Computer Simulation and Evaluation of Static Line Deployment Procedures

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Computer simulations of static line deployment of paratroopers are performed using a nonlinear transient finite element model. The model consists primarily of three-dimensional cable elements to represent the static line, un-inflated canopy, suspension lines and risers, and three-dimensional brick elements to model the paratrooper body. The deployment process is divided into three distinct phases which are captured using various constraint equations within the model. The model is calibrated for a standard T-10 parachute system using a limited amount of data extracted from video of actual paratrooper deployments. The calibrated model is then used to perform parametric studies where various system properties are changed to evaluate the sensitivity of the system to these changes. The parametric study includes changes in paratrooper weight, paratrooper exit velocity, paratrooper exit direction, aircraft velocity, and static line length. A method is presented to use the static line deployment model with flow fields obtained from large scale computational fluid dynamics simulations.

I. Introduction

PARACHUTE systems have traditionally been designed using semi-empirical methods supplemented by extensive laboratory and field testing [1]. This approach to design results in high development costs and may slow the transition from concept to final product by requiring multiple prototypes and testing programs. The ability to predict the behavior of parachute systems using computer models will complement the existing design methods and potentially speed up the design process and reduce development costs.

In this paper, a computer model is developed to simulate the dynamic behavior of paratroopers during initial deployment. The initial deployment process begins when the paratrooper exits the aircraft and ends when the parachute has been fully extracted from the deployment bag. The initial deployment is followed by inflation of the parachute and terminal descent of the paratrooper to the ground. For large scale deployments, it is standard practice for each paratrooper to use a static line which is a cable connecting the paratrooper's deployment bag to an anchor line within the aircraft. As the paratrooper falls away from the aircraft, the static line stretches to full length and extracts the parachute from the deployment bag [1].

Although static line procedures and hardware have been established [2], abnormal deployments still occur that may result in serious injury or death of a paratrooper and termination of the mission [3]. Therefore, improved procedures for initial deployment of paratroopers remain a high priority. The deployment problem, however, is extremely complex from an engineering viewpoint and the existing procedures have primarily been developed, out of necessity, by trial and error. These procedures, therefore, may only be appropriate for specific operating conditions,

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such as a specific type of aircraft, aircraft speed, paratrooper weight, etc. The number of system parameters is large and physical testing is cost prohibitive. Therefore, alternate methods of analysis for this problem are desirable.

A review of the technical literature indicates that a limited amount of work related to the paratrooper deployment problem has previously been performed. From an engineering viewpoint, the paratrooper deployment problem is highly dynamic and nonlinear, which makes it extremely difficult to formulate and solve analytically. On the other hand, numerical and computational methods have advanced significantly since the 1960s. Purvis developed a basic discrete element model in 1984 to predict parachute extraction during deployment [4]. Although this work is related to the paratrooper deployment problem, the modeling used is somewhat simplistic and significantly better methods have been developed in the twenty years since this was performed.

In this paper, a geometrically nonlinear transient finite element (FE) model is used to simulate static line deployment (SLD) of paratroopers. The theoretical foundation of this model is given by Accorsi *et al* [5]. In the following section, the mechanical model used for the paratrooper and parachute system is described. Next, the mechanical model is calibrated using a limited amount of data extracted from video of actual paratroopers. The calibrated model is then used to perform a small parametric study where various system properties are changed. Finally, a method is presented to use the SLD model with flow fields obtained from large scale computational fluid dynamics (CFD) simulations.

II. The Static Line Deployment Model

The SLD model is used to simulate the period prior to inflation of the canopy, and therefore the canopy is modeled as a three-dimensional deformable cable as opposed to being modeled with three-dimensional membrane elements which is necessary for post inflation behavior. The SLD model is otherwise very general and can be used to simulate the deployment of a variety of parachute systems and payloads. As shown schematically in Fig. 1, the SLD model consists of an anchor point, static line, parachute canopy, suspension lines, risers, body, deployment bag and equipment bag. Three-dimensional geometrically nonlinear cable elements are used to model the static line, parachute canopy, suspension lines and risers. These cable elements have properties of distributed mass, distributed drag, and stiffness in tension but not compression. As discussed later, two node damper elements are also included to model stripping forces which are coincident with all these cable elements. Truss elements are used to hold the equipment bag in position in front of the body. Truss elements are identical to cable elements except that they also have stiffness in compression. The equipment bag is modeled using a point mass element.

