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Parachute Load Prediction using a Combination of Empirical Data and Fluid Structure Interaction Simulations

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This paper describes the analysis of a ribbon parachute system using existing parachute analysis software and techniques currently available within the parachute industry. A novel combination of an internally developed trajectory and loads analysis code and a commercially available Finite Element Analysis code was used to provide a detailed parachute analysis methodology. System level analysis was performed using an internally developed code DCLDYN (DeCeLerator DYNamics). DCLDYN was used to generate a parachute inflationary model based on existing drop test data. The inflationary model was then used to assess parachute performance parameters at edge-of-the-envelope operational conditions. This phase defined the maximum parachute forces for all nominal parachute performance scenarios. In order that the predictable variability observed in parachute performance was considered, a Monte Carlo stochastic simulation was conducted to provide a probabilistic understanding of the maximum parachute forces. The Monte Carlo simulation utilized the variability of inflationary performance identified in the drop test data as well as parachute knowledge and experience from Airborne Systems. The end result being that the nominal and maximum parachute forces were obtained for each corner of the current operational envelope. The nominal and maximum parachute force conditions for the worst corner of the operational envelope, for each parachute, were then assessed at a more detailed level using the commercially available code LS-DYNA. Utilizing a combination of the two codes enables the user to draw on the benefits of a broad source of experimental data from 90 years of recovery system design at Airborne Systems and at the same time exploit the powerful finite element methods now available from commercial codes. This work identified the design driving operational scenario and will also be used to help guide future test conditions.

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I. Introduction

Typical questions often asked of the parachute engineer are: “can we use this existing parachute for this new application?” or “will this parachute still work if we use it in these conditions?”. Parachute systems can be expensive and time consuming to test and qualify, so a reliable and efficient means of answering these questions is a valuable capability. This paper describes the use of a novel analysis methodology to assess the worst case operational loading for an existing 24 ft diameter ribbon parachute.

The analysis approach described in this paper combines heritage test data, an empirically based trajectory and loads analysis code, Monte Carlo stochastic simulations, and a commercial finite element analysis (FEA) code.

II. Analysis Software

A. DeCeLerator DYNamics (DCLDYN)

The parachute inflationary behavior and trajectory analysis was performed using DCLDYN. The FORTRAN based tool was developed in the Apollo era and has evolved with the demands of the parachute industry. DCLDYN was integrated with Monte Carlo methods to provide sensitivity analysis to key parachute and vehicle parameters, and initial conditions.

DCLDYN predicts the motion and trajectory of a payload during deceleration by the aerodynamic drag of an attached parachute system. The parachute/payload system is modeled as two coupled bodies in planar motion. The vehicle has three degrees of freedom (horizontal and vertical translation, pitch rotation); the parachute has two degrees of freedom (horizontal and vertical translation). The two bodies are connected via a non-linear spring. The spring tension vs. elongation curve is modeled with three distinct regions (mechanical elongation, limit elongation, and unloading) to capture the hysteretic effects of the system. The parachute model includes many non-linear terms including time variant drag area and mass. The model approximates the parachute shape, volume, and added mass during inflation based on empirical data.

B. LS-DYNA

The more localized parachute loading environment for the parachute was simulated using the Livermore Software Technology Corporation (LSTC) transient dynamic Finite Element Analysis code LS-DYNA[1]. Airborne Systems has over a decade long heritage of using this tool to simulate and analyze the behavior of parachute systems. Additionally, Airborne Systems has worked with LSTC to incorporate particular parachute related algorithms. This relationship, in combination with the continual improvement and reduction in price of high-end computational hardware, has enabled the fidelity of parachute analysis to improve over the past few years.

III. Parachute Design and Test Data

The parachute investigated for this work is a hybrid Kevlar-29/ nylon 20° conical ribbon parachute fabricated from 24 gores with 24 suspension lines. It is constructed from fifty-four continuous horizontals and seven verticals per gore. The top 21 ribbons are reinforced selvage nylon, and the remaining ribbons are Kevlar-29. The parachute is reefed for high altitude deployment, and deployed using a gas generator.

During development in the late 1970’s the parachute was subjected to static tests, rocket sled free-flight tests, aircraft drop tests, and rocket-boosted flight tests. The original design and development of the parachute is described in detail by W. B. Pepper Jr in Ref 2.

