The DCLDYN Parachute Inflation and Trajectory Analysis Tool – An Overview

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The Irvin Aerospace (Irvin) trajectory and parachute inflation tool DCLDYN (Decelerator Dynamics) has been in existence for many years, with algorithmic portions beginning in the later stages of the Apollo program. The ensuing years, particularly the past ten, have provided a number of added simulation capabilities and upgrades, building on these basic algorithms. Some of these capabilities include:

1) **Air Delivery Modeling to include cargo motion restrictions while inside a delivery aircraft**
    a. **Floor friction and restraints**
    b. **Models for gravity drop**
    c. **Tip Off model for the aircraft ramp**
2) **Ejection seat models to include:**
    a. **Rocket/Catapult performance**
    b. **DRI and similar exposure calculations**
3) **Significant cargo models that include:**
    a. **High end aerodynamic models that include multiple Mach and AOA tables**
    b. **Multiple harness attachment point models for re-orientation simulations**
    c. **Aerodynamic databases that closely compare to those from other customers such as NASA**
4) **A Trajectory Restart Capability that Greatly Reduces the effort to complete trajectories with multiple parachutes**
5) **Monte Carlo Analysis by completing an outer loop around the basic DCLDYN tool**
6) **Significant variants that provide additional capabilities, including:**
    a. **Customer deliverable simulation that is designed to attach to a customer simulation**
        i. **Fully 6 DOF Parachute**
        ii. **Called from customer simulation, provides high fidelity parachute model for flight models**
    b. **Re-orientation variant that provides high fidelity in parachute harnesses between cluster confluence and vehicle**
        i. **Includes harness release and damper input channels for investigation of the dynamics maneuver and potential controls.**
7) **The use of FEA tools, as appropriate to complete the above tasks**
    a. **Differences between rigid and flexible representation of the parachute**

This paper will present an overview of the above capabilities and the related algorithms. Additionally, we will discuss future capabilities we are working to incorporate into this unique tool.

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I. Basic Algorithm

DCLDYN models the vehicle/parachute system as 2 point masses, one for the vehicle and one for the parachute system. Initially (before parachute deployment begins) the parachute pack is contained with the vehicle, therefore there is only one point mass (vehicle mass and parachute system mass). After deployment begins, there are two coupled masses, the vehicle and the parachute system. The parachute system mass decreases as the parachute deploys (i.e. riser deploys, then suspension lines deploy, etc.). These coupled masses are connected by an elastic spring, (i.e. riser and suspension lines) which is assumed to be linear (See Fig. 1). At line stretch an estimated percentage of the parachute mass is snatched (accelerated to the vehicle velocity). During inflation, the parachute mass increases due to the added mass of the air contained ‘inside’ the inflating parachute.

DCLDYN models the vehicle and parachute in 3 DOF or planar motion. The motions are X-axis translation (i.e. range) and Z-axis descent or climb (i.e. altitude), and pitch plane rotation.

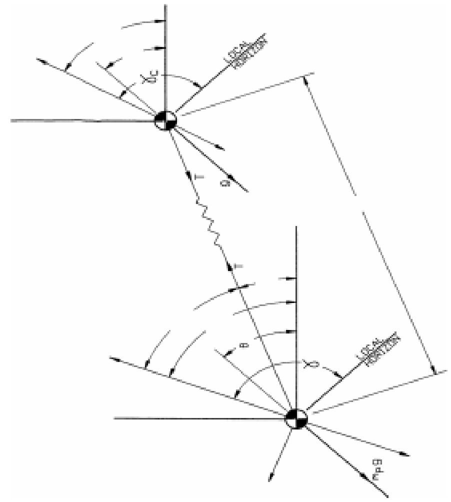

Figure 1.

The vehicle equations of motion are as follows:

$$m_C \dot{V}_C = -D_C - m_C g \sin\gamma_C - T\cos(\gamma_C - \gamma_P - \alpha_P) \tag{1}$$

$$m_C V_C\left[\dot{\gamma}_C - V_C \cos(\gamma_C / r)\right] = T\sin(\gamma_C - \gamma_P - \alpha_P) - m_C g \cos\gamma_C \tag{2}$$

$$V_C = V_{CO} + \int_0^t \dot{V}_C \, dt \tag{3}$$

$$\gamma_C = \gamma_{CO} + \int_0^t \dot{\gamma}_C \, dt \tag{4}$$

The parachute equations of motion are:

$$(m_P + m_A)\dot{V}_P + V_P \dot{m}_A = T\cos\alpha_P - D_P - m_P g \sin\gamma_P \tag{5}$$

$$(m_P + m_A)V_P\left[\dot{\gamma}_P - V_P \cos(\gamma_P / r)\right] = L_P - m_P g \cos\gamma_P - T\sin\alpha_P \tag{6}$$

$$V_P = V_{PO} + \int_0^t \dot{V}_P \, dt \tag{7}$$

$$\gamma_P = \gamma_{PO} + \int_0^t \dot{\gamma}_P \, dt \tag{8}$$

Space position:

$$\zeta_C = \zeta_{CO} + \int_0^t V_C \sin\phi_C \, dt \tag{9}$$

$$\xi_C = \xi_{CO} + \int_0^t V_C \cos\phi_C \, dt \tag{10}$$

$$\zeta_P = \zeta_{PO} + \int_0^t V_P \sin\phi_P \, dt \tag{11}$$

$$\xi_P = \xi_{P0} + \int_0^t V_P \cos\phi_P \, dt \tag{12}$$

$$L = [(\zeta_C - \zeta_P)^2 + (\xi_C - \xi_P)^2]^{1/2} \tag{13}$$

$$Y_C = Y_{C0} + \int_0^t (V_C \sin\gamma_C)dt \tag{14}$$

$$Y_P = Y_{P0} + \int_0^t (V_P \sin\gamma_P)dt \tag{15}$$

$$r_C = R_0 + Y_C \tag{16}$$

$$r_P = R_0 + Y_P \tag{17}$$

Angular position:

$$\phi_C = \theta_C + \gamma_C - 90° \tag{18}$$

$$\theta_C = \theta_{C0} - \int_0^t V_C \cos(\gamma_C / r)dt \tag{19}$$

$$\phi_P = \theta_P + \gamma_P - 90° \tag{20}$$

$$\theta_P = \theta_{P0} - \int_0^t V_P \cos(\gamma_P / r)dt \tag{21}$$

$$\alpha_P = \phi_P - \delta \tag{22}$$

$$\delta = \tan^{-1}[(\zeta_C - \zeta_P)/(\xi_C - \xi_P)] \tag{23}$$

A. Added Mass

The inflating parachute variable mass characteristics are simulated by a mode approximating the effects of shape and volume changes during inflation. The total added mass (m_A) is comprised of included mass and apparent mass:

$$m_A = m_I + m_a \tag{24}$$

The volumetric growth of the canopy is derived, therefore the included mass is expressed as:

$$m_I = \rho V \tag{25}$$

The apparent mass terms for transient parachute shapes in potential flow are non-existent. Therefore, the approach is taken to approximate the inflating parachute by an ellipsoid of revolution for which a potential flow solution exists. Specifications of the ellipsoid are constrained at each point during inflation by setting one axis of the ellipsoid equal to the instantaneous projected radius while the magnitude of the remaining axis is computed from the appropriate time dependent volume. Thus, the parachute progresses from a prolate to an oblate ellipsoid.

In accordance with the above:

$$m_a = k_1 \rho R_P^3 \left(\frac{4\Pi}{3}\right) \tag{26}$$

where k_1 is obtained by calculating C as follows:

$$C = \left[\left(\frac{3}{4\Pi}\right)\left(\frac{V}{R_P}\right)\right]^{1/2} \quad \text{for } C/RP > 1 \tag{27}$$

$$C = \left(\frac{3}{4\Pi}\right)\left(\frac{V}{R_P{}^2}\right) \quad \text{for } C/RP \le 1 \tag{28}$$

Additionally, the time rate of change of the added mass is needed to solve the parachute equations of motion.

$$\dot{m}_A = \frac{d}{dt}(m_I + m_a) \tag{29}$$

$$= \rho\dot{V} + (3k_1 R_P^2 \dot{R}_P + R_P 3\dot{k}_1)\rho\frac{4\Pi}{3} \tag{30}$$

where differentiation of input data generates $\dot{V}$, $\dot{R}_P$, and $\dot{k}_1$.

