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Basic Design of a Repositioning Event

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A repositioning event is defined as when a payload must change orientation during steady-state parachute descent to prepare for landing or other operation. This paper describes one methodology for the design of a repositioning system along with a generalized case study. A simulation of an unmanned aerial vehicle repositioning is performed to give qualitative data comparisons that would otherwise only be available through flight testing. The repositioning event simulation is used to demonstrate compliance of a three-legged harness system with given repositioning design requirements of the case study. Additional simulations are performed to demonstrate the effects of different stiffness materials as well as use of attenuation to control rotation motion.

Nomenclature

UAV	=	unmanned aerial vehicle
CG	=	center of gravity
MOI	=	moment of inertia

I. Introduction

THIS paper presents one approach for the basic design of a repositioning event of a payload at a point in time post main parachute inflation and during steady state descent. This process has been refined through experience gained on repositioning designs on programs such as supersonic UAV recovery, cargo deployable weapon systems, and other systems.

The requirement to reposition mid-air is generally due to the limitations of payload structure and geometry, it is often the case that a payload is designed to bear peak deceleration forces through a single point. This single point attachment results in a suspended orientation that is unsuitable or undesirable for landing or other system operation. This problem can be solved by employing a mid-air repositioning event that allows the payload/vehicle/etc. to align to a new, predetermined orientation. In addition to the design approach, this paper also presents the results of a generalized case study of the recovery and reorientation of a UAV.

For the purposes of this paper, the UAV is assumed to be descending under parachute nose down and, to avoid damage to the vehicle on landing, will reorient to approximately 95 degrees from vertical (5 degrees nose up), landing on the underside of the vehicle. This method of recovery lends itself nicely to dry land recovery for vehicles that are re-used, as damage can be minimized or avoided completely. This application can also be combined with airbag impact landing attenuation.

As part of the design approach, this document will highlight advanced modeling techniques that allow for the prediction of initial and final hang angles, harness and vehicle attachment point loading, and other dynamic events that occur during the reorientation process. Details such as harness interfacing, triggering methods, and other similar system details will not be presented as these are outside the scope of the simulation being considered.

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II. Design Approach and Case Study Results

The following sections detail the approach taken to design a repositioning system. Specifically, the following sections detail the repositioning system requirements, identification of necessary design inputs required for the system, and a general methodology for system design. Additionally, the outputs of the system design are discussed. Since this design approach has been generalized, it can be applied to any repositioning event design, from basic to complex.

A generalized case study has been created for the purposes of this document. Each design approach section will contain the applicable results of the case study and should provide a comprehensive look at what is required for the design of a repositioning system.

A. Repositioning Requirements

In order to design a reorientation system, the key requirements for that system must be defined. The key requirements are comprised of, as a minimum, the final reorientation angle and load limits of the attachment hardware. The reorientation angle is the angle that the payload/vehicle/etc. achieves for touchdown or other system operation. This angle is a defined application need and depending on the system, this angle may be as critical as ±5 degrees or less. Depending on the maximum allowable load transferred to the vehicle attachment points, the reorientation system may have additional restrictions. If there is more flexibility in the vehicle design, the attachment point capacity may be designed based on the outcome of the reorientation simulation loads.

Although other design requirements may exist, these requirements are two of the most basic aspects of the system.

The case study being presented has the following design requirements.

1) The final angle of the vehicle shall be 95° ± 5° from vertical with the nose of the UAV pointing slightly up and with the tail touching down first.
2) Harness loading shall be less than 3,000 pounds at each attachment point.

B. Design Inputs

In addition to the design requirements, appropriate design inputs must be specified in order to make further calculations and simulate the reorientation event. The following list describes the minimum information that should be provided as design inputs. Additional information may be provided depending on system requirements and complexity.

1) Coordinate system and origin (relative to vehicle)
2) Vehicle mass
3) Vehicle CG
4) Vehicle MOI
5) Location and number of attachment points
6) Attachment point maximum load (if predefined)

The following list details the design inputs for the repositioning event case study.

1) Coordinate system and origin (relative to vehicle)
   The coordinate system origin for the vehicle is located at the tip of the nose with axes directions given in Figure 1.

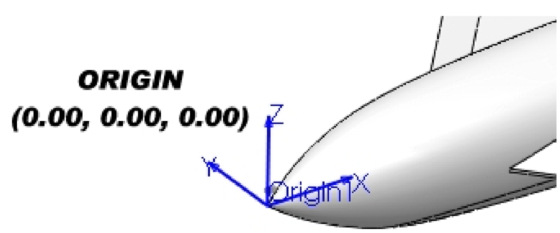

Figure 1: Coordinate System Origin Location

2) Vehicle mass
The vehicle mass is 2,000 pounds. The vehicle is 180.00 inches long and has a wingspan of 113.21 inches; this is presented in Figure 2.

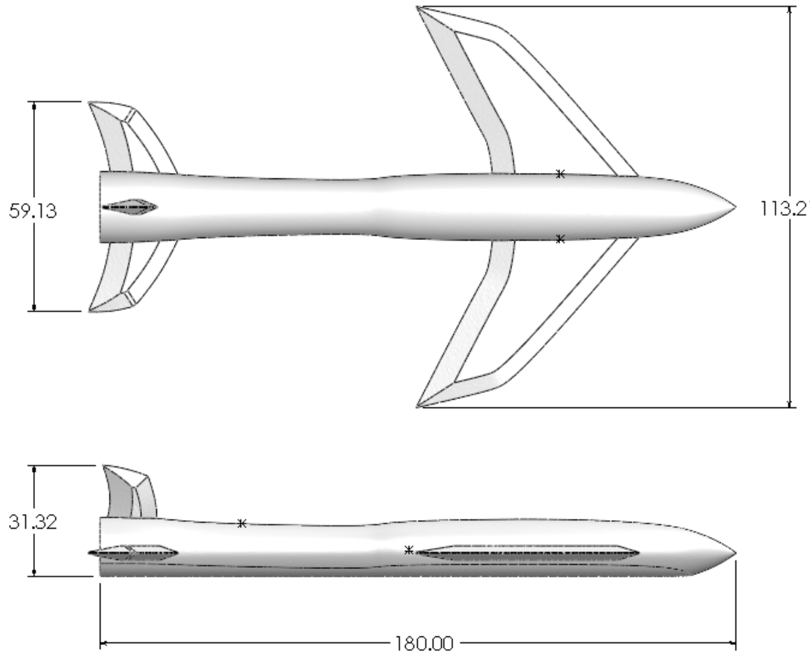

Figure 2: Vehicle Dimensions

3) Vehicle CG
The vehicle CG has a known location of (92.70, 0.00, 0.69) inches relative to the origin.

4) Vehicle MOI
The vehicle MOI data are given as:
Moments of inertia: (pounds * square inches)
Taken at the center of mass and aligned with the output coordinate system.

Ixx = $4.07\text{x}10^5$	Ixy = 4.19	Ixz = $2.86\text{x}10^4$
Iyx = 4.19	Iyy = $4.84\text{x}10^6$	Iyz = 0.13
Izx = $2.86\text{x}10^4$	Izy = 0.13	Izz = $5.19\text{x}10^6$

5) Location of attachment points
   The vehicle used for this design effort has four attachment points. Prior to the reorientation event, the vehicle is held from a single attachment point during parachute descent. This point is located at coordinate (180.00, 0.00, 10.02) relative to the origin. Once the reorientation process begins, this single harness is released and the vehicle will perform its reorientation sequence. After release from the initial attachment point the vehicle is held by three harnesses, creating a three-leg riser system. The forward riser attachment points are located at (50.00, ±9.26, 2.00). The aft riser attachment point is located at (140.00, 0.00, 8.25). Figure 3 shows the location of each attachment point.