The parachute has also been regularly tested since its original development and this more recent test data was used during this work to develop parachute inflationary models.

The results of this parachute analysis study were used by Murray, J.C. and Wolfe W.P. for evaluation of environment sensors, Ref 3.

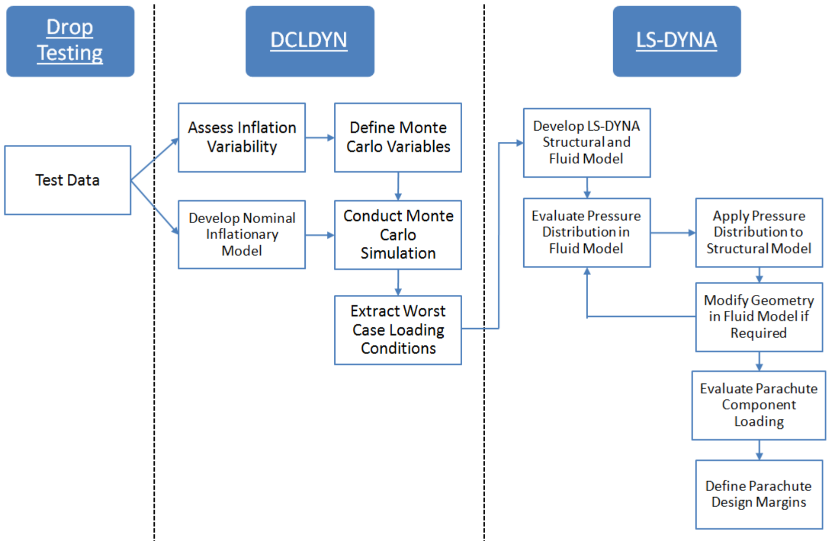

Figure 1. Analysis Methodology Flow Chart

IV. Analysis Methodology

The methodology developed to generate parachute design margins is depicted in Figure 1. Test data was used to develop DCLDYN models that were used to generate worst case input conditions for LS-DYNA models.

C. DCLDYN

A specific inflationary model was constructed in DCLDYN for each of the 8 drop tests. Each model was developed using the initial conditions and the drop test results. As such the models were not predictive but they did reflect the parachute inflation performance and provided an understanding of the variability of that inflation performance. The test data and the models indicated how the performance of the parachute varied based on the deployment Mach number, M. Parachute inflation time and variability increased at M>0.9. This variation was accounted for later in the analysis process when performing the Monte Carlo simulations.

The test data were sufficient to develop a nominal inflationary model and provide assistance regarding inflation parameter variability. The drop test data were not obtained at extreme initial conditions so the model was used to develop nominal performance parameters for the edges of the operational envelope. This also helped identify the design driving operational scenario.

Monte Carlo simulations were then performed for each of the four edge-of-the-envelope operational release conditions. Velocity, flight path angle, pitch angle, altitude, and deployment force were the release condition variables that were dispersed. Drag area, CG location, mass, and pitch moment of inertia were the payload variables that were dispersed. Parachute drag area, filling time, and drag area profile were also Monte Carlo variables that were dispersed. Each Monte Carlo simulation consisted of 1,000 DCLDYN analyses. Statistics were generated for the maximum parachute drag, maximum parachute riser force, and the final payload velocity and pitch angle. Figure 3 illustrates the parachute drag time history data for all 1,000 DCLDYN analyses for a single edge-of-the-envelope release condition. Figure 2 depicts the maximum riser tension distribution for the same release condition Monte Carlo simulation.