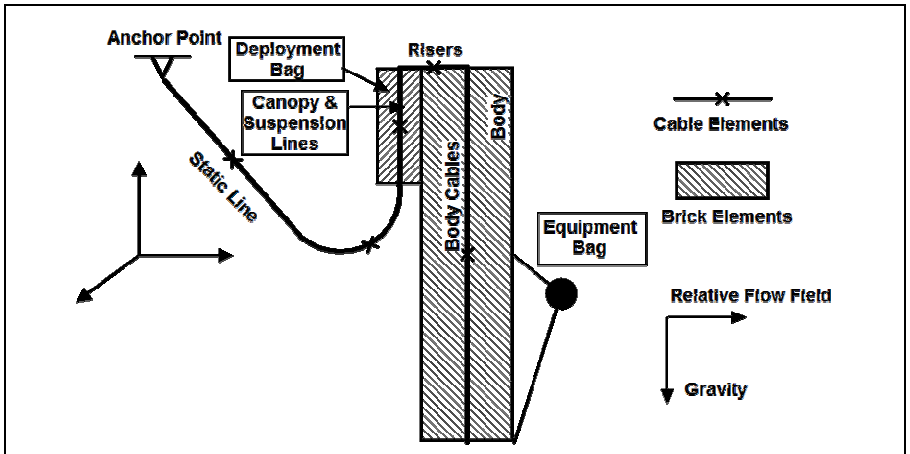

Figure 1. Two-dimensional schematic of the static line deployment model.

The paratrooper body and deployment bag are modeled with three-dimensional geometrically nonlinear continuum or "brick" elements. Brick elements have properties of distributed mass and stiffness. Their primary purpose in this model is to provide the correct mass distribution of the body and correct positioning of the equipment and deployment bags. Cable elements were added to the vertical centerline of the body to model velocity dependent drag on the paratrooper body. A technical description of the drag model used is given by Benney *et al* [7].

Initially, the deployment bag contains the parachute canopy, suspension lines, and a portion of the risers. These elements are distributed evenly inside the deployment bag with prescribed lengths that are much smaller than their true lengths. These elements are held in place inside the deployment bag by constraint equations, which fix the position of their nodes with respect to one edge of the deployment bag element. Likewise, the deployment bag is initially constrained to the body using three sets of constraint equations. One constraint equation is applied at the top and one at the bottom, and the third constraint equation prevents the deployment bag from rotating about the body axis.

The actual SLD model used to simulate deployment is shown in Fig. 2a. This model contains about 100 nodes resulting in approximately 300 degrees of freedom. Orientations relative to the aircraft are shown in Fig. 2b. The SLD exits the aircraft in the transverse direction. For the results presented here, a uniform flow field in the horizontal direction is assumed but efforts to more accurately model the flow field are described in a later section.

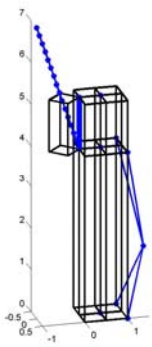

Figure 2a. The SLD model

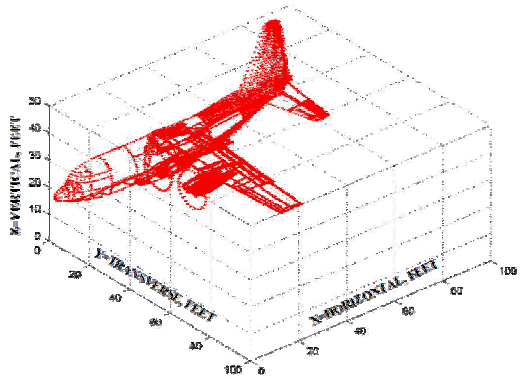

Figure 2b. Orientations relative to aircraft.

The static line deployment process was divided into three separate phases, as shown in Fig. 3. Phase 1 begins when the paratrooper exits the aircraft and ends when the static line is fully elongated. At this point, the static line pulls the deployment bag off the paratrooper's back at the bottom causing the deployment bag to rotate about the top prior to beginning the parachute extraction. Phase 2 corresponds to this part of the process. Phase 3 starts when the parachute system begins to be extracted from the deployment bag and ends when the parachute system is fully extracted.

The unique behavior associated with each of these phases is modeled primarily by retaining or removing the constraint equations. During phase 1 all constraints are active, which holds the cable elements within the deployment bag and fixes the deployment bag on the paratrooper body. For phase 2, the constraints at the bottom of the deployment bag are removed, which allows the deployment bag to rotate about its top. At the beginning of phase 3, all constraints on the deployment bag are removed, which allows the deployment bag to separate from the paratrooper body. During phase 3, the constraints that hold the cable elements within the deployment bag are sequentially removed to allow these elements to be extracted from the deployment bag. A special algorithm is implemented that tracks the length of the element that is currently being extracted. When this length reaches its true length, the algorithm removes the next constraint, which allows the next cable element to be extracted.

III. Calibration of the SLD Model

The SLD model requires various mechanical properties as input which are difficult to estimate theoretically and have not been measured experimentally. These include, for example, the total drag on the paratrooper including the deployment and equipment bags and damping forces that are inherent in the system. Therefore, the model was calibrated using the limited amount of data that could be extracted from video of actual paratrooper deployments.