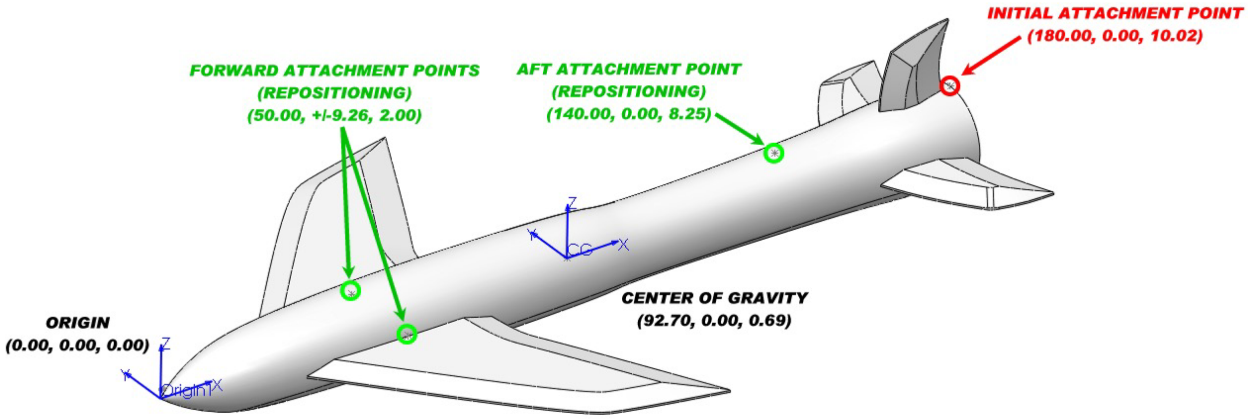

Figure 3: Attachment Point Locations

C. Design Methodology

The following methodology defines system attributes and completes the design of the reorientation system. The methodology provided below can only be followed if design requirements and inputs have been defined. For the purposes of this case study, a 3-legged harness system has been baselined for stability reasons. This system has two forward harnesses and a single aft harness.

1. Establish Forward Harness Lengths

The forward harnesses, shown in Figure 4, are the harnesses that will be loaded first during a reorientation event as the vehicle drops and begins to rotate. The length of each harness, as a minimum, must be the running length between the initial attachment point and the forward harness attachment point along all storage channels and routing tracks. Additional slack may be added to this harness length to allow for freedom of movement, depending on the specific application. It is important to note that a reorientation system may be designed using "manufactured length" dimensions or dimensions that include any length change in the harnesses due to material elongation at an applied load. Whether to include material elongation in determining actual harness lengths will be dependent on the level of fidelity required by the system angle requirements. Overall elongation is more important on systems with long harnesses and tight angle tolerances or small repositioning angles.

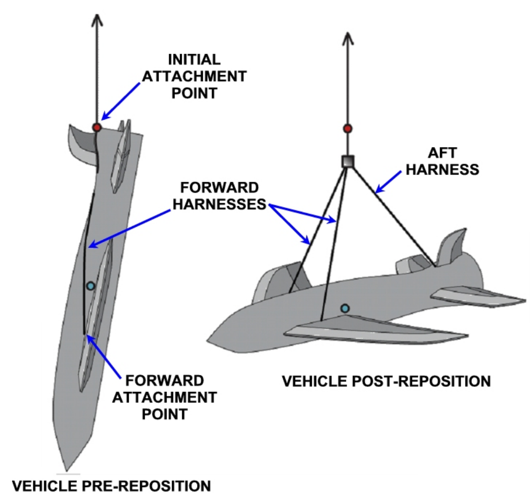

Figure 4: System Harness Locations

System drop distance is defined as the vertical distance the vehicle will fall before all slack has been removed from the forward harnesses and a rotation of the vehicle begins. This distance is approximately calculated as the difference between the forward harness length and the forward to initial attachment point distance. Any additional "slack" designed into the forward harnesses will directly affect the system drop distance.

As discussed previously, the forward harness lengths are based on vehicle geometry and harness routing. For the purposes of this design, a forward harness length of 145.00 inches has been selected. This selection is an approximation as no routing channels or paths were designed for the purposes of this paper.

The difference in length of a forward harness and the X-axis distance between initial and forward attachment points is 15 inches. This distance represents the approximate drop distance of the system. This drop distance is well within manufacturing tolerances on a harness of this length. Harnesses applicable to the reorientation system have, on approximation, a typical manufacturing tolerance of 1% or ± 1.5 inches, whichever is less.

2. Define Aft Harness Lengths

In order to design a system that fulfills application requirements, reorientation harnesses must be designed such that they provide the correct predetermined reorientation angle. When the forward harness lengths are known, the aft harness length can be found using a constrained 3-Dimensional model of the harness legs at the final repositioning angle, where the CG is located directly underneath the parachute riser. This model allows updates to reorientation angles, harness lengths, CG location (inevitable on any program), attachment points, and other variables with real-time results. This method of design allows for making changes to system variables without rebuilding a new model each time. Harness design is based on a three-leg system for stability as seen previously in Figure 4.

Based on the system properties defined up to this point, including forward harness length, CG location, attachment point locations, and the desired final repositioning angle, an aft harness length of 148.00 inches was calculated. The constrained model for this output is given in Figure 5; note that only one forward harness is modeled due to symmetry. As discussed, any changes to the previous list of variables allows for real-time updates to the aft harness length.

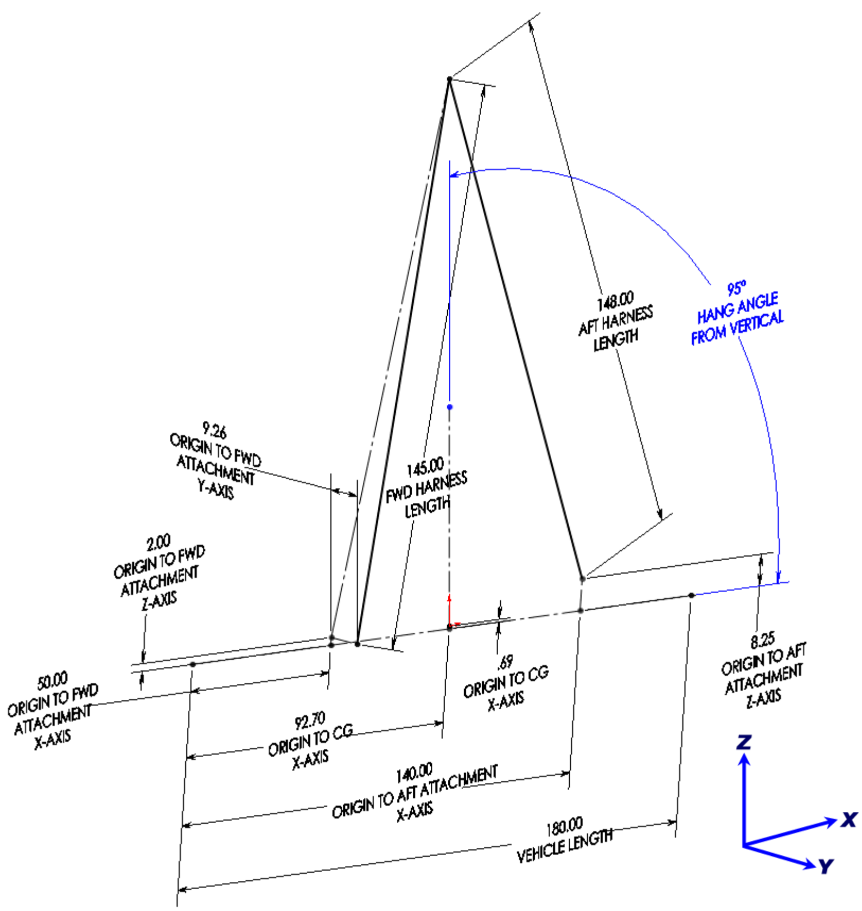

Figure 5: Harness Schematic - Nominal Lengths

It was important to determine if standard manufacturing tolerances, in this case ±1.5 inches, were enough to cause the system to be outside of the design requirements of a 95° ± 5° reorientation angle. A worst-case harness length combination for the system is 146.50 inches for both the forward and aft harnesses. Applying these harness lengths to the model resulted in a system reorientation angle of 93 degrees, as shown in Figure 6. This angle falls within the design requirements of the system, as such the chosen harness geometry was suitable for use.

