides little during reefed flight.

Figure 12. Glide angle vs height for test 4.

Figure 13. Steady state drag coefficient and axial force coefficient for test 4.

Figure 13 shows the difference between calculating drag coefficient based on resultant velocity or calculating axial force coefficient based on rate of descent, as described in the H.G. Heinrich Parachute Systems Short Course. It can be seen that a drag coefficient calculated by assuming vertical descent of the parachute is in error by approximately +100%.

C. Inflation

Figure 14 shows the test results from this program compared to the flat circular legacy data from Knacke1, 2. The reefed drag area ratios found on these tests were higher than expected from legacy data. The test data are well correlated, with the exception of the test at 0.048 RLLR, which appears to be below trend. This particular test was the first reefing stage of the test 8, which had a duration of 3 seconds, rather than 10 seconds on the other tests.
Knacke$^1$ presents different curves for different types of parachute, the solid circular and extended skirt parachutes have the lowest reefed drag area ratio for a given reefing line length ratio, and ribbon parachutes have the highest reefed drag area ratio for a given reefing line length ratio. The data for a 14% porosity ribbon parachute with a solid crown, (series RO2 in Reference 2) are shown in Figure 15. These data show a good correlation between the performance of the legacy ribbon parachute and the recent solid polyconical testing.

To understand the difference between our test results and the legacy ribbon data on one hand and the legacy flat circular on the other hand, the reefed drag area data for the solid circular was scaled by a factor of 2, based on the assumption that the fully open axial force coefficient calculated using rate of descent was used to normalize the reefed drag area coefficient, instead of using the fully open drag coefficient calculated using airspeed; i.e. accounting for glide. These scaled data are shown in Figure 16. This shows a good correlation with the test data and with the legacy ribbon parachute data for reefed drag area ratios of 18% and higher.

VI. Conclusions

Seven tests with a 1500 lb payload were successfully conducted at a variety of reefing ratios. The results for reefed drag area against reefing line length suggest that the commonly-used reference work Knacke$^1$ and the source paper quoted therein$^2$ are incorrect for high glide angle parachutes, due to confusion induced by incorrectly using rate of descent to calculate drag coefficient.

Use of GPS on the test vehicle allowed measurement of velocity to a high accuracy for a low cost, compared to other methods used in previous campaigns.

Use of wind control vehicles is essential to the understanding of the flight of parachutes in free-flight.

VII. Acknowledgements

The authors would like to acknowledge the efforts of all of the personnel at Cirrus Aircraft for their contribution to the test program. We would also like to thank the drop aircraft pilot Jim Blumenthal, parachute packer Brian Johnson, payload rigger Tony Kasher and instrumentation engineer Shane Glynn for their contributions.