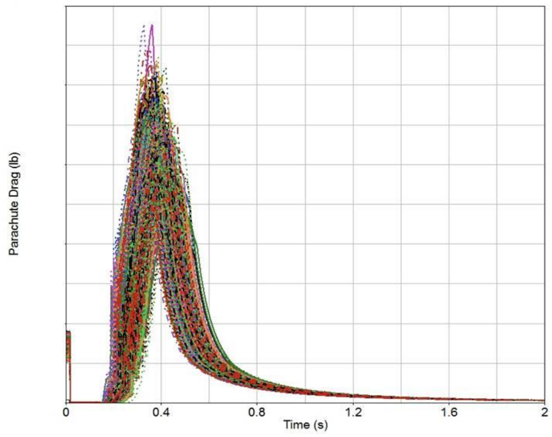

Figure 3. Monte Carlo Parachute Drag Time History

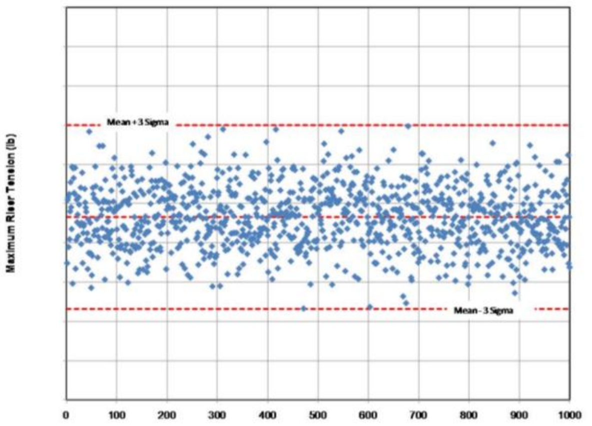

Figure 2. Monte Carlo Maximum Parachute Riser Tension Distribution

The results from the Monte Carlo simulations defined the conditions when maximum total parachute load is observed for both a nominal and maximum dispersed parachute operation for the 4 extreme payload release conditions. Table 1 presents the nominal and maximum dispersed peak parachute force for the worst edge of the envelope release condition. These conditions were used as model inputs for the LS-DYNA structural and fluid models.

Table 1. Nominal and Maximum Dispersed Peak Parachute Force for Worst Case Release Condition

	Nominal	**Maximum Dispersed (4.37 sigma)**
Altitude	19,998 ft	19,987 ft
Velocity	954.8 ft/s	958.9 ft/s
Air Density	0.001268 sl/ft^3	0.001268 sl/ft^3
% Full Open Drag Area	79.2 %	129.4 %

D. LS-DYNA

LS-DYNA was used to simulate and analyze component level loading characteristics for the ribbon parachute based on the conditions defined by the DCLDYN results. The code was used for two critical steps in the analysis process. The first step involves the deformation of the parachute ‘constructed’ geometry to a geometry representative of the parachute shape at the time of maximum parachute drag. This process takes the parachute from a 2D drawing to a 3D representation of the parachute at the time a maximum drag. The second step takes this estimation of the deformed shape and subjects it to a flow field whose parameters are defined by the DCLDYN results. This second step enables a more accurate deformed shape of the parachute to be developed.

Perhaps the most critical step of the modeling process is to accurately replicate the geometry of the ‘constructed’ parachute. With the more common hardware FEA models this process is relatively simple: a CAD model is imported and then a computational mesh is applied to that 3D volume. For soft-goods like parachute fabrics this process is considerably more complicated. The flexibility of the fabrics and the construction techniques used to assembly the parachute mean that 3D CAD models of parachutes rarely exist; indeed all parachutes at Airborne Systems are manufactured from 2D drawings.

A mesh generation tool is used to create a representative parachute mesh of 2D shell elements and 1D cable seatbelt elements; the Altair Engineering HyperMesh software was used for this purpose.

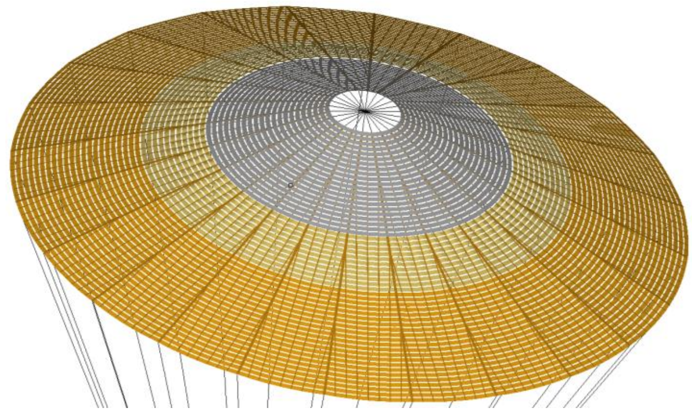

Figure 4. 24 ft Diameter Ribbon Parachute Computational Mesh

Figure 4. 24 ft Diameter Ribbon Parachute Computational MeshFigure 4 displays the computational mesh of the 24 ft diameter ribbon parachute in the constructed geometry form. The suspension lines, radials, skirt band, ribbons, verticals, vent band, and vent lines are all defined in the computational mesh. The suspension and vent lines are constructed from 1D cable type elements, and the remaining components are 2D membrane shell elements.