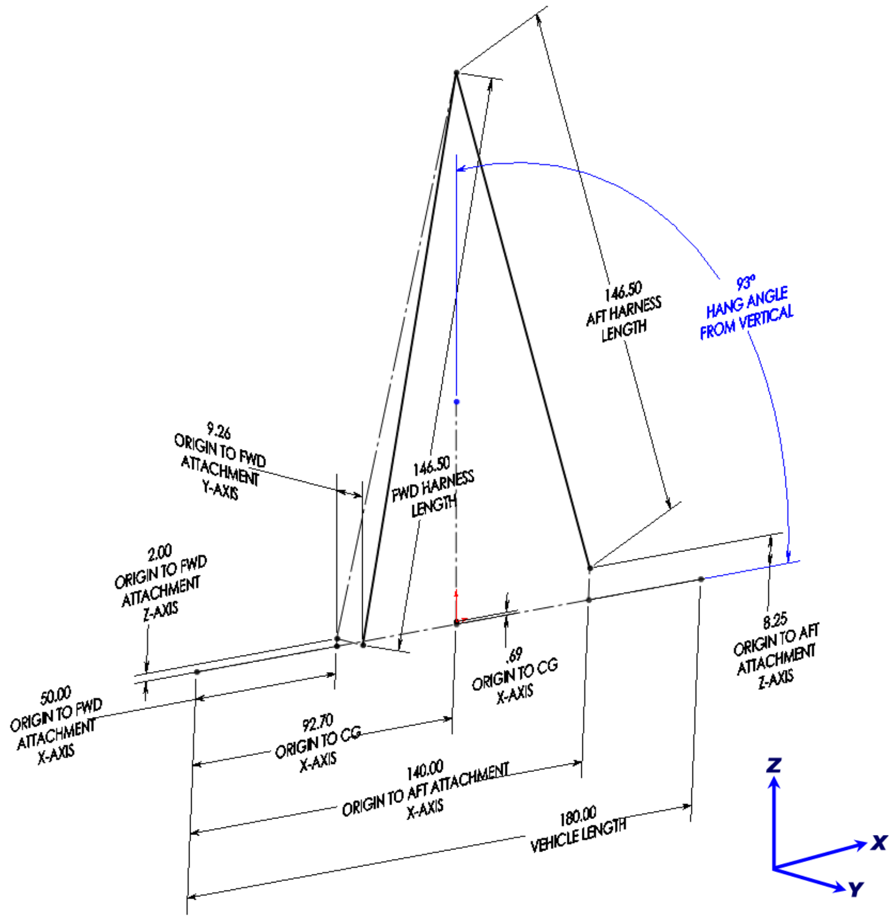

Figure 6: Harness Schematic - Worst Case Tolerance Lengths

3. Choose Materials of Construction

The final step in completely defining the reorientation system harnesses is to choose the base material of construction. Common materials for harnesses of this application include Nylon, Kevlar, Spectra, and Vectran. These materials can be procured in webbings or cords of varying strength and have unique attributes. While each of the listed materials maybe available in the same strength rating, the elongation properties of the materials are quite different. Nylon webbing, as an approximation, will have a 25% elongation at failure. Kevlar, Spectra, and Vectran materials will experience approximately 3% elongation at failure.

The harness material selections are generally based on the differences in material elongation needed for stability or load absorption. Concerning the forward harness, it would not be advantageous to allow the vehicle to fall and load a "springy" material, as this will introduce additional pitch producing energy into the system and result in a longer time before the vehicle becomes stable. Since the aft harness must stop the rotational movement of the vehicle during the reorientation event, a cushioning material is preferred. If Kevlar, Spectra, or Vectran were used on the aft harness, there would be a large load spike at the end of the vehicle rotation, due the material's inability to stretch under load. A harness made of Nylon will absorb some of the load force during rotation because it can stretch. The ability of a Nylon harness to stretch, in a way, "softly catches" the vehicle with the aft harness.

Although the specifics of harness design are outside of the scope of this paper, it is important to note that harnesses must be comprised of loops with an identical number of plies on each side. This basic guideline, along with material strength, will provide sufficient information to complete the reorientation simulation.

System geometry and design requirements may dictate that the vehicle will have a large sweep angle during reorientation. A large angle of movement has the possibility of invoking a system that will not dampen out naturally to a steady state condition in a predefined time period. This problem can be rectified through the use of attenuation stitching. A specific stitch pattern can be developed that will slow the rotation of the vehicle during the reorientation event. By slowing the rotation of the vehicle, there is a decrease in aft harness maximum loading.

For the purposes of the case study, the forward harnesses have been modeled as Kevlar with a total strength rating, nominal, of 12,000 pounds. The aft harness has been modeled as Nylon, again with a strength rating of 12,000 pounds. Additionally, the aft harness has been modeled with and without an attenuation factor to determine if the system will benefit for the inclusion of attenuation. For comparative purposes, the simulation has also been run with three Kevlar harnesses.

4. Run Simulation

Due to the dynamic nature of the reorientation event, it becomes necessary to use a transient dynamic simulation software to more accurately capture the loads seen in the harnesses during the loading events. The simulation efforts were required to verify that the selected materials and material strengths are robust enough to sufficiently allow for vehicle reorientation. The inclusion of this simulation step helps to reduce risks and costs associated with testing.

The explicit solver within LS-DYNA was employed to perform the reorientation analysis. A finite element model was created of the vehicle, harnesses, and a representative parachute system. The preliminary harness strengths defined in sub-section 3 above were used for the calculation of harness stiffness. The initial conditions of the simulation correspond to the point in time just as the repositioning event begins, during steady state descent under the parachute system. As the simulation starts, the vehicle begins to reorient to its naturally determined static hang angle as predicated by the reorientation harness lengths. By the end of the reorientation simulation, the vehicle is resting at its natural hang angle and the reorientation harnesses load share per the design. Once the simulation has run to completion, outputs such as local harness loads, angular velocity and acceleration, as well as resulting shock loading on the vehicle (if applicable) may be identified.

It is important to define the system's initial hang angle, as this will be a simulation input. The initial hang angle is the angle of the vehicle X-axis relative to gravitational vector prior to repositioning. This angle was used in the dynamic simulation as a "starting point" for vehicle position. Based on system properties, the vehicle hang angle was 6.1° as seen in Figure 7.

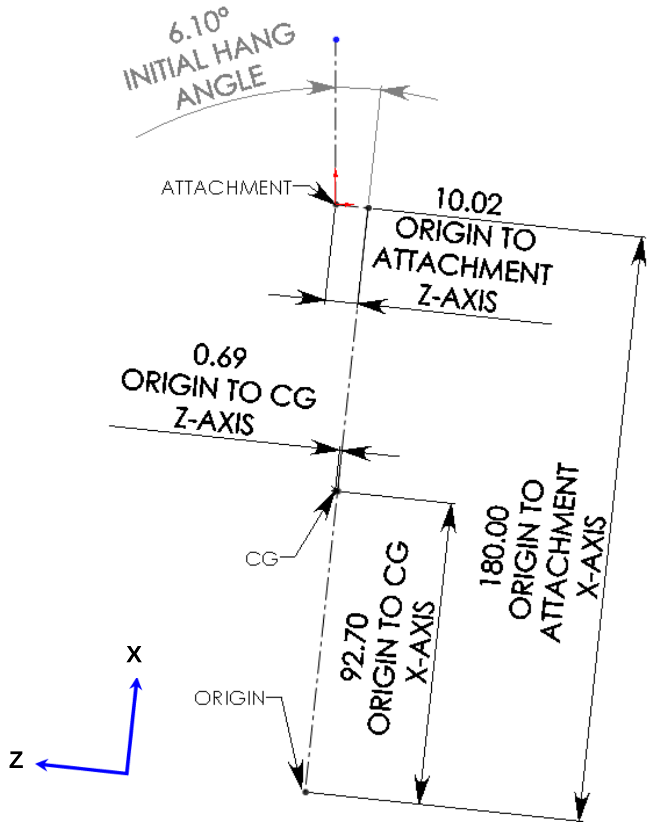

Figure 7: Harness Schematic - Initial Hang Angle

The results of the case study are presented in Section III. For the purposes of this study, only pitch angle and harness loads have been presented.