A. Phase 1

As shown in Fig. 3, all of phase 1 is captured by video. From this video, the horizontal and vertical positions of the paratrooper as a function of time can be extracted. This data is used to calibrate the drag on the paratrooper. Also, the duration of phase 1 can be measured from video. The horizontal and vertical positions of five paratroopers

during phase 1 obtained from video are shown in Fig. 4 and 5, respectively. Also shown as solid curves are the results predicted by the SLD model using the calibrated drag value. Fig. 6 shows both the horizontal and vertical displacements with the averaged data for the five paratroopers. The agreement between the predicted results and data is good.

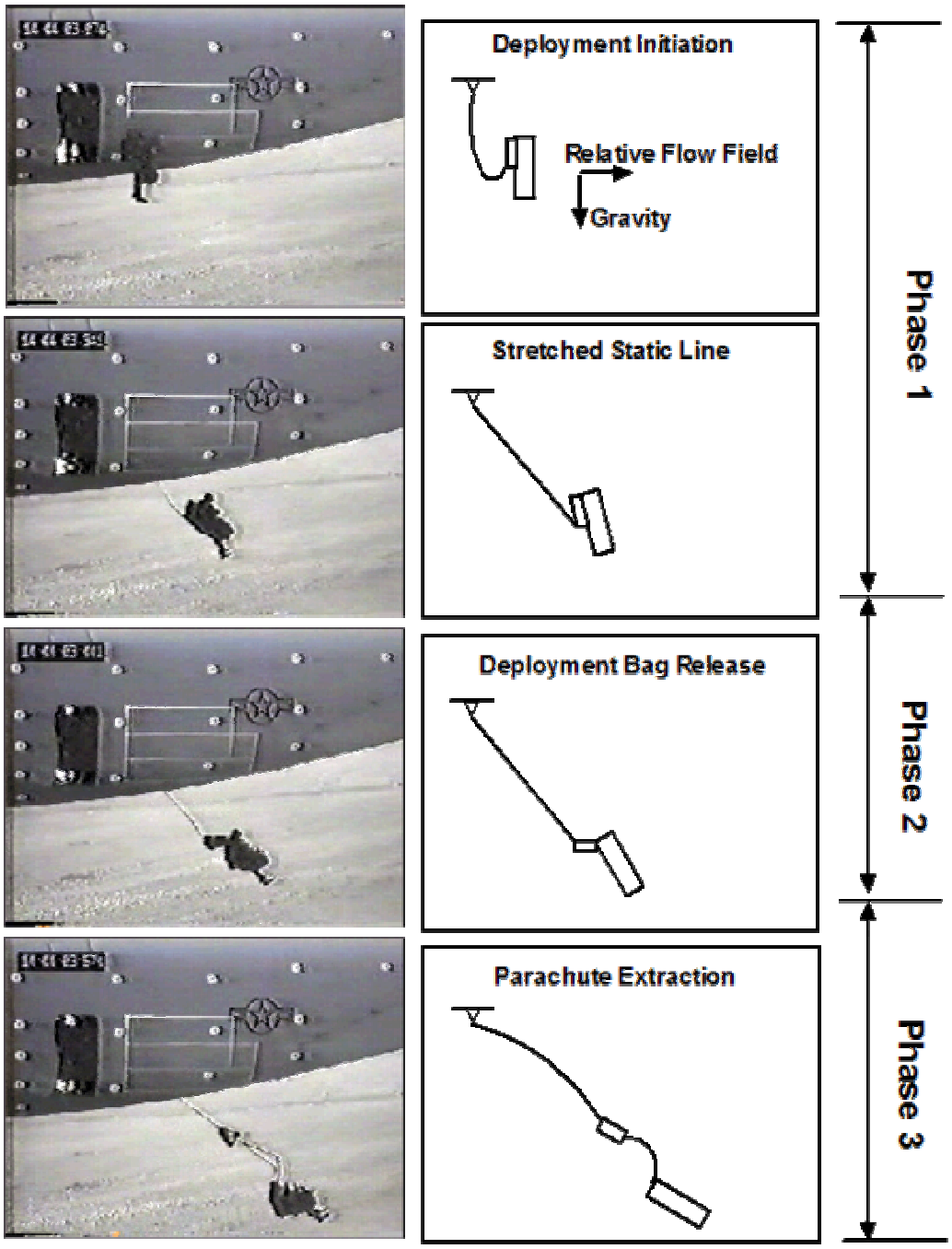

Figure 3. Division of the deployment process into three phases.

The simulation of phase 1 is run for a time of one second with 10,000 time steps. The static line reaches its full length in approximately 0.7 seconds. Fig. 7 shows the final configuration of the model obtained from the phase 1 simulation, which is used as the initial configuration for the phase 2 simulation. In this figure, the static line is blue, the canopy, suspension lines, and risers are green, and the paratrooper body is red.

