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Effect of Orion Post-Touchdown Parachute Release Time on Vehicle Rollover

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Summary

The effects that the Orion parachutes have on the vehicle response once the vehicle lands on the ground are examined in this report. A concern with the Orion landing is that structural accelerations will cause vehicle and/or crew injuries or that the vehicle may roll over. The parachute effects are thought to have the potential of pulling the vehicle over during conditions such as higher winds or in some cases stabilizing the vehicle by preventing its motions after touchdown. A collection of representative landing conditions is used to assess the post-touchdown parachute release effect, and it was determined that, in general, there is no significant advantage or disadvantage to releasing the parachutes past the time when the vehicle touches ground. For landing conditions when there is a high horizontal wind, retaining the parachutes has a detrimental effect on vehicle rollover because the drag force on the parachutes pulls the vehicle over. Under this condition, some form of automated parachute release should be a requirement given that an attached parachute may cause the vehicle to roll over. An automated system would ensure that the release occur within 0.50 sec of touchdown (time when parachute regains tension), which is not enough time for a crew-operated manual release.

Introduction

The purpose of this study was to investigate the effects that the Orion parachutes have on the vehicle response once the vehicle lands on the ground. A concern with the Orion landing is that structural accelerations will cause vehicle and/or crew injuries or that the vehicle may roll over. The parachute effects are thought to have the potential of pulling the vehicle over during conditions such as higher winds or in some cases stabilizing the vehicle by preventing its motions after touchdown. In this study, a simplified parachute model was developed and coupled to an Orion structural model. Simulations were then performed with vertical and horizontal landing initial conditions and horizontal wind. The effect of releasing the parachutes at different times after touchdown was investigated in terms of vehicle accelerations and rollover.

Parachute Model

The LS–DYNA finite-element model originally created for the crew module (refs. 1 to 4) is extended to include the parachutes and parachute lines connecting the parachute to the crew module. Although Orion is expected to utilize three primary parachutes for landing, for the purposes of this study, the effects of the parachutes and lines are simplified by combining the effects of the three parachutes using a single parachute (fig. 1). The parachute itself is modeled as a lumped mass whose weight is equal to the total expected parachute weights. The connecting lines are modeled as a single line with elastic properties and pre-tensioning. The line is preloaded with an initial tension equal to the weight of Orion so that the coupled vehicle-parachute system is in equilibrium just before touchdown with the ground. The “cable”

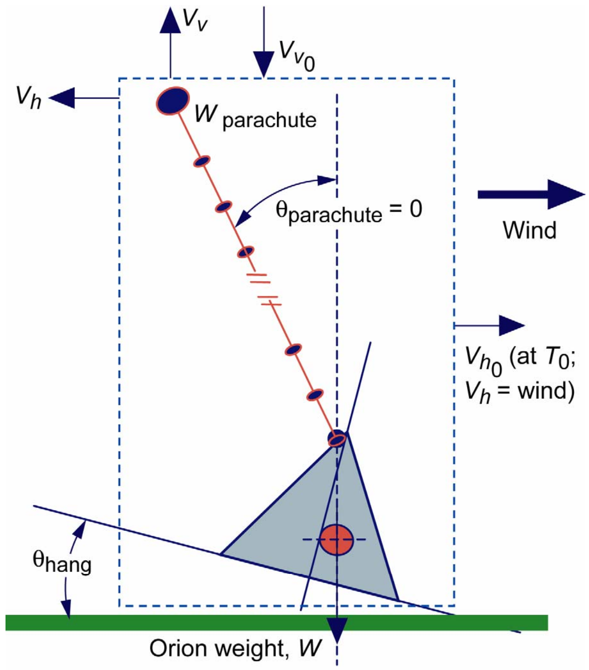

Figure 1.—Parachute model. Horizontal velocity, V_h; horizontal velocity at time zero, V_{h_0}; vertical velocity, V_v; velocity at time zero, V_{v_0}, weight of parachute, $W_{parachute}$; time zero, T_0; hang angle, θ_{hang}; hang angle of parachute, $\theta_{parachute}$.

element available within LS–DYNA is used to model the line so that it transmits load when it is in tension and carries no load when it is slack. The mass of the line is distributed along its length, and the mass of the parachute is concentrated at the top of the rigging.