5. Perform Design Verification

Following the simulation, a comprehensive look at the system is performed. Although the reorientation angle itself can be derived from geometry, the dynamic loading of the system is something that comes exclusively from the simulation. This loading must be compared to the harness strengths selected for the system to ensure that there are sufficient margins of safety for the application. Similarly, the vehicle loading limits must be reviewed to make sure attachment points are of adequate strength for the predicted loading. It is at this point that material changes, harness length changes, and other design attribute changes are implemented to alter the results of the simulation, if required.

D. Design Output

If the design methodology presented previously is followed, there will be sufficient data available to complete the design of the reorientation system. The design output is comprised of the following.

1) Harness Definition: Following simulation results, the reorientation harnesses will have complete definition. This definition includes material of construction, length, and construction tolerances that ensure compliance with design requirements.
2) Hang Angle / Reposition Angle Verification: Based on the selected harness lengths, the hang and reposition angles of the system are verified to meet the required final hang angle.
3) Harness / Vehicle Loads: The repositioning simulation provides a time based history of both harness loads and pitch angle. Loading values are compared with harness strength and attachment point limit loads to determine margins of safety of the system.

All applicable design outputs are presented in Section III.

III. Simulation Results

The following section details the results and design verification of the generalized case study introduced previously.

A. Simulation Results

1. Model Description / Definition

The LS-DYNA simulation consists of four primary components: the canopy, the suspension structural grid, the reorientation harness system, and the suspended vehicle.

The canopy is modeled using a combination of a force and point mass to characterize both the drag performance and the apparent mass of the air enclosed in the parachute fabric, respectively. The model includes a nonlinear drag force calculation that captures changes in dynamic pressure and associated drag force, assuming a constant drag area, of the canopy.

The suspension structural grid in this system consists of radials, suspension lines, and a riser. These components are modeled in the transient dynamic code LS-DYNA, with elements that only carry loads in tension. The radials, suspension lines, and risers are modeled with linear load and unload curves (i.e., no hysteretic damping is modeled).

The reorientation harness system comprises two forward harnesses and one aft harness. The forward Kevlar harnesses are modeled with linear load and unload curves (i.e., no hysteretic damping) and the aft harness is modeled with unique loading and unloading curves based on the hysteretic properties of Nylon webbing. These loading curves are derived from independent research efforts of Airborne Systems. The lengths of the forward and aft harnesses dictate the dynamics of the carriage assembly during reorientation and the final orientation.

The simulation start time, time zero, is the point when the vehicle is just released from the initial attachment point. All data presented is based on this start time.

2. Assumptions and Constraints

A closed system modeling approach was used to simulate the reorientation event. In order to reduce the overall complexity of the model some assumptions were made that have a conservative impact on the reorientation results. The main LS-DYNA modeling constraints are listed below, followed by a brief explanation of each of these constraints:

- The motion of the canopy has been limited to the global vertical axis.
- The vehicle is considered to be a rigid body
- There are no aerodynamic damping effects taken into consideration

The vehicle itself was allowed to yaw and roll; however, because this geometry was symmetric and the vehicle was modeled as a rigid body, it did not experience any roll or yaw rotations.

No aerodynamic effects such as drag, crosswinds, etc. were taken into account during this simulation. Since the goal of this analysis was to capture the harness loads time history, the omission of payload drag contributions to the model only results in increased harness loads and is considered a conservative assumption.

3. Simulation Results – Harness Load

Harness loads have been collected, as a function of time, for reorientation systems comprised of Kevlar forward and Nylon aft harnesses or all Kevlar harnesses. Additionally, each system has been modeled with and without attenuation in the aft harness. Based on design experience a system comprised of Kevlar forward harnesses and a Nylon aft harness with attenuation is the optimal solution. Additional data is being presented to show the capabilities of the simulations and provide justification on the selected design.

Figure 8 presents the harness loading for the proposed design. As seen in the figure, the aft harness is minimally loaded as the vehicle starts to rotate. The aft harness then becomes loaded up to a designed attenuation load; in this case, 1,000 lbs. Throughout the harness extension, the attenuation stitches are broken. At the end of the attenuation phase the aft harness is free to be loaded to whatever energy the system imparts on it, in this case approximately 2,750 pounds. The forward harnesses are loaded to a maximum value of approximately 1,900 pounds. The maximum forward harness loading occurs as the vehicle falls from its initial attachment point onto the forward harnesses. These loading values are well within the design strength of the harnesses. Additionally, these values are below the load limits of the vehicle attachment points.

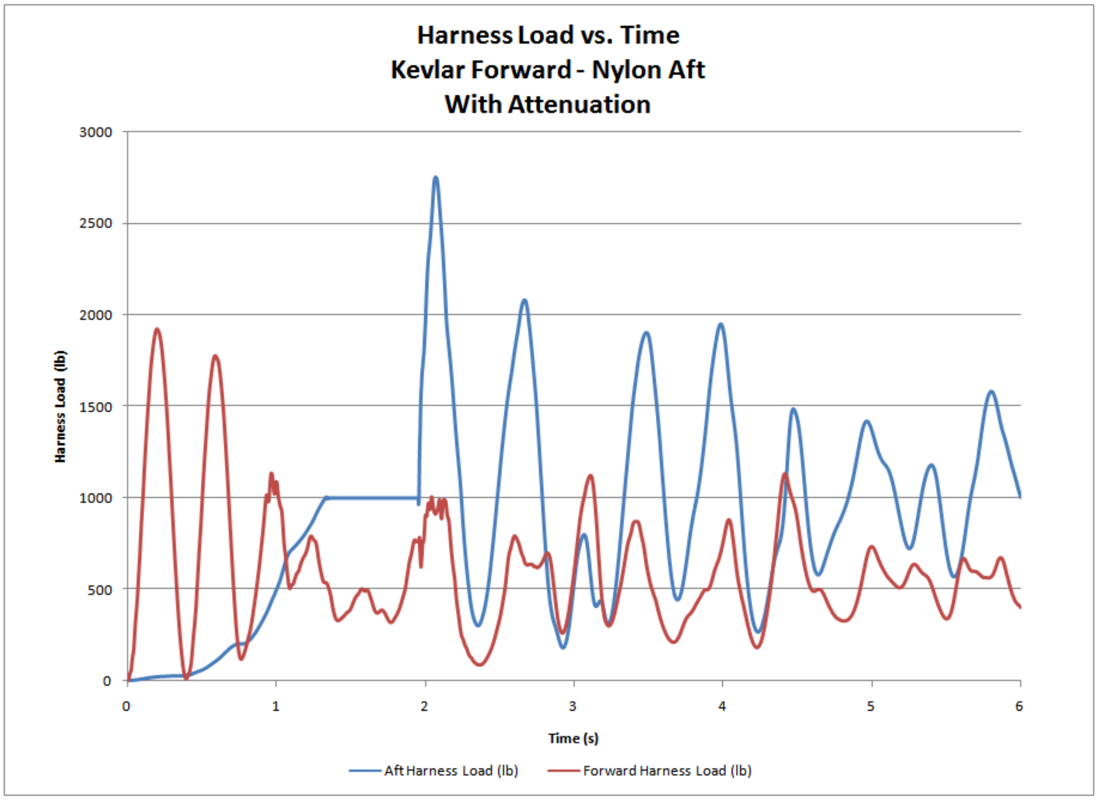

Figure 8: Harness Load vs. Time for Attenuated Kevlar/Nylon System

Figure 9 presents the results of the same simulation with the omission of the attenuation stitching. The figure shows that the loading on the aft harness is a series of sharp peaks, reaching a maximum of approximately 5,600 pounds. The forward harnesses are loaded to a maximum value of approximately 1,900 pounds, just as with the attenuated system. It is also noted that the forward harnesses have loads that reach nearly zero during the aft harness load spikes. Figure 10 shows the position of the vehicle during a load spike event, note the slack present in the forward harnesses. The omission of attenuation also causes the aft harness to be fully loaded approximately one-half of a second sooner than the attenuated case. This time difference is due to the omission of attenuation tear-out time in the aft harness. It is a general observation that all loading values are greater for the non-attenuated system after approximately one second, the time at which the aft harness begins being loaded. Although the harness design is capable of the loading presented for the non-attenuated case, the load of the aft harness exceeds the maximum allowable vehicle attachment point load. As such, attenuation is required for the system in order to meet design requirements.