B. Deployment Time Calculation

DCLDYN calculates a good estimate of the deployment time. The parachute component weight input data provided in an input file makes the DCLDYN deployment time calculation unique. This data allows the mass of the parachute system to vary as the system is deployed. Also, the dynamic pressure wake loss factor and minimum required extraction force can vary during deployment. A deployment force value may also be input. This inputted force can be used to model deployment techniques such as drogue guns, extraction rockets, or mortars, where a relationship between deploying force and time can be estimated. DCLDYN uses all this input data, along with the equations of motion given above, to calculate the distance (spring length) between the parachute and vehicle.

C. Snatch Force

An important and useful feature of DCLDYN is the ability to estimate the snatch force that a deploying parachute imparts on a vehicle. This is possible because DCLDYN assumes that the parachute mass and vehicle mass are connected by an elastic spring consisting of the riser, suspension lines, and radials. DCLDYN calculates the spring constants to calculate the force in the connecting spring.

Three spring constants (K, K2, K3) are required, one for each of the linear regions: Mechanical elongation (ME), Limit elongation (LE), and Unload (UL) (Fig. 2).

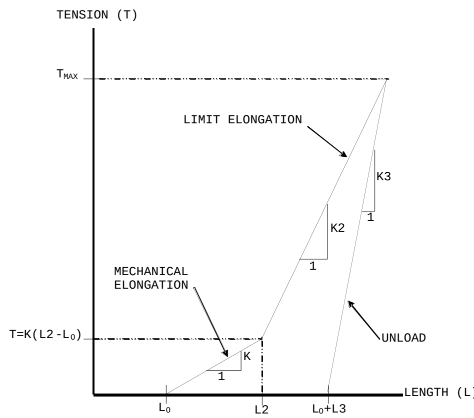

Figure 2.

II. Special Models

A. Air Delivery

The air Delivery model in DCLDYN includes computation of the forces associated with the aircraft floor system while the cargo is in the aircraft. These include capabilities for both gravity drop and cargo extraction. The basic algorithm includes the following forces associated with the aircraft floor:

1) Friction from the floor system
2) Gravity force vector based on the current deck angle
3) Application of extraction parachute forces
4) Elimination of aerodynamic forces while in the aircraft

Additionally, a tip off force is computed as the cargo leaves the aircraft ramp. This computation includes the elimination of this force, once the cargo has rotated sufficiently to clear the ramp.

B. Crew Escape

The crew escape model includes a series of calculations related to ejection seat applications. This includes the application of rocket motor force time history to allow simulation of the ejection stage. The force time history includes location, force and direction to allow simulation of later generation ejection seats.

When this model is activated, and additional set of parameters are computed and output. These include the Dynamic Response Index (DRI) and related parameters, allowing for a preliminary assessment of the exposure of the occupant to the escape accelerations.

C. Aerodynamic Models

The basic aerodynamic inputs into DCLDYN include C_l, C_d, C_m, and C_{mq} versus angle of attack. If vehicle specific data is not available, these inputs can be given generic values, and the vehicle is modeled as a point mass. It is also possible to include vehicle aerodynamic data over a range of Mach numbers, through a separate look up file.

III. Special Inputs

In recent years, we have added a significant number of special input parameters. Hot and Cold day atmospheres were added to augment the basic Standard Day atmosphere. These are still available and are employed routinely.

Additional capabilities include special inputs that are user defined. A wind versus altitude look up table (LUT) option is provided. Also, a LUT implementation for a user defined atmosphere is included, allowing all required inputs to be specified. The combination of the two provides powerful capabilities for a number of conditions.

A. Wind Data

Wind inputs are used to compute cargo and parachute location in Euler coordinates. The basic computational algorithm assumes that the parachute forces are computed in the wind relevant axis system. An additional set of integrators compute the Earth relevant (or Planetary) coordinates based on assumed motion with the wind. For large parachutes, and relatively steady winds, this assumption is very applicable.

In a recent test, pre-flight predictions, including seasonal wind variations, were validated, as the cargo location at the prescribed time was very close to the actual measurement.

Our use of this capability also includes a Monte Carlo class assessment of the seasonal winds for a particular delivery. In these cases, our customer delivers sample wind profiles, usually 500 – 1500, for the expected mission month(s). Monte Carlo analysis of this profile provided a predication of possible cargo locations for the next phase of the flight. These data are then used to analyze the next phase of the cargo flight. Fig. 3 provides a ‘Meat Ball’ plot of the cargo position at the end of the parachute flight.