The parachute force is applied at the location of the parachute mass and is computed from the simple drag equation:

$$F = C \times V^2$$

where F is the parachute force, C is the parachute coefficient, and V is the velocity of the parachute mass, which may be determined from the relationship

$$C = \frac{1}{2} \times \rho \times C_d \times A$$

where ρ is the air density, C_d is the drag coefficient of the parachute, and A is the area of the parachute. An alternative approach to computing the parachute force is to use the equilibrium conditions for a nominal landing to compute the coefficient C. For a nominal landing, the parachute force must equal the Orion weight W so that

$$W = C \times V^2$$

For this study, the nominal vertical velocity is 26 ft/s and the Orion weight is 13 046 lb, leading to a parachute coefficient of 0.134 lb sec^2/ft^2. For the present study, this coefficient is used for both the vertical and horizontal directions. This is a reasonable approximation of the actual parachute forces since the parachutes tend to orient themselves so that they efficiently oppose the direction of the wind and vehicle motions. Currently, tests are being performed on Orion parachute systems and as this data is processed, a better understanding of the parachute forces will be defined. However, for the present study, this simplified model of the parachute system and forces is sufficient to explore the effects of the parachutes once the vehicle touches ground.

The parachute force is implemented in the LS–DYNA simulation via a series of lookup tables for various wind conditions. During each time step in the transient simulation, the computed vertical and horizontal velocities at the location of the parachute mass are used along with the lookup tables to extract a parachute force in each of the horizontal and vertical directions. These forces are then applied at the parachute mass location and used to compute the structural response for the time step. When there is a horizontal wind present, the horizontal wind force is added to any forces generated from the transient motion of the parachute mass.

The vertical parachute force F_v is defined as

$$F_v = 0.134 \times V_v^2 \quad \text{lb}$$

and the horizontal force F_h is defined as

$$F_h = 0.134 \times \left(V_{\text{wind}}^2 + V_h^2\right) \quad \text{lb}$$

where V_v and V_h are the vertical and horizontal velocities of the finite-element node at the location of the parachute mass, and V_{wind} is the horizontal wind force.

Figure 2 shows a comparison of the parachute forces computed using the above formulation and the vertical parachute force obtained using the parameters supplied by Lockheed Martin in the memorandum CEV–LRS–07–001. For descent velocities within those expected for Orion, there is very close agreement

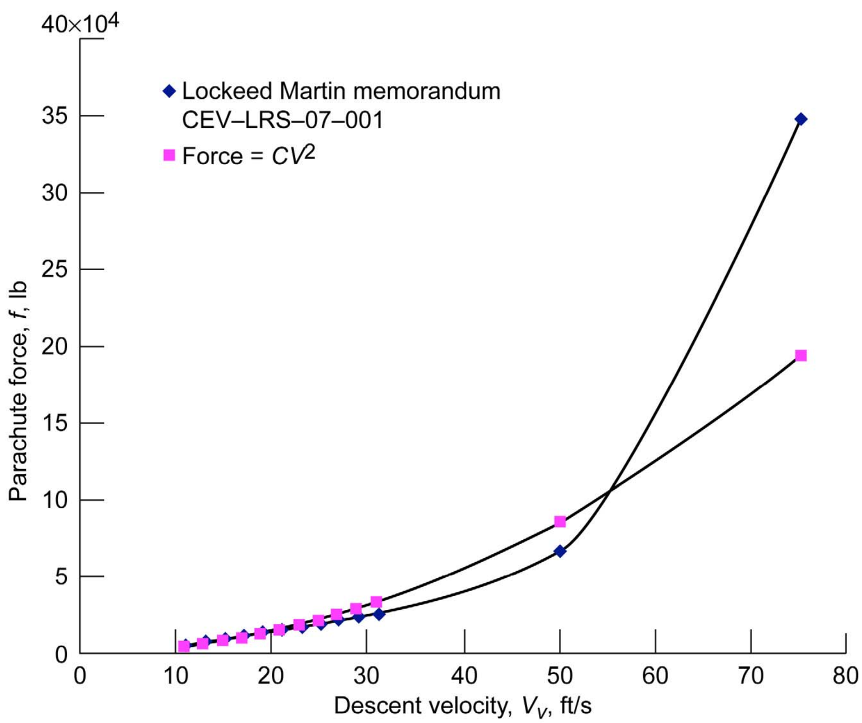

Figure 2.—Comparison of parachute descent force.