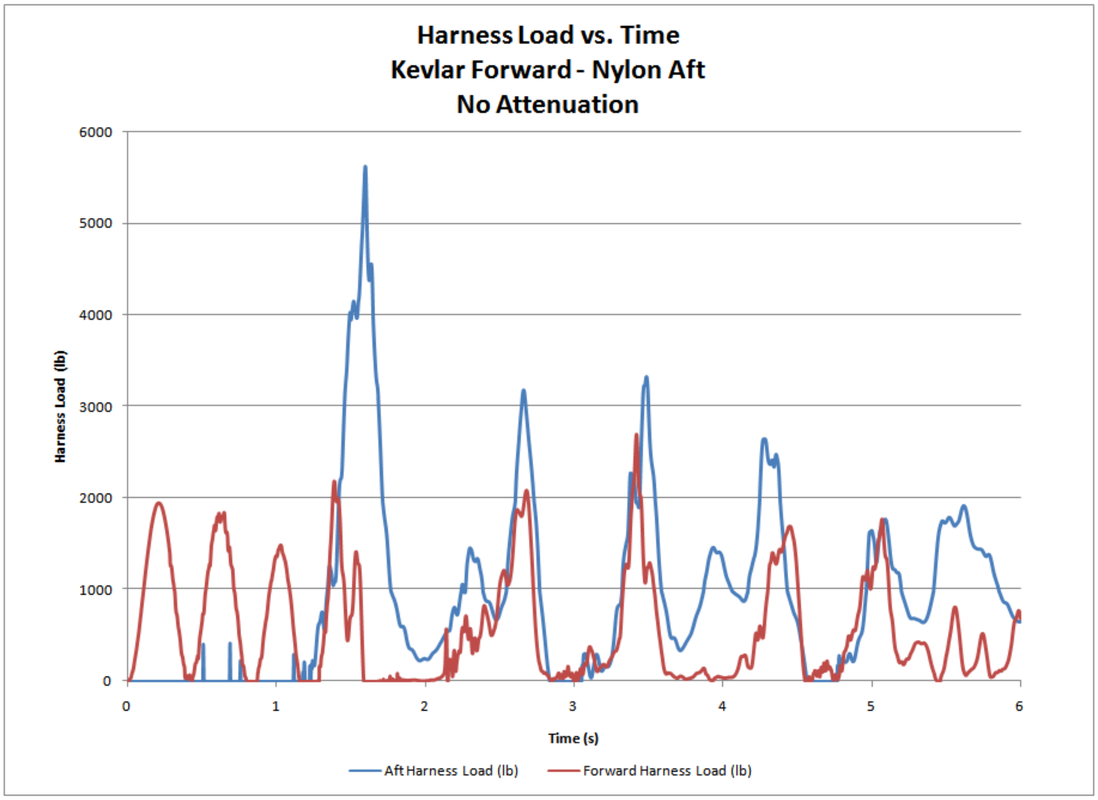

Figure 9: Harness Load vs. Time for Non-attenuated Kevlar/Nylon System

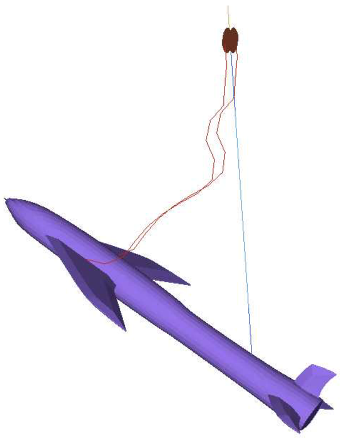

Figure 10: Vehicle during Unloading of Forward Harnesses, t = 3 seconds

Figure 11 and Figure 12 present the same information as above, however, for systems comprised entirely of Kevlar. It is of interest to note that the Kevlar aft harness loading is higher, as compared to Nylon, in all cases. The higher loading is a direct result of the material's inability to stretch and absorb energy from the reorientation event. While the harness design is adequate for both cases, the aft harness loading exceeds the maximum allowable vehicle attachment point load.