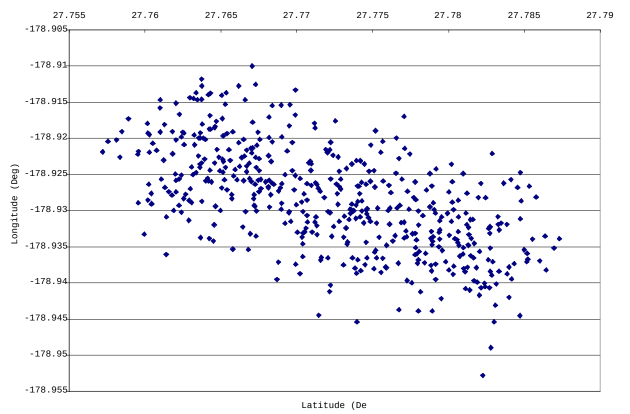

Figure 3. ‘Meat Ball’ Plot of Cargo Position due to Wind Variations

B. Atmospheric Data

The DCLDYN model provides a number of levels of user input related to the atmospheric data. The most simple level is a Standard Day Earth atmosphere with zero winds.

At a slightly higher level, keyword inputs allow the selection of Hot and Cold day atmosphere models, and similarly, a constant wind for all altitudes can be provided for cases where wind velocity variation with altitude is minimal.

Another keyword input allows the selection of a single available Mars atmosphere, including the parameters of density, pressure, and speed of sound, versus altitude. This single atmosphere has been compared to more detailed atmospheric models, and is useful for quick checks of Mars conditions.

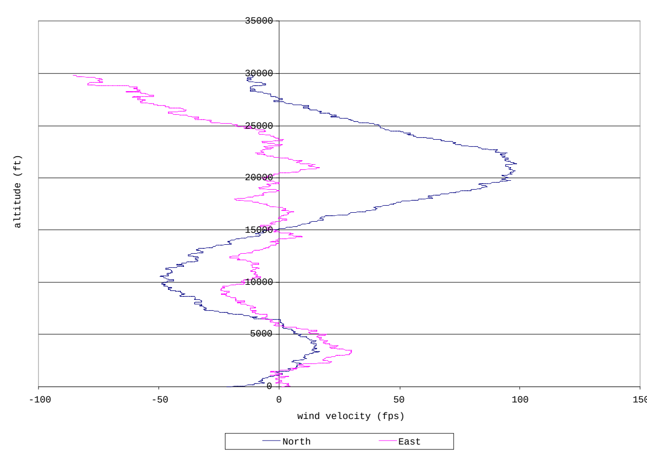

Figure 4. Wind Velocity Distribution for an Earth Flight

Finally, a full input of both wind and atmospheric data is available. This approach uses Look Up Table (LUT) versus altitude format, allowing for both Earth and planetary inputs of wind and atmosphere files. Examples of the importance of these inputs include the large variations of atmospheric density on Mars and the large variations of seasonal wind profiles on Earth. Fig. 4 and Fig. 5[‡] provide examples of the variations in these profiles.

IV. Stochastic and Monte Carlo Analysis

The Monte Carlo capability for DCLDYN was developed to support a specific customer need involving the variation of trajectory input data such as initial deployment conditions, parachute drag area, and parachute inflation time. Additionally, the customer provided a large set of atmospheric data including wind drift and density versus altitude. These also become an input into the simulation exercise.

We are now reviewing the Altair Hyper Study tool, which could provide a simpler implementation to the development of the Monte Carlo analysis, as well as automated capture of a large number of the basic results.