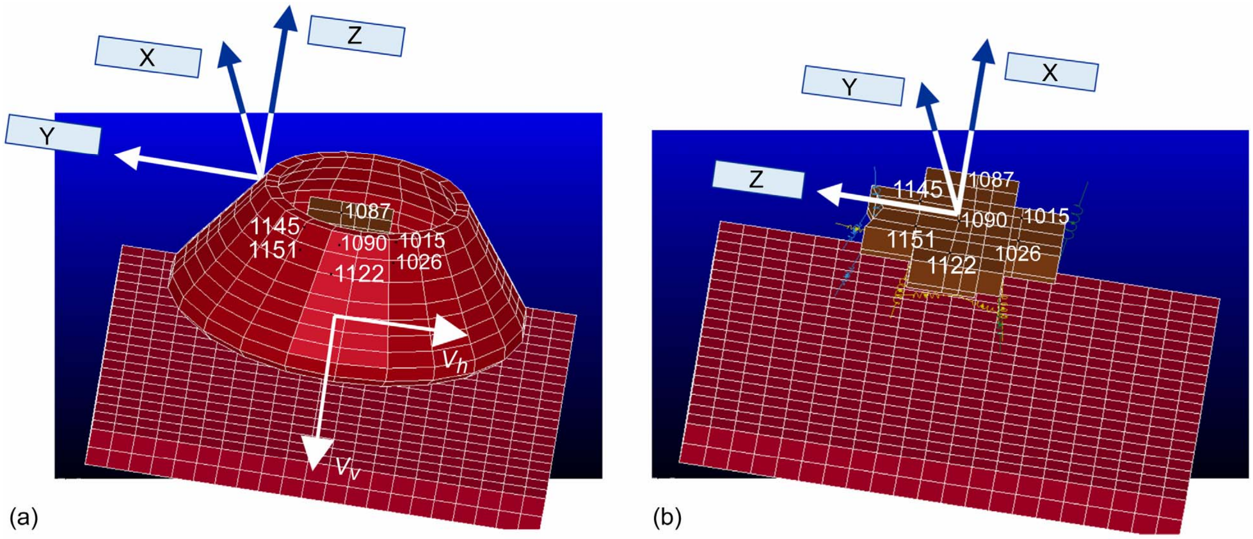

Figure 3.—Seat attenuation model based on Lockeed Martin 604 model. (a) Global coordinate system. (b) Brinkley local coordinate system (pressure vessel not shown).

between the above formulation and that of Lockheed Martin. At higher-than-expected velocities, there is a divergence between the parachute forces because the Lockheed Martin formulation uses a parachute drag coefficient that increases with descent velocity (thus increasing the drag force), whereas the above formulation uses a constant drag coefficient.

The finite-element program LS–DYNA is used to perform the analysis of crew module landings with parachute attachments. This commercially available program is selected because of its ability to simulate the complex transient dynamic behavior of the crew module impacting a landing surface. The crew module model is a collection of structural parts. The main portion of the vehicle, consisting of the pressure vessel, associated structure, and internal components, is modeled as a rigid part having inertia properties equivalent to the Lockheed Martin 604 crew module design (fig. 3(a)). The total weight of the vehicle is 13 046 lb, which is lighter than the currently projected design but is an adequate value to use for the purposes of the present study.

Inside the crew module pressure vessel is the astronaut pallet (fig. 3(b)). The pallet supports the astronaut seats and is supported by 15 energy-absorbing landing struts. A portion of the vehicle inertia properties is allocated to the pallet (modeled as a rigid part) to account for the astronaut and seat weights. Although the pressure vessel and pallet are modeled as structurally rigid and nonenergy absorbing, the pallet struts are modeled as energy absorbing because they provide the primary source of landing load attenuation.

The parachute and rigging are attached to the Orion finite-element model so that the parachute attachment point passes through the vehicle center of gravity with the vehicle oriented at the desired hang angle (fig. 4). The chute is attached approximately 190 ft from the vehicle attachment point. The vehicle model shown in the figure includes a triangular-shaped parachute; however, this is for visualization purposes only and as mentioned previously, the parachute is modeled as a concentrated mass.

For the purpose of the present study, the landing surface is assumed to be a relatively soft soil. The soft soil model has the effect of lessoning the resulting vehicle accelerations, compensating for the fact that most of the vehicle structure is modeled as rigid. A coefficient of friction of 0.60 is used to model the contact friction between the vehicle and soil surface.