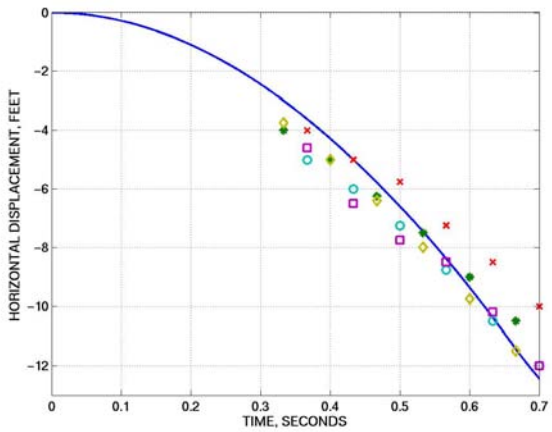

Figure 4. Horizontal displacement of paratrooper during phase 1, SLD model and video data.

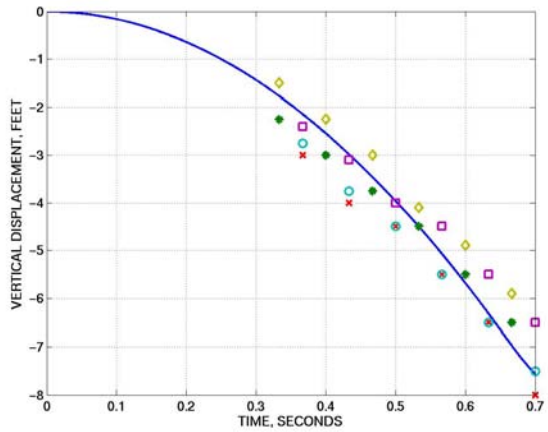

Figure 5. Vertical displacement of paratrooper during phase 1, SLD model and video data.

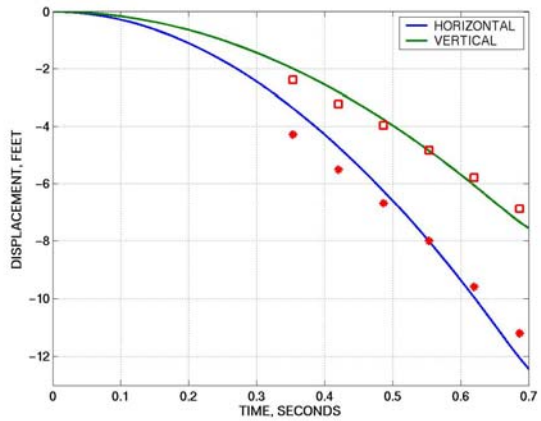

Figure 6. Horizontal and vertical displacement of paratrooper, SLD model and averaged video data.

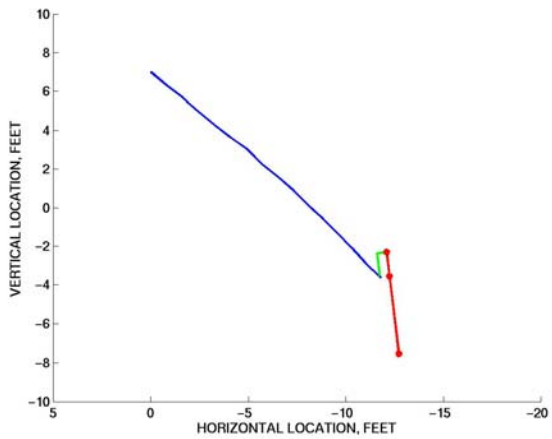

Figure 7. Final configuration of the SLD model for phase 1.

B. Phase 2

Following phase 1, phase 2 simulates the release of the deployment bag from the paratrooper's harness. This is modeled by turning off two of the three constraints holding the deployment bag on the paratrooper. The third constraint pins the top of the deployment bag to the shoulder of the paratrooper. This produces the expected rotation of the deployment bag as shown in Fig. 8. Phase 2 lasts approximately 0.02 seconds and no additional model calibration was performed for this phase. The final configuration obtained from the phase 2 simulation is then used as the initial configuration for phase 3.

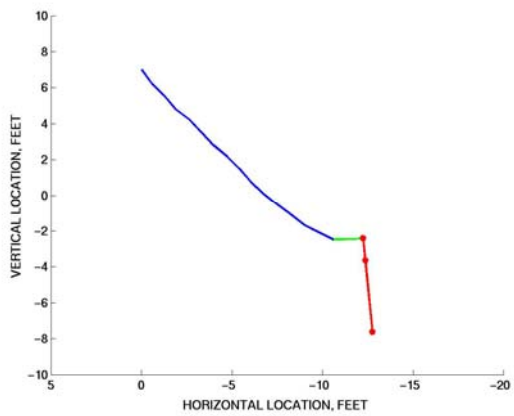

Figure 8. Final configuration of the SLD model for phase 2.