An LS-DYNA model is created to apply a predefined pressure profile to the interior surface of the parachute. For the initial model, a uniform constant pressure was used for the complete internal surface, meaning that the pressure on the parachute was constant as a function of ribbon position.

It was at this point that the first unexpected benefit of this analysis process was realized. Figure 5 illustrates a von Mises fabric stress contour plot of an intermediate pressure loading model. The plot highlights the region of transition from nylon to Kevlar ribbons as an area of high stress. This highly stressed area is caused by the large difference in relative stiffness between the two fabrics.

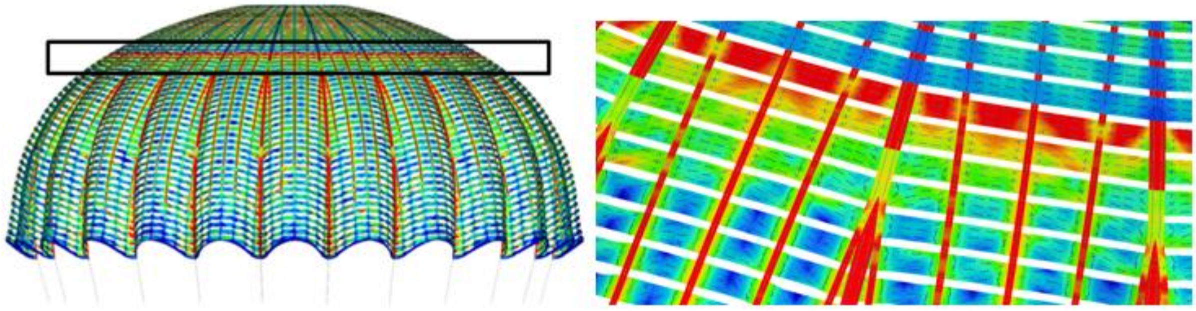

Figure 5. Area of Highly Stressed Elements in the Ribbon Material Transition Region

Further review of the original drawing package located a note which specified that added fullness was to be included in the first 8 Kevlar ribbons. A fullness of 4% was to be included in the first Kevlar ribbon, which was reduced linearly to 0% over the next 8 ribbons.

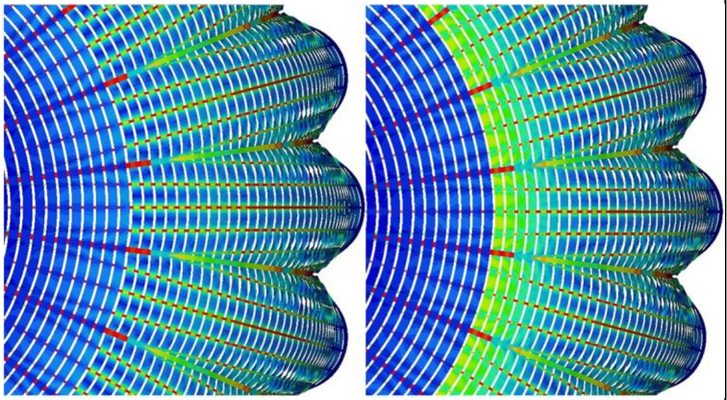

Figure 6. Comparison of Stress Contours, Left: Fullness Right: No Fullness.

Figure 6 displays the impact of incorporating this fullness, or slack fabric, into the LS-DYNA model. The influence of this design feature can be clearly illustrated; it reduces the running loads in the Kevlar ribbons and enables the load to be more effectively distributed throughout the canopy. Including fullness greatly reduces the likelihood of ribbon failures in these particularly highly stressed regions. Subsequent to this analysis effort it was understood that similar lessons were learned during the initial test drops of this canopy, which resulted in the fullness percentages described above.

This parachute also incorporates foreshortened vent lines. Foreshortening of the vent lines relieves stress risers in the region near the vent band and directs the parachute drag load into the structural grid of the canopy. Figure 7 shows how neglecting the necessary vent line foreshortening would increase the load in the crown of the canopy and alter the 'in flight' shape of the inflated parachute.