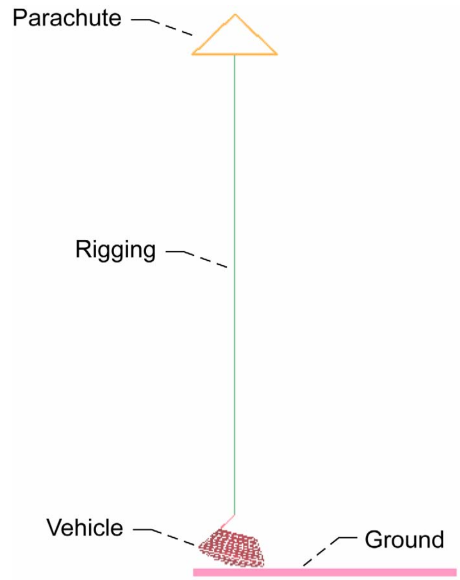

Figure 4.—Orion with parachute.

Parachute System Elasticity

Before proceeding with the assessment of the effect of parachute release times, it is necessary to measure the importance of the effect of the parachute system elasticity. For example, if a very stiff rigging configuration responds significantly differently from a soft system, it is essential that these differences be identified and that the system either be modeled as closely as possible to the actual "to-be-built system" or the differences be identified so that relevant information is available to subsequent designers.

The overall parachute system elasticity is a combination of the elasticity contributed from the harness, riser, parachute suspension lines, and air embedded in the inflated parachute. To assess the total overall effect from these components, they may be viewed as a single spring that connects the parachute to the vehicle. When the parachute pulls on the vehicle, the air inside the chute compresses and provides flexibility in the system, as do the rigging lines and riser. Although the parachute design may utilize materials such as nylon or Kevlar, which are readily characterized, the total system elasticity is more difficult to calculate because it is a combination of rigging material, geometry, and aerodynamics. In fact, when the rigging pulls on the parachute, compression of the air inside the parachute occurs and may provide more elasticity than all the rigging materials combined.

To provide a reasonable assessment of the system elasticity or to at least determine if elasticity considerations are even a significant issue, three different system stiffnesses are examined to assess their effect on the overall system response. The three stiffnesses are (1) a relatively rigid system in which the entire parachute/rigging elongates only 1 percent of its length when the weight of Orion is hung from it (i.e., 13 046 lb hung from a 190-ft parachute system stretches the system ~2 ft); (2) a medium system that elongates 2 percent of its length; and (3) a relatively soft system that elongates 5 percent of its length.

The crew module rotation and acceleration resulting from vertical and horizontal landing velocities of 26 and 37 ft/s, respectively, are shown in figures 5 and 6 for the three levels of stiffness. The hang angle is 0°. For all three stiffnesses, the parachute is kept attached to the vehicle for the duration of the simulation. In practice, the parachute would be released at some prior time rather than at the full 3 sec; however, for the purpose of assessing the effect of the parachute/rigging stiffness, the parachute is kept attached for the full duration. As depicted in figure 5, the fact that the vehicle rolls over regardless of the system stiffness is an expected response for a 0° hang angle and horizontal velocity. Furthermore, there is no significant difference among the three levels of stiffness. The simulation resulting from the softest stiffness does roll over slightly less than the other two stiffnesses, but the difference in rollover angle is not large. The accelerations at the location in the vehicle where the crew is seated are almost identical regardless of the level of stiffness. The medium level of stiffness will be used for subsequent simulations because this level is thought to be the most reasonable characterization of the actual stiffness.