C. Phase 3

During phase 3, the canopy and suspension lines are sequentially extracted from the deployment bag. This phase begins with all three deployment bag constraints removed, which allows the paratrooper to separate from the deployment bag and static line. As each cable element within the deployment bag elongates, constraint equations are sequentially turned off, allowing the next cable element to be extracted from the deployment bag. Fig. 9 shows several configurations of the SLD model during a typical phase 3 simulation.

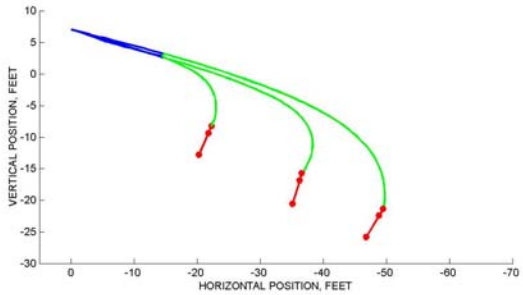

Figure 9. Several configurations of the SLD model during phase 3.

Several mechanical properties were evaluated to calibrate the SLD model for phase 3 simulations, which included numerical and physical damping, and parachute mass and drag distribution. The only data that is available from the video are the times when the suspension lines are fully extracted and when the canopy is fully extracted. In addition to this data, stability of the numerical model is also an issue. Calibration was performed by examining how these mechanical properties affected the predicted extraction times and stability of the model.

Numerical damping tends to remove high frequency behavior without affecting the fundamental low frequency behavior, which is desirable in this application to stabilize the cable extraction without retarding the paratrooper body motion. Several phase 3 simulations were performed with varying amounts of numerical damping. In general, it was found that numerical damping enhanced stability without adversely affecting the paratrooper motion. Therefore, numerical damping was used for all the simulations.

A large number of phase 3 simulations were performed which varied the mass, drag and mechanical damping distributions on the suspension line and canopy cables, and the effect of these changes on the predicted extraction times were evaluated. From video data, the suspension line extraction times ranged from 0.43 to 0.50 seconds and the canopy extraction time ranged from 0.80 to 0.86 seconds from the beginning of phase 3. The final calibrated SLD model for phase 3 uses uniform mass and drag distributions in the suspension line and cable elements, but uses different damping values in these two components to model stripping forces during extraction. The calibrated SLD model gives suspension line and canopy extraction times of 0.48 seconds and 0.80 seconds, respectively.

IV. Static Line Deployment Parametric Study

In this section, a small parametric study is performed to evaluate how changes in several system properties affect the overall behavior of the system. The calibrated model from the previous section is used as the baseline for this study. The effect of changes in paratrooper weight, paratrooper exit velocity, paratrooper exit direction, aircraft velocity, and static line length are evaluated by comparison with the baseline. These five cases are referred to as cases P1 to P5, respectively. For each case, the system configuration in the XZ plane (see Fig. 2b) at two times during phase 3 and the transverse displacement of the paratrooper body is examined.

For the first parametric study (P1), the paratrooper weight is reduced from 200 lb. for the baseline to 100 lb. The weight of the equipment bag (50 lb.) and parachute system (30 lb.) remains fixed. Therefore, the total weight for this case is 180 lb. versus 280 lb. for the baseline (36% reduction). All other properties (i.e. damping, drag, etc.) are the same for this case and the baseline. Results for this case are shown in Fig. 10 and 11. Reduction in overall weight results in significantly higher horizontal displacement and slightly lower vertical displacement as shown in Fig. 10. As shown in Fig. 11, the transverse displacement is significantly smaller for the reduced weight case.

For the second parametric study (P2), the paratrooper exit velocity was increased from 5 ft/s for the baseline to 10 ft/s. For both cases, the paratrooper exits the aircraft in the transverse (Y) direction and enters a horizontal flow field (X direction) and vertical gravity field (Z direction). As seen in Fig. 12, the increase in exit velocity has virtually no effect on the horizontal and vertical position of the paratrooper. As expected, there is a significant increase in the transverse displacement for this case which is shown in Fig. 13.

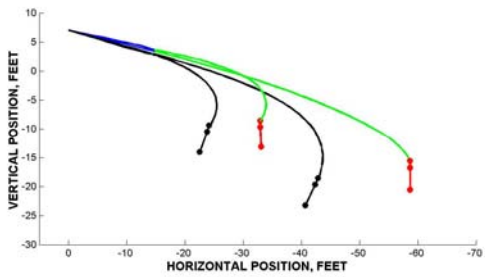

Figure 10. Configuration in XZ plane, P1 (color) and base (black)