The LS-DYNA structural models were constrained with permanent reefing lines to reflect the instantaneous drag area present at the time of peak parachute drag force, as defined in Table 1. The resulting geometry was then exported and used for the LS-DYNA fluid model.

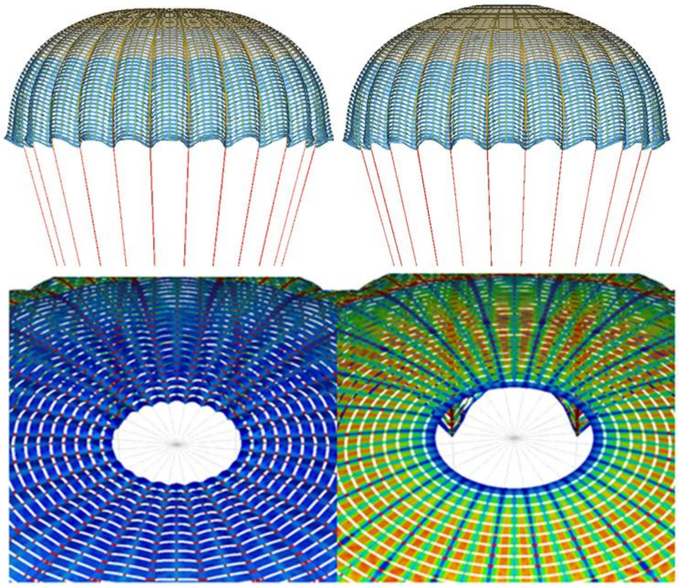

Figure 7. Comparison of Stress Contours, Left: VL Foreshortening, Right: No VL Foreshortening.

The next step was to subject this instantaneous geometry to a representative fluid flow. Given the relevant geometric features of these parachutes, particularly the ribbons and the spacing between them as they relate to the size of the parachute as a whole, the resulting necessary fluid mesh density restricts what could be accomplished from a typical FSI simulation standpoint. Because the ribbon spacing is relatively small, it requires a substantial number of fluid elements to accurately model the flow between each ribbon. Given Airborne Systems' current computing hardware capabilities, the number of fluid elements required to model the entire parachute with a representative fluid domain was far greater than could be efficiently managed. By taking advantage of the axisymmetric nature of the parachute geometry, and by making the assumption of axisymmetric flow around the parachute, the resulting fluid domain size can be dramatically reduced and enable higher fidelity results on a more focused area. Consequently, a thin slice of fluid encompassing half of the parachute diameter was determined to be representative of the system. Figure 8 depicts the LS-DYNA fluid model.