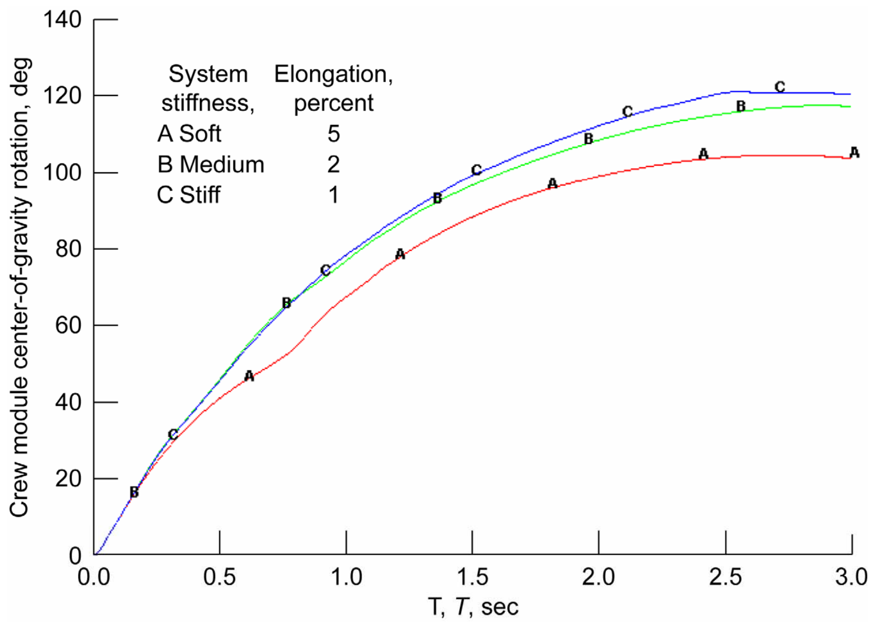

Figure 5.—Effect of rigging stiffness on crew module rollover. Parachute remains attached; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s.

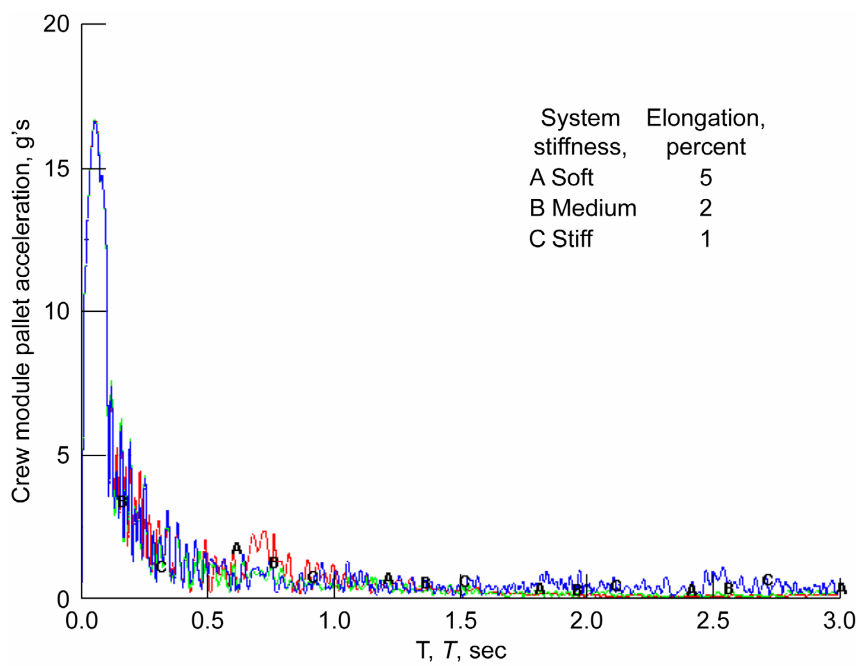

Figure 6.—Effect of rigging stiffness on pallet acceleration. Parachute remains attached; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s; no roll.

Results

The effectiveness of releasing the parachute from the crew module at different release times post-touchdown is examined for vertical and horizontal landing velocities of 26 and 37 ft/s, respectively. A 37-ft/s horizontal velocity is used because this velocity represents one of the more extreme conditions and is most likely to cause a higher incident of rollovers. The 15° hang angle is fairly optimal for vehicle stability in the presence of a horizontal landing velocity, whereas a flat 0° hang angle may be advantageous for a purely vertical landing. For the 15° hang angle, the parachute is attached to the vehicle so that the attachment point is vertical to the vehicle center of gravity with the vehicle oriented at a 15° hang angle.

The transient rigging force is shown in figure 7. The force starts out at 13 046 lb, which is equal to the weight of the vehicle and the initial tension in the rigging just before the vehicle touches ground. Upon touchdown, the rigging force quickly decreases as the ground stops the vehicle from further vertical motion, and the parachute continues to descend. At 0.17 sec, the rigging goes completely slack. The rigging remains slack until near 0.4 sec when the tension begins to increase as the horizontal wind load drags the parachute beyond where the vehicle is contacting the ground.

Figure 8 depicts the effect on vehicle roll of releasing the parachute at different times beyond the time when the vehicle touches ground. When the parachute is released right at touchdown (chute quick release), the vehicle roll is a minimum as compared with all the other release times examined. Regardless of whether the release time is at 0.17 sec (when the rigging first becomes slack) or at 0.08 or 1.00 sec, the vehicle roll is very similar. However, the roll is greater than when the parachute is released at 0.0 sec. When the parachute is kept attached for the duration, the horizontal wind force on the parachute dominates and pulls the vehicle over.