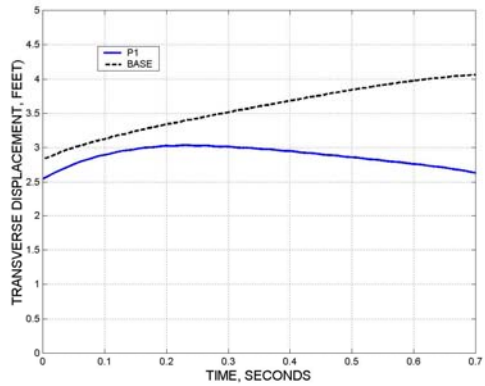

Figure 11. Transverse displacement, P1 and Base

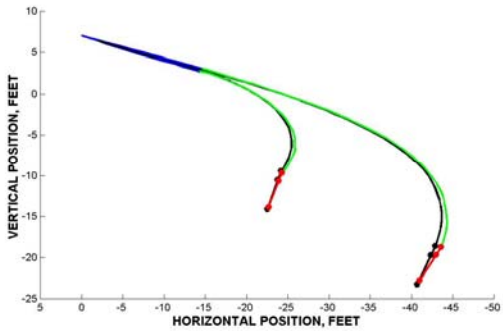

Figure 12. Configuration in XZ plane, P2 and base

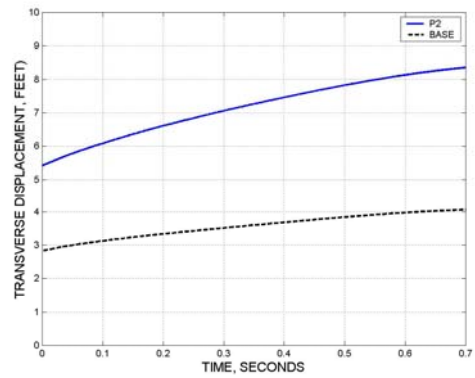

Figure 13. Transverse displacement, P2 and Base

For the third parametric study (P3), the paratrooper exit direction is changed from the transverse (Y) direction for the baseline to 45^0 into the flow field in the horizontal direction. As expected, this change has the effect of increasing the horizontal displacements and decreasing the transverse displacements as seen in Fig. 14 and 15.

For the fourth parametric study (P4), the aircraft velocity is decreased 10% from 236 ft/s (140 knots) for the baseline to 212 ft/s (126 knots). The primary effect of this change is to reduce the drag force in the horizontal direction resulting in a decrease in the horizontal displacement as seen in Fig. 16. For this case, the corresponding changes in the vertical (Fig. 16) and transverse (Fig. 17) displacements are small.

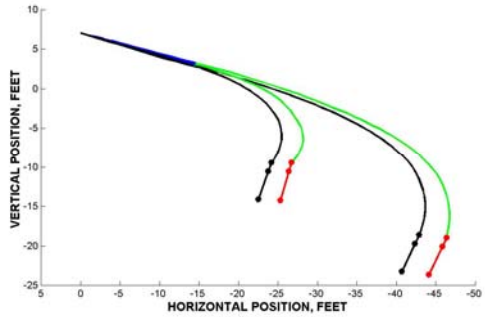

Figure 14. Configuration in XZ plane, P3 and base

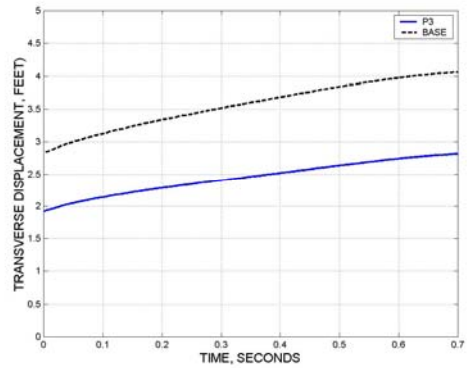

Figure 15. Transverse displacement, P3 and Base

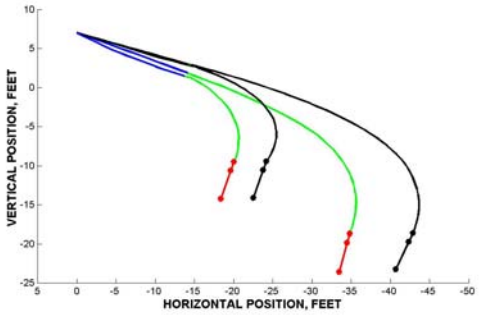

Figure 16. Configuration in XZ plane, P4 and base

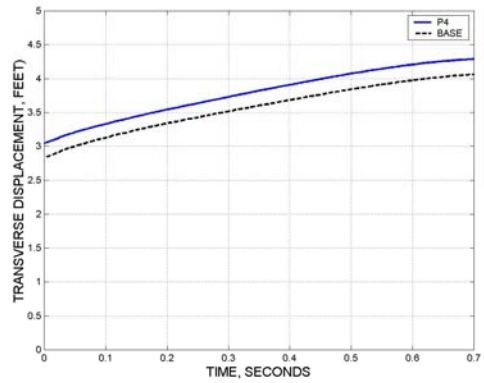

Figure 17. Transverse displacement, P4 and Base

For the fifth parametric study (P5), the length of the static line is reduced from 15 feet for the baseline to 12 feet. As seen in Fig. 18 and 19, this change has only a minor effect on the horizontal, vertical, and transverse displacements of the system. Considering that the length of the entire system (static line + canopy + suspension lines + risers) is about 64 feet, the insensitivity of the results to the 3 feet change in static length is understandable.