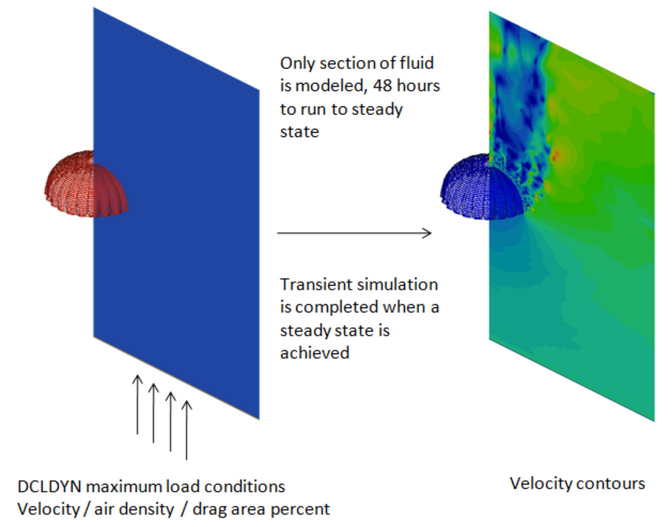

Figure 8. LS-DYNA Flow Field Generation

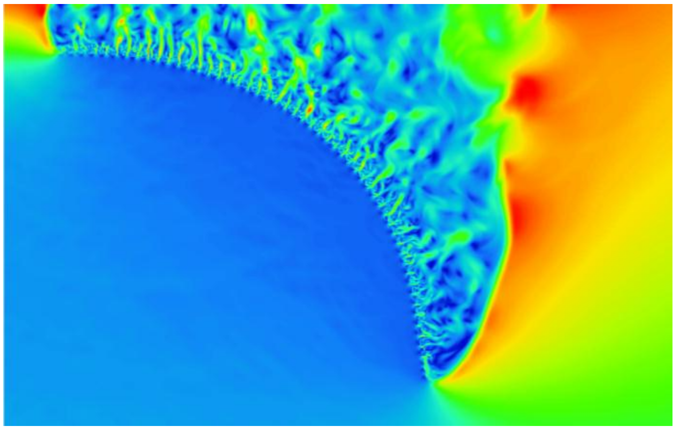

Figure 9. Fluid Flow Velocity Contours

The fluid model is used to define the differential pressure acting on the parachute at the instant the parachute reaches the point of maximum parachute force. This differential pressure can be extracted and applied separately to the structural model shown in Figure 4.

Figure 9 illustrates the contours of fluid velocity surrounding the section of the ribbon canopy in the fluid mesh.

The uniform pressure that was originally applied in the structural simulation was then updated to reflect the data obtained from the fluid model and the simulation was re-run to acquire a new more accurate parachute canopy shape. That simulation was allowed to reach its steady state and then the axisymmetric parachute canopy mesh section was again exported into the fluid mesh and another iteration of the flow field simulation was conducted. Upon the completion of the fluid simulation, another C_p curve was generated and this process was continued until the difference in geometry was negligible, (1-2 iterations). This canopy shape is then considered to be representative of the parachute canopy under these particular flight conditions. As such, the resulting principal stresses in the 2-D shell elements (fabric running loads) should be characteristic of the stresses that the actual parachute canopy fabric will experience in flight at the point of maximum total parachute load. Table 2 displays the difference in parachute component loading between the peak parachute force for the nominal and the maximum dispersed scenarios.

Table 2. Normalized Parachute Component Loading

	Nominal (79% CdS)	**Maximum Dispersed (130% CdS)**
Crown Ribbons	1	0.92
Mid Ribbons	1	1.22
Skirt Ribbons	1	1.25
Radials	1	1.09

V. Conclusions

This paper has described the use of a novel parachute analysis methodology that combined an empirically based heritage parachute design code and Monte Carlo simulations with a commercially available transient dynamic finite element code to provide an analytical predictive capability. The methodology is based on an understanding of the limitations of the modeling and a requirement to balance the variations in the design and operational conditions with the accuracy of the model. The methodology is focused on being an efficient addition to current analysis activities and not a means of creating good images.

The commercially available code LS-DYNA has been utilized for its advanced fabric membrane element formulations and its unique fluid structure interaction capabilities. LS-DYNA is a commercial version of the DYNA3D code developed at Lawrence Livermore National Laboratories.

A particular benefit of the analytical methodology described herein is that it's split into discrete sections. This allows the individual sections to be independently verified and validated as opposed to a single all encompassing code that is almost impossible to verify or debug.

This analysis study has highlighted several benefits of the process outlined herein outside of the final results:

- Accurate assessment of ribbon fullness and a visual understanding of the benefits of such a parachute design feature. Sandia personnel noted during the study that this area of the parachute had caused failures in testing and ribbon fullness had been incorporated as a result of these failures. The use of this computational process in such a new parachute design would have identified these issues early in the design cycle and as such significantly reduced program cost and risk.
- The visualization of the influence of foreshortening the parachute vent lines was particularly useful in explaining the value of such design features. Vent lines are often foreshortened on existing parachutes, although the extent of the foreshortening is based on experience or testing and not on any analytical process. The methodology in this paper could be used to quantify the extent of the foreshortening required for future parachutes.
- Sizing of parachute pocketbands are another area that is often based on experience and likely requires several iterations to optimize. This design feature could easily be assessed using the analysis methods described in this paper.

Acknowledgments

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References

[1] Hallquist, J. O., "LS-DYNA Theoretical Manual," Livermore Software Technology Corporation, 1998.

[2] Pepper Jr, W. B., "Design and Development of the 24 ft Diameter Hybrid Kevlar-29/Nylon Ribbon Parachute," Paper # 79-0433, 6th AIAA Aerodynamic and Balloon Technology Conference, 1979

[3] Murray, J.C., and Wolfe, W.P., "Quantification of Margin and Uncertainty Study of Deceleration Environment Sensors for a Ribbon Parachute," 21st AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, 2011 Dublin, Ireland.