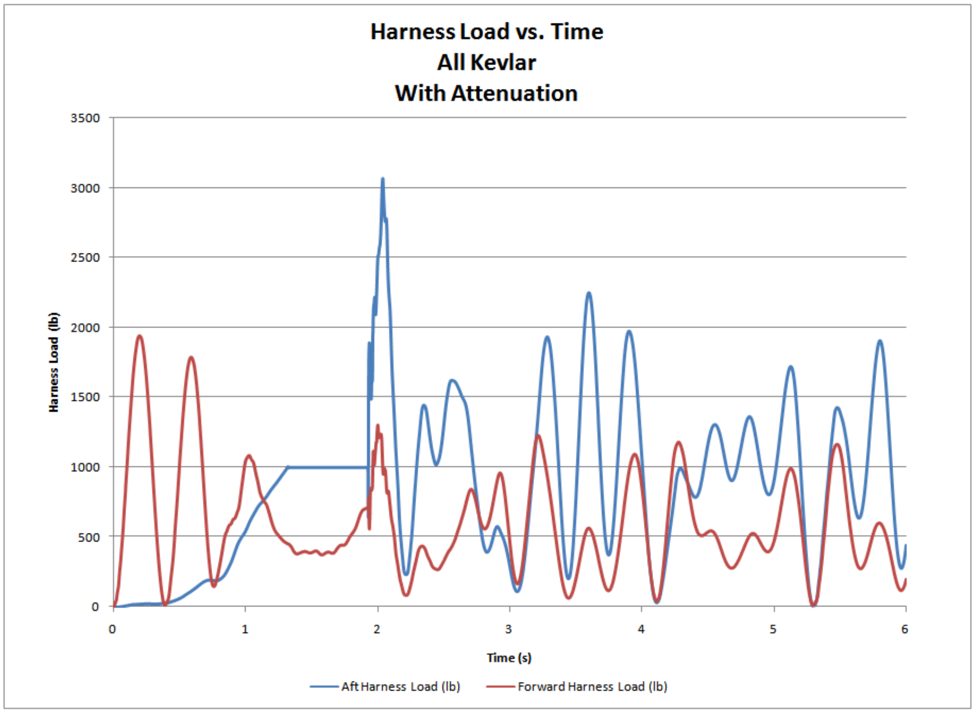

Figure 11: Harness Load vs. Time for Attenuated Kevlar Only System

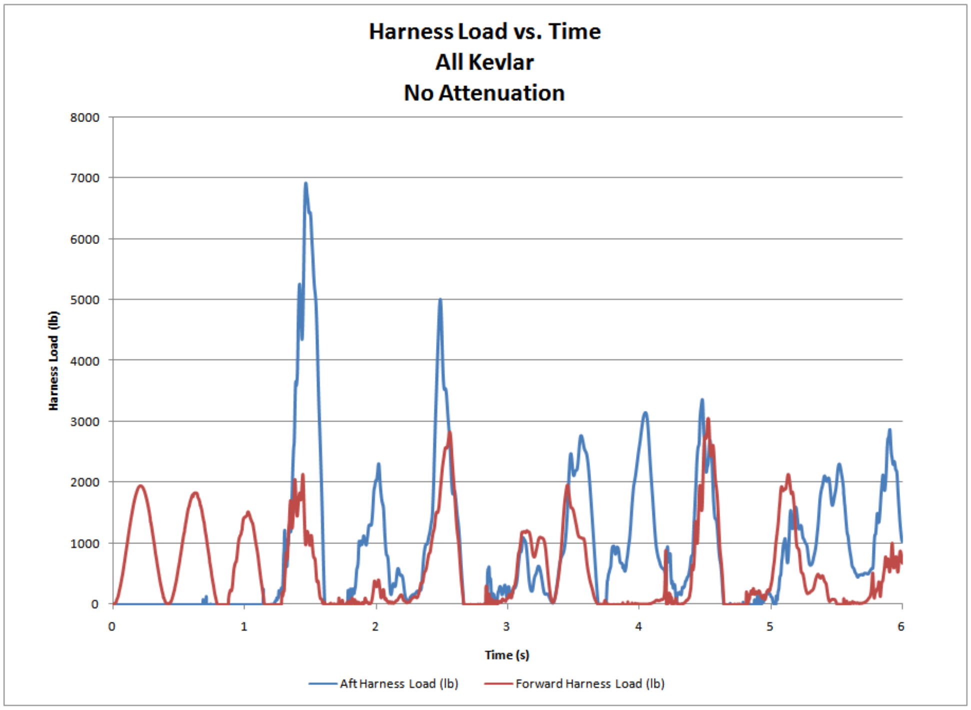

Figure 12: Harness Load vs. Time for Non-attenuated Kevlar Only System

Figure 13 and Figure 14 present composite plots for the data presented previously for comparative purposes.

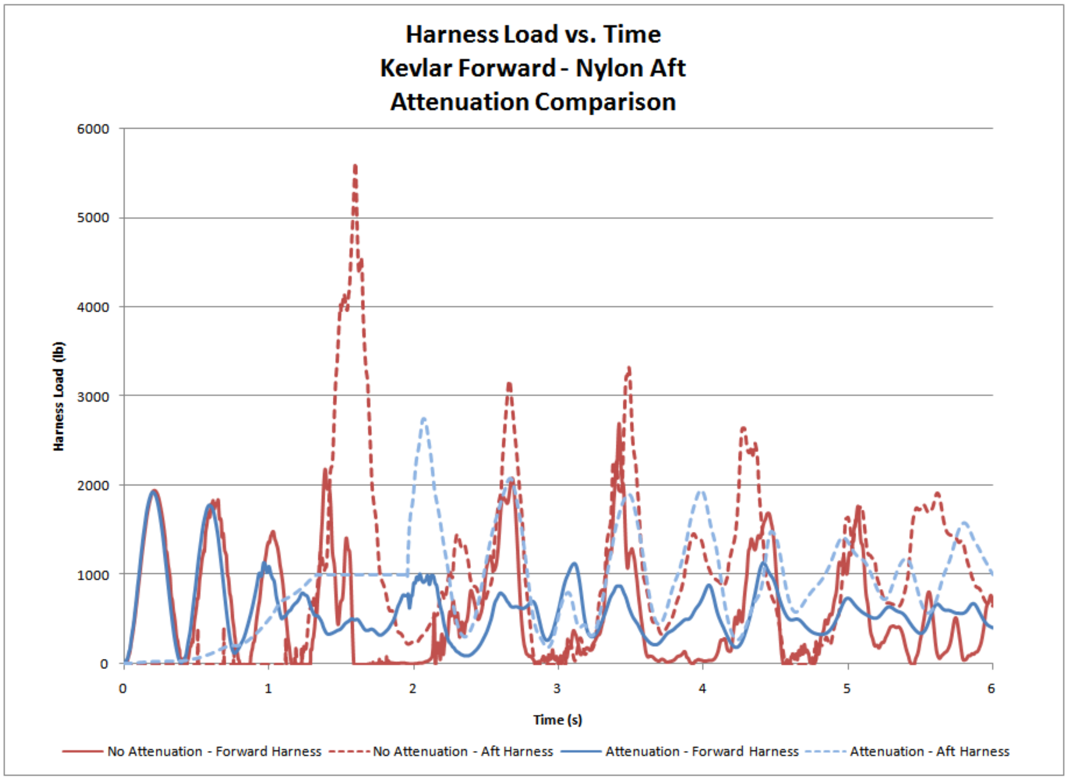

Figure 13: Harness Loading vs. Time for all Kevlar/Nylon Systems

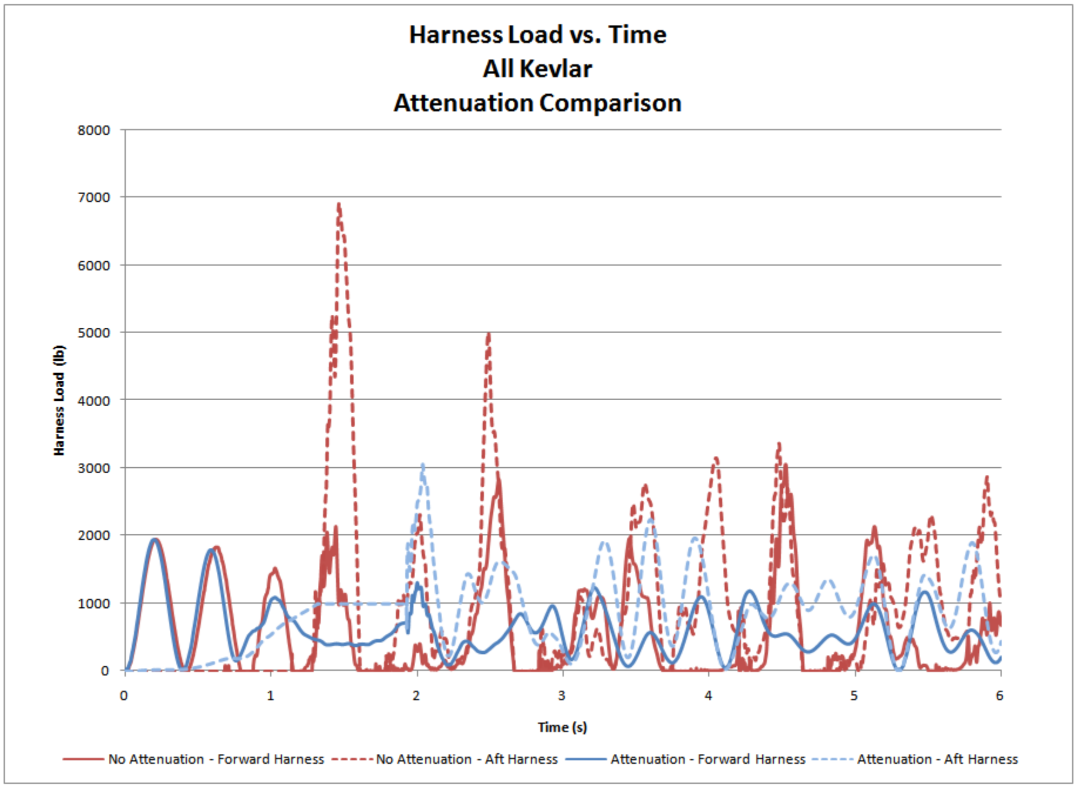

Figure 14: Harness Loading vs. Time for all Kevlar Only Systems

4. Simulation Results – Vehicle Pitch Angle

The rotational position as a function of simulation time for the two attenuated systems can be seen in Figure 15. The vehicle begins the reorientation sequence at approximately 6 degrees from the vertical (clockwise about the local y-axis). As the reorientation event progresses, the rotational velocity of the vehicle is slowed by the attenuation built into the aft harness. As the attenuation stitches are broken, the vehicle continues to rotate towards its final position. It is seen in the graph that both systems exhibit similar behavior. Each system dampens to approximately 95 degrees (5 degrees nose up), although the Nylon harness system dampens out faster due to the ability of the Nylon to absorb rotational energy from the system. There is a definitive difference between the vehicle rotations with respect to time for the attenuated system and the non-attenuated systems, seen in Figure 16.