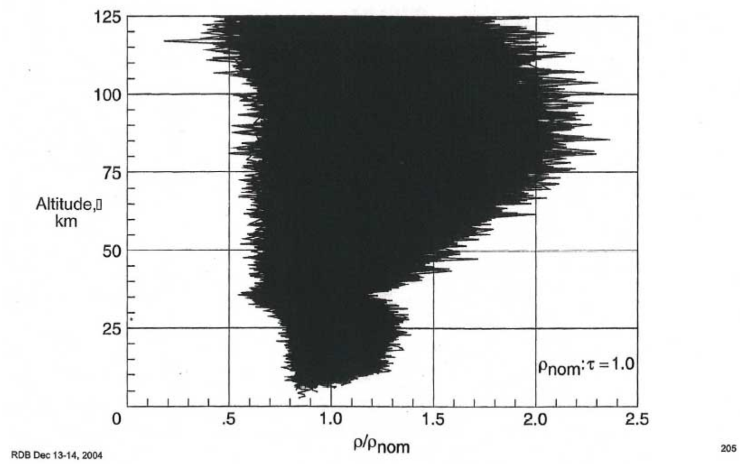

Figure 5. Atmospheric Density Distribution for Mars

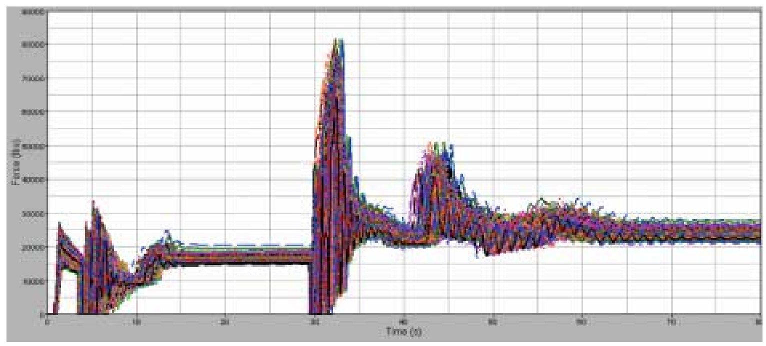

Figure 6. Summary of force time histories for a large number of runs.

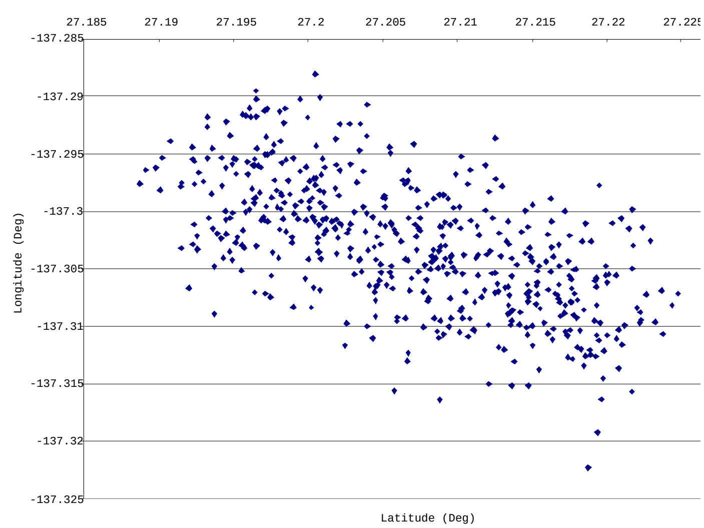

Figure 7. An example of cargo position at a specific point in the flight.

A. Scripts as an Outer Loop

Our first approach, still in use, to the development of a Monte Carlo capability was to create a series of scripts that create the required files for the analysis. These include wind and atmosphere input files converted from the customer provided data file to DCLDYN format. Our experience is that the customer format is not always the same from program to program.

The basic input decks are also created for each Monte Carlo simulation. Here, parameters such as delivery airspeed, altitude, and heading are varied. Uniform and Gaussian distributions are available, and variation ranges are agreed upon with the customer, before the analysis is begun.

Next the simulations are conducted. Often a number of individual steps are required. For instance, in an air delivery case, the extraction phase is modeled and the simulation is terminated at parachute release. Each individual case is then restarted using the end flight

[‡] Planetary Entry, Descent and Landing, Dr. Robert D. Braun

conditions from the previous case. This allows the performance of the descent main parachute system to be modeled effectively and accurately.

For other systems, different stages of parachutes or additional simulations might be required. For instance, in an Air Launch Target simulation, a mass change occurs at target release. Another series of simulations allow for tracking of the parachutes and expended cargo pallet/cradle after target release.

Data derived from this database include peak forces, used to complete an enhanced structural analysis, and position of the system versus time. A very large number of parameters are created, and the review of data can be extensive. For instance, we had concluded that the database generated by a recent analysis contained approximately 190 MM numbers. Fig. 6 and Fig. 7 provide examples of output results.

B. Altair HyperStudy

Irvin uses the HyperWorks Suite of tools to support FEA and FSI analysis of a number of systems. One of the tools included in the suite is HyperStudy, which features significant capability for Design of Experiments (DOE), Stochastic, and Optimization analysis of systems. These capabilities are currently being used in our FEA and FSI simulations. However, we believe that the same tool is extensible to parachute trajectory analysis. The HyperStudy script interface allows the basic tool to interface with most text based simulation input decks, such as the DCLDYN input format.