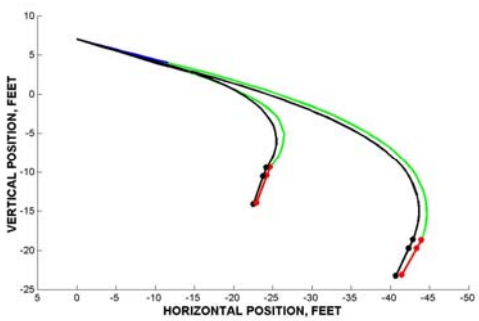

Figure 18. Configuration in XZ plane, P5 and base

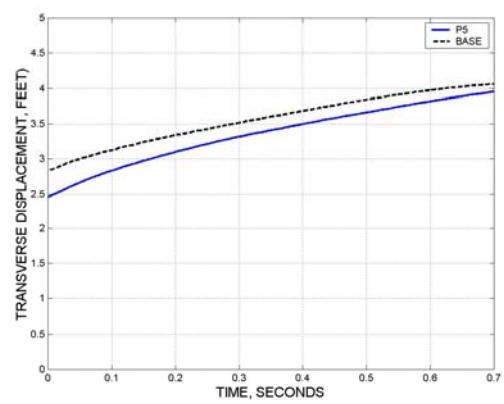

Figure 19. Transverse displacement, P5 and Base

V. Improved Flow Field Modeling

The SLD results presented here assume a uniform flow field in the horizontal direction. Of major concern for paratrooper deployment is the effect of the true non-uniform flow field surrounding the aircraft under various operating conditions. To this end, efforts have begun to incorporate the SLD model into non-uniform flow fields obtained from large-scale CFD simulations. A brief description of the methodology developed to date is presented.

Large-scale CFD simulations for the flow field surrounding a C130 aircraft were performed by the U.S. Air Force Academy (Colorado Springs) using the Cobalt CFD code (www.cobaltcfd.com). The CFD models have unstructured meshes that contain on the order of 3.5 million fluid elements that extend far away from the aircraft body. For the current work, the effect of the non-uniform flow field on the SLD model will be modeled but the effect of the SLD model on the flow field will be ignored. With this approximation, the CFD flow field is only computed once, whereas the SLD model is computed numerous times to generate a time history.

To facilitate this approach, a pre-processing procedure was developed to (1) extract the fluid velocities from the entire CFD field to a predefined rectangular volume near the aircraft and (2) project the velocities from the unstructured nodal points to a regular Cartesian grid within the rectangular volume. The rectangular fluid volume is defined by the boundaries where the SLD model is expected to traverse during the deployment. This pre-processing

procedure significantly reduces the amount of data needed from the entire CFD field and simplifies the velocity "look-up" procedure by using a regular Cartesian grid. The pre-processing procedure is performed once for a given CFD field.

The surface of the C130 aircraft and a typical SLD rectangular fluid volume are shown in Fig. 20 and 21. The flow velocity components in a vertical (XZ) plane located at transverse (Y) distance of 10 feet from the aircraft centerline are shown in Fig. 22, 23 and 24.

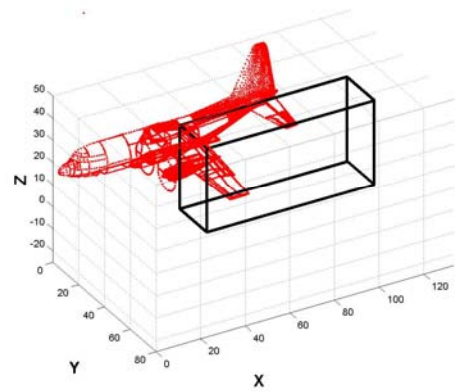

Figure 20. Three-dimensional view of aircraft surface and SLD rectangular fluid volume.

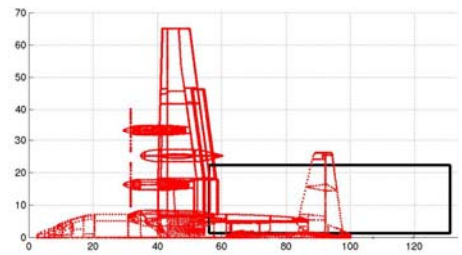

Figure 21. Top view of aircraft surface and SLD rectangular fluid volume.