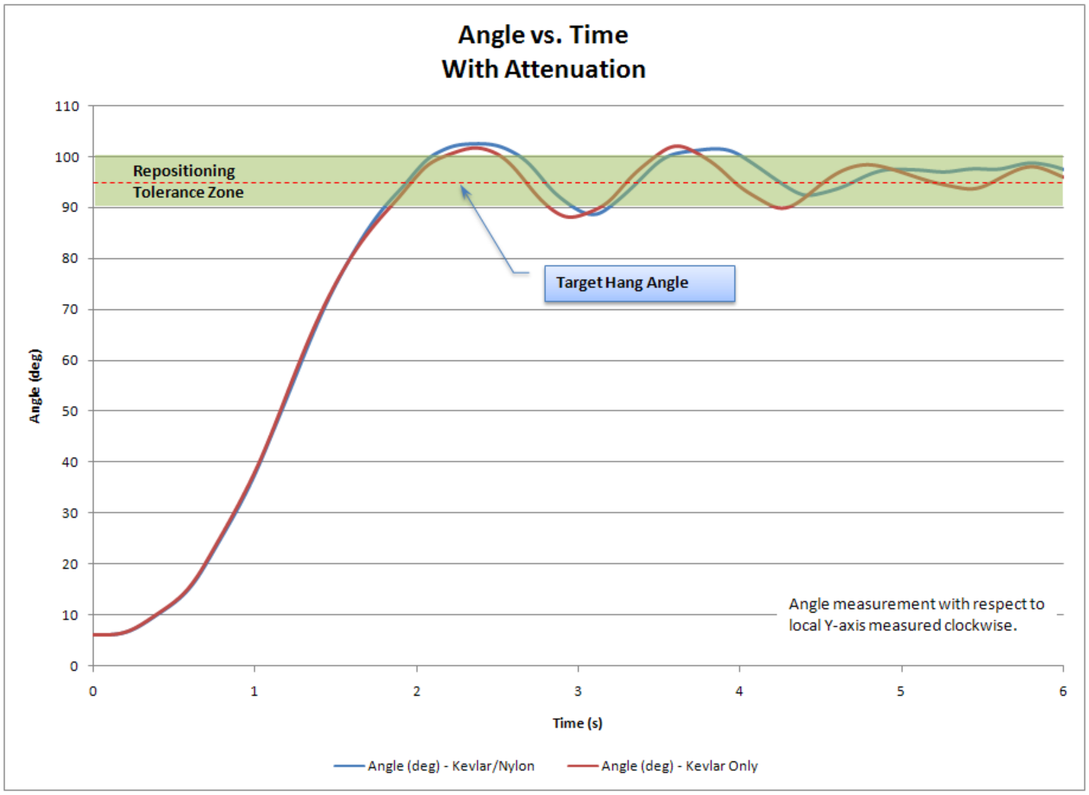

Figure 15: Angle vs. Time for Attenuated Systems

As seen in the non-attenuated system pitch-angle plot, Figure 16, the system experiences a high level of over-rotation. This over-rotation is directly related to the omission of the attenuation in the aft harness, as there are no forces to slow the vehicle as it begins to rotate. Additionally, the high level of over-rotation creates a system that does not dampen out to a satisfactory level, as was achieved with the attenuated systems.

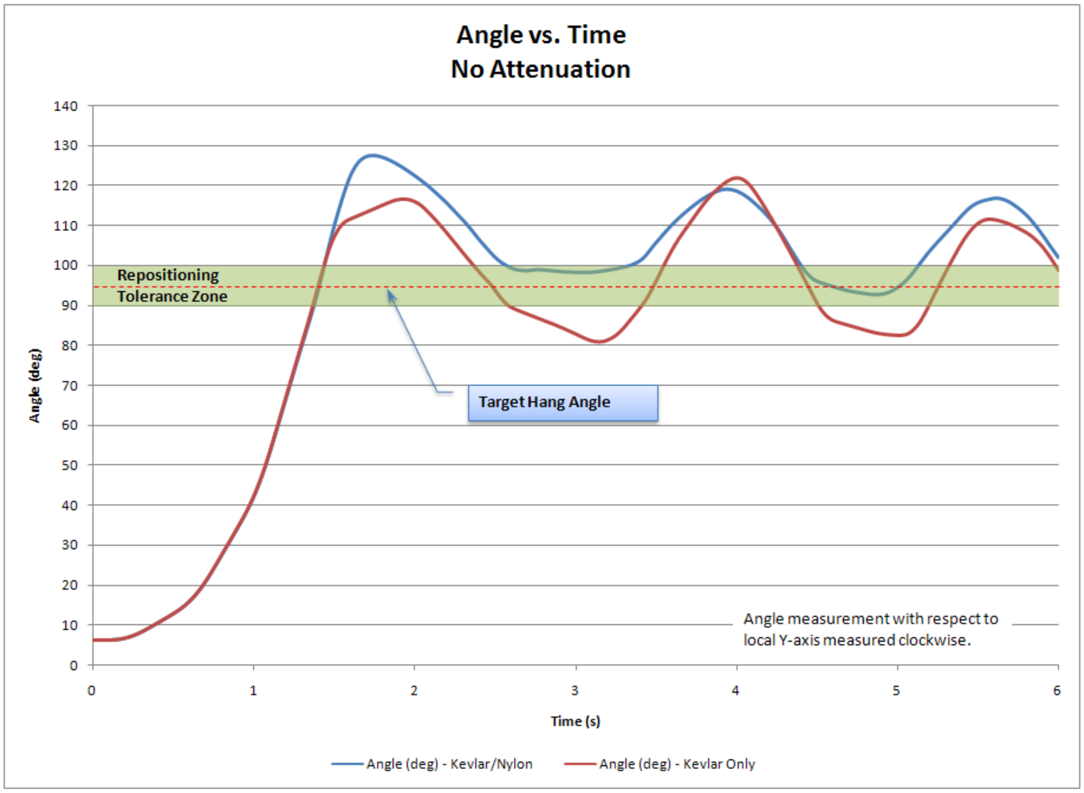

Figure 16: Angle vs. Time for Non-attenuated Systems

5. Reorientation Sequence

Figure 17 detail the movement of the vehicle during the reorientation sequence. This image is based on the simulation for a system comprised of Kevlar forward harnesses and a Nylon aft harness with attenuation stitching. The data for this sequence was previously presented in Figure 8 and Figure 15.