Assuming we can complete the required interfaces for additional files, such as wind and atmospheric data, the HyperStudy tool will offer a level of sophistication not currently available. Some of these include:

1) Full review of important results during the simulation
2) Summary of all key results with no additional processing
3) DOE Class analysis – we are currently using this for an FEA class analysis
4) Stochastic Analysis – what is the effect of a certain parameter
5) Optimization Analysis – have used this for airbag landing performance

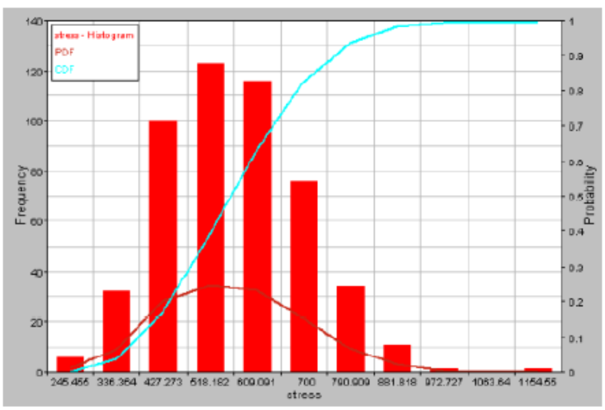

Figure 8.

While the handling of data seems trivial, we can assure the reader that when 1500 run cases, potentially involving 2-3 different configurations each, are involved, this data processing becomes significant. More importantly, the DOE class analysis and optimization are beginning to become a portion of the Irvin tool set.

Using the optimization capabilities found in HyperStudy, the optimization of a parachute trajectory is possible. For instance, this tool would aid in efficiently determining the best parachute system for a minimum altitude recovery at a given load, or the best sequence for a minimum load recovery with a given altitude loss. While we all work these optimizations on an intuitive and iterative basis, our experience with similar work in the airbag landing world has shown that the computer provides better optimization than our engineering based iterations.

Fig. 8 and Fig. 9 provide example results from an optimization and stochastic simulation analysis. These results are not related to parachute trajectories, but similar results will be available once we have integrated the trajectory and study tools.

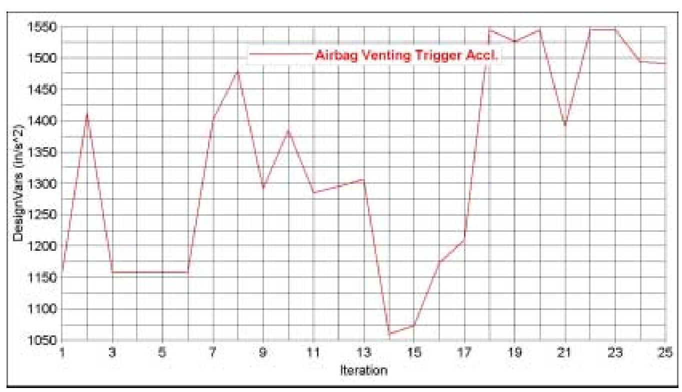

Figure 9. Optimization Result

V. Special Variants

A couple of special variants of the basic DCLDYN algorithms exist. These were created to provide specific capabilities as required by customers. While neither of these models provide the level of detailed capability and varied input as reported above, they do deserve mention, as they provide another level of analysis capability and customer support. The variants described include a full 6 DOF version of the DCLDYN parachute model that is designed to couple to a customer's 6 DOF simulation of a basic aircraft/spacecraft. The other significant variant is a three body simulation (3 DOF per body) which provides a reference for a parachute confluence fitting and harness leg suspension. This model allows the detailed review of vehicle motion and harness loads during highly dynamic events, such as vehicle re-orientation.

A. Six DOF Variant

Several years ago, one specific Irvin customer required a 6 DOF version of the DCLDYN parachute simulation. Irvin created this model and worked with the customer to integrate the parachute model into a larger model of the customer aircraft. In this program, we successfully coupled the parachute simulation to the customer simulation for an aircraft stall recovery.

This sophisticated analysis included all of the nonlinear parachute inflation terms discussed above. The parachute module was called by the higher vehicle simulation and parachute forces were returned to the vehicle simulation for input into that model.