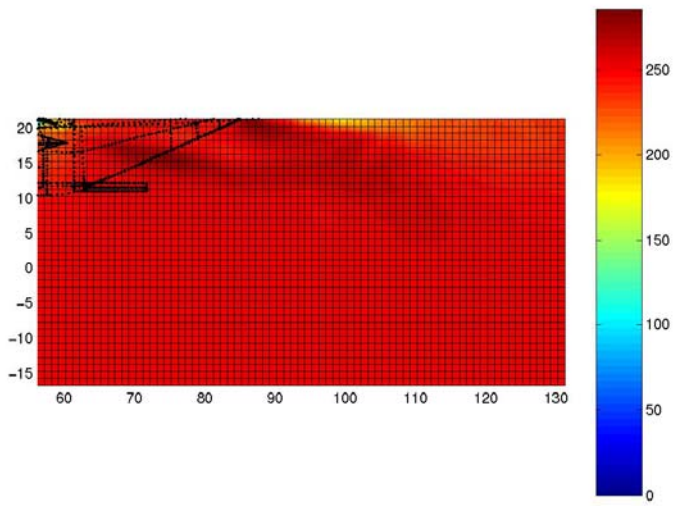

Figure 22. Horizontal (X) velocity field in XZ plane at Y=10 feet in ft/s.

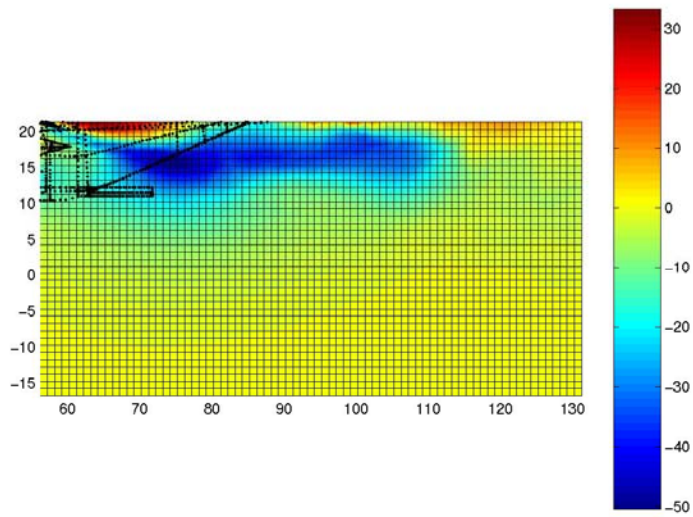

Figure 23. Transverse (Y) velocity field in XZ plane at Y=10 feet in ft/s.

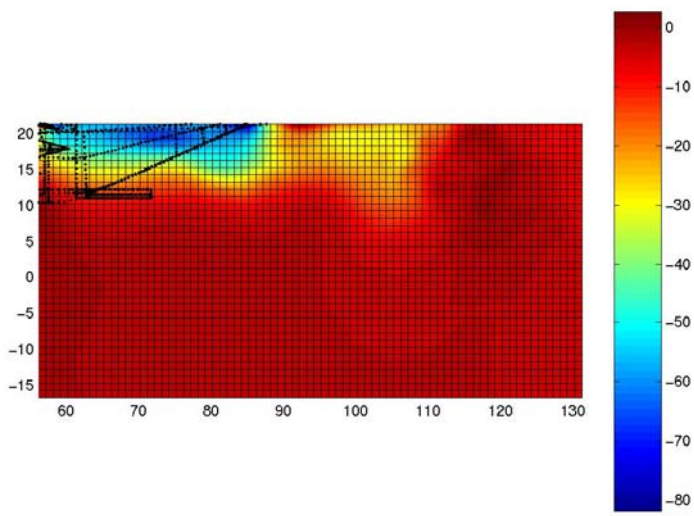

Figure 24. Vertical (Z) velocity field in XZ plane at Y=10 feet in ft/s.

VI. Conclusions

A geometrically nonlinear transient finite element model was developed to simulate static line deployment of paratroopers. The model is quite general and can be applied to a variety of airdrop systems during deployment. In the current work, the model was applied to a standard paratrooper and T-10 parachute system deployed from a C130 aircraft. The model consists primarily of cable elements to model the static line and parachute system and brick elements to model the paratrooper body. In this work a uniform flow field surrounding the aircraft was assumed. The flow field is used to calculate the instantaneous drag forces on the paratrooper and parachute system during the deployment.

Based on a limited amount of data that could be extracted from video of actual paratroopers during deployment, several input properties of the model were calibrated that included damping and drag parameters. The calibrated model was then used to perform a small parametric study that evaluated the effects of paratrooper weight, paratrooper exit velocity, paratrooper exit direction, aircraft velocity and static line length on the deployment process. Specific conclusions for each case were found. Additional data from actual deployments is desperately needed to further validate the computer model and parametric studies.

A methodology was also presented to use the SLD model with flow fields obtained from large-scale CFD simulations. This work will continue during the current year.

Acknowledgments

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