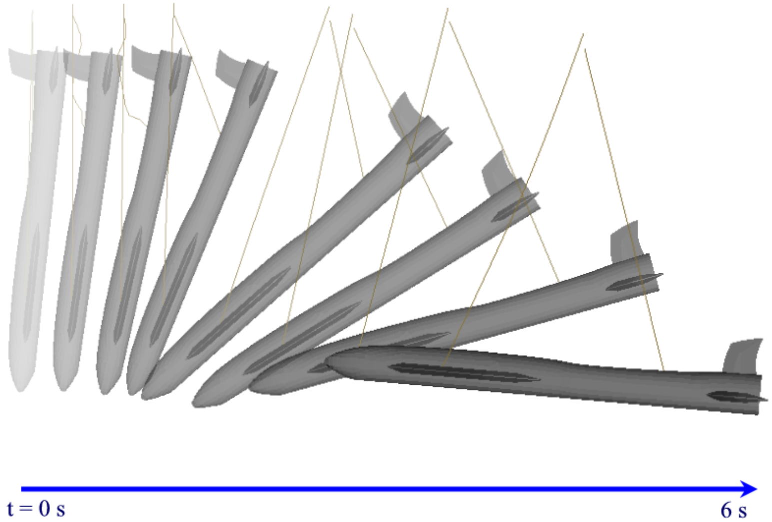

Figure 17: Chronological Progression of Reorientation Sequence for Unmanned Aerial Vehicle (Kevlar Forward/ Nylon Aft Harness with Attenuation Scenario)

IV. Simulation vs. Flight Data

The following section provides a brief comparison of simulation predictions with actual flight data of a repositioning event. Figure 18 presents a pitch-angle time history of an actual repositioning event along with the simulation prediction. In this case, the simulation had accurately predicted the flight results. Further, the design of the system was successful in placing the payload within the repositioning angle tolerances. As with the case study presented in this paper, the repositioning simulation used to obtain the data in Figure 18 does not include any aerodynamic damping effects. As such, it is seen that the simulation data tends to exaggerate the rotation angle as the payload swings back (second trough), which is conservative. As a note, the simulation data presented is based on a short simulation time. The limited data is due to the computing power required to perform the simulation and system capabilities at the time this simulation was performed.

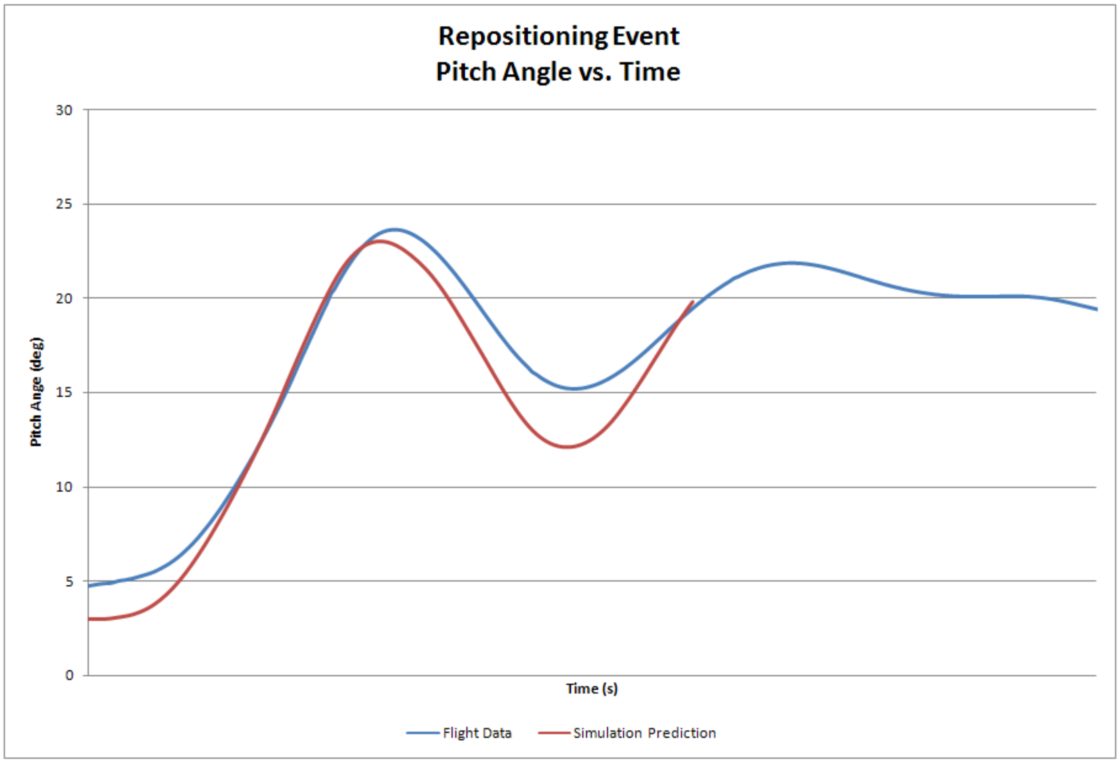

Figure 18: Pitch Angle vs. Time - Flight Data and Simulation Comparison

The pitch-rate time history for the same flight data presented above has been captured and compared with simulation. Figure 19 shows that the simulation was a reasonable representation of the speed at which the payload rotated during the repositioning event. As noted earlier, there are no external aerodynamic effects modeled in the simulation. This lack of aerodynamic damping can be seen in the second peak in the data, where the simulation has predicted a faster rotation than was experienced.

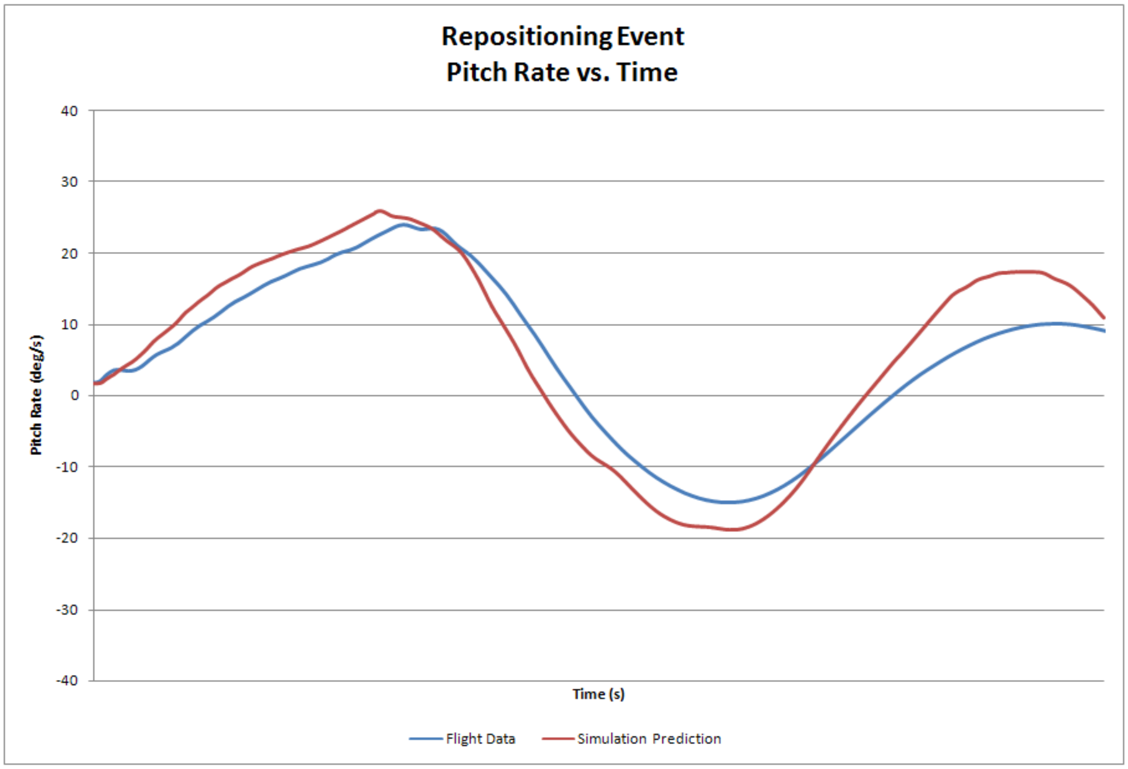

Figure 19: Pitch Rate vs. Time - Flight Data and Simulation Comparison

V. Conclusion

Based on the simulation results presented in this paper, and close comparisons to flight data, it is evident that a repositioning event that has been designed according to the basic design approach presented herein can reasonably and conservatively predict reorientation performance with regards to final repositioning angle, rotational velocity, and therefore by inference, validation of maximum harness loads. By modeling these events, the system designers are able to get a better understanding of vehicle dynamics during reorientation, leading to harness and vehicle designs that can be optimized based on simulation results rather than extensive and / or iterative testing. Additionally, the accuracy of the simulation will give designers freedom to design systems that operate at a specific angle, whereas this option may have been difficult to achieve previously.