We successfully completed stall recovery simulations of the subject aircraft. We were also working to complete simulations of a spinning aircraft, however, having the detailed aerodynamics to simulate a spinning aircraft, to this day, remains somewhat elusive. Towards that end, our analysis took the approach of a classic spin mode analysis, which used parametric prediction of spin modes. In these cases, we were able to demonstrate that the addition of the parachute aerodynamics changed the parametric predictions, such that the spin mode was eliminated. This remains an available approach for spin and stall analysis, particularly for programs that do not have the development dollars to complete a spin tunnel entry.

The simulation tool remains available to couple to any customer simulation. We have used this tool conceptually to review parachute performance for re-entry vehicles (Kistler) and for models of Para-Trooper exit. Fig. 10 provides a time history of angle of attack for a 'locked in deep stall' and a parachute recovery.

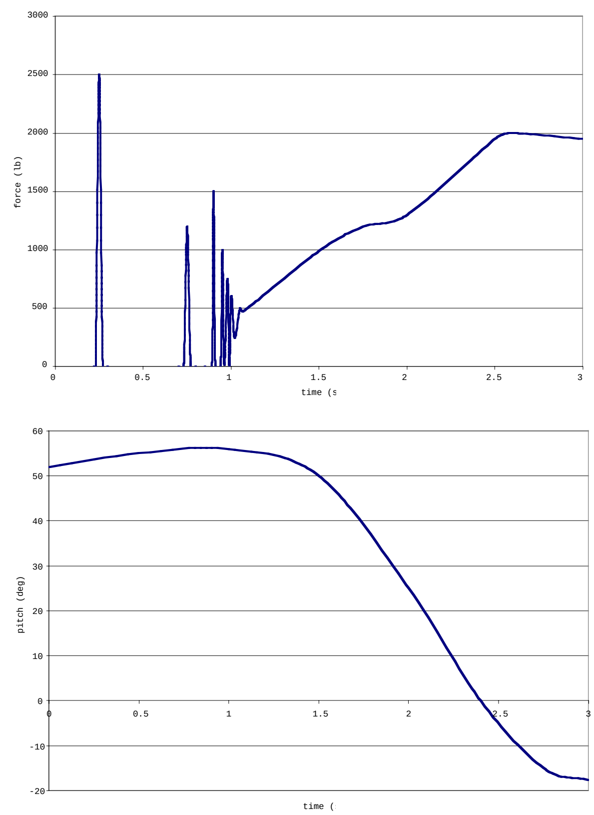

Figure 10. Aircraft Pitch Attitude and Parachute Force during a Simulated Stall Recovery

B. Three Body Model

Another significant variant is our 3 body, 9 DOF model. This model was created during the EELV program as the position of the parachute confluence fitting and harness legs were extremely important to that spacecraft configuration. Fig. 11 provides an illustration of the parachute harnesses in relation to the fragile and potentially sharp Space Shuttle Main Engine (SSME) nozzle. Also, there was a potential that contact between the parachute and nozzle could occur while the nozzle was still hot, providing an additional risk to the recovery system.

Figure 11.

On other programs, the ability to predict parachute forces during vehicle re-orientation has been an important issue. Both FEA based tool and this DCLDYN tool are available for those predictions. However, when the vehicle aerodynamics are a significant part of the re-orientation maneuver, this DCLDYN variant provides the ability to input the relevant aerodynamic terms for the cargo vehicle. A simple example of this situation is the Kistler second stage, which completes this maneuver under drogue parachute.

VI. Conclusions

The Irvin DCLDYN program is a powerful tool for performing parachute trajectory simulations. The basic version is used at Irvin on a daily basis to complete a variety of systems analysis including primary parachute design, basic system sizing and test trajectory development.

We have had multiple opportunities to validate the basic algorithms, both against test data and trajectory tools used by others, such as NASA JSC.

Significant variants of the basic tool exist for unique cargo motions, multi-body simulations and coupling to other simulations, such as customer vehicles or unique plant models.

Finally, a basic capability exists to provide higher order investigations, such as stochastic analysis through the Monte Carlo approach. We are currently increasing these capabilities, by coupling to a commercial tool already used for FEA class analysis. This will provide capabilities for enhanced stochastic analysis, particularly during the data extraction effort. Additionally, Design of Experiment (DOE) analysis, and system optimization will be possibly. We may shortly reach a state, where our tools are optimizing a recovery trajectory, rather than relying on tried and true engineering rules of thumb.