Figure 9 shows the resultant acceleration at the location of the crew members for the different values of parachute release times. The maximum acceleration occurs below 0.20 sec and since the maximum occurs so quickly after touchdown, it is the same regardless of when the parachute is released. Beyond the peak acceleration, the acceleration profiles are very similar for all the release times, except for the case in which the parachute is not released. For this case, the second peak in the acceleration profile near 0.50 sec is larger than that for the rest of the cases. This peak occurs after the vehicle has bounced off the ground and incurs a second landing. The peak is larger for the parachute without release because the parachute pulls the vehicle higher off the ground than it does for the other cases in which the parachute is released.

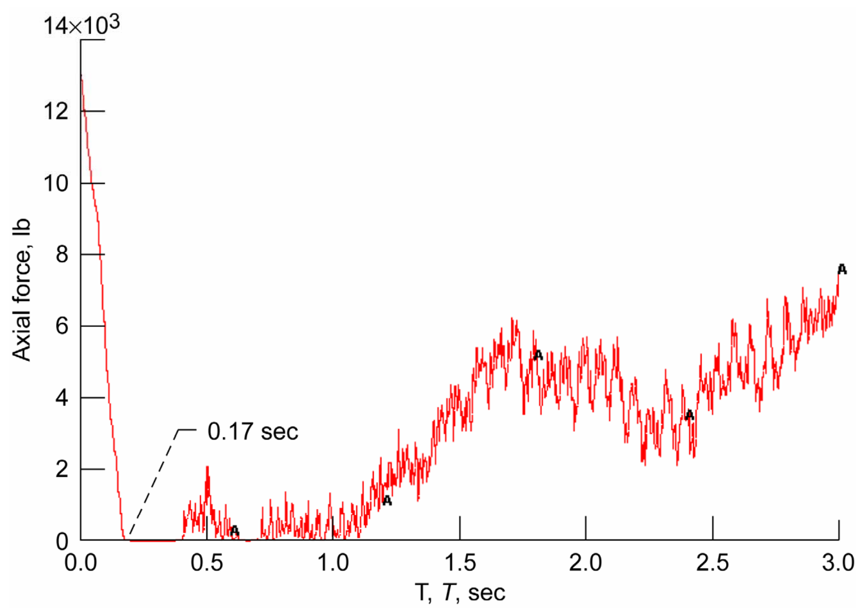

Figure 7.—Rigging force without chute release. Hang angle, θ_{hang}, 15°; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s.

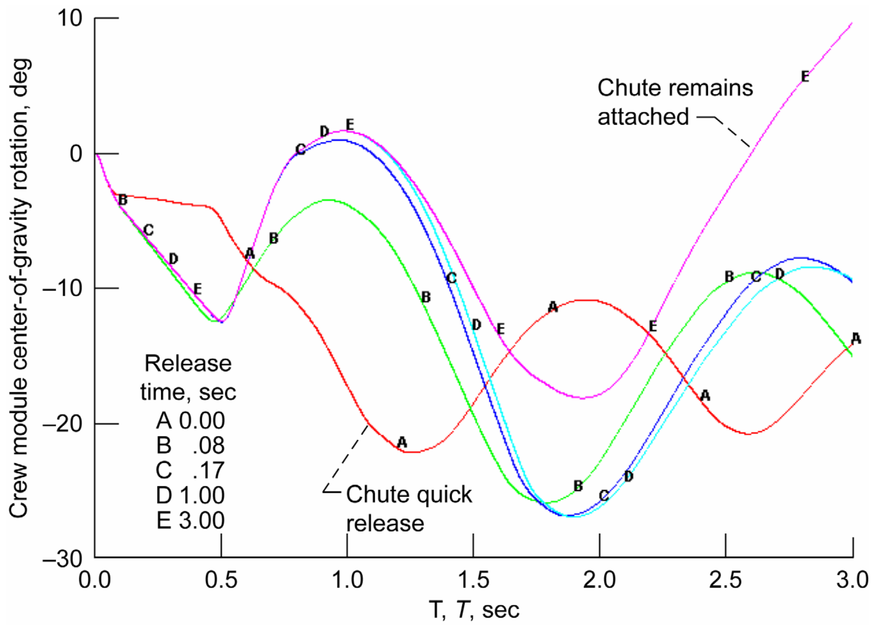

Figure 8.—Effect of parachute release time on vehicle rollover. Hang angle, θ_{hang}, 15°; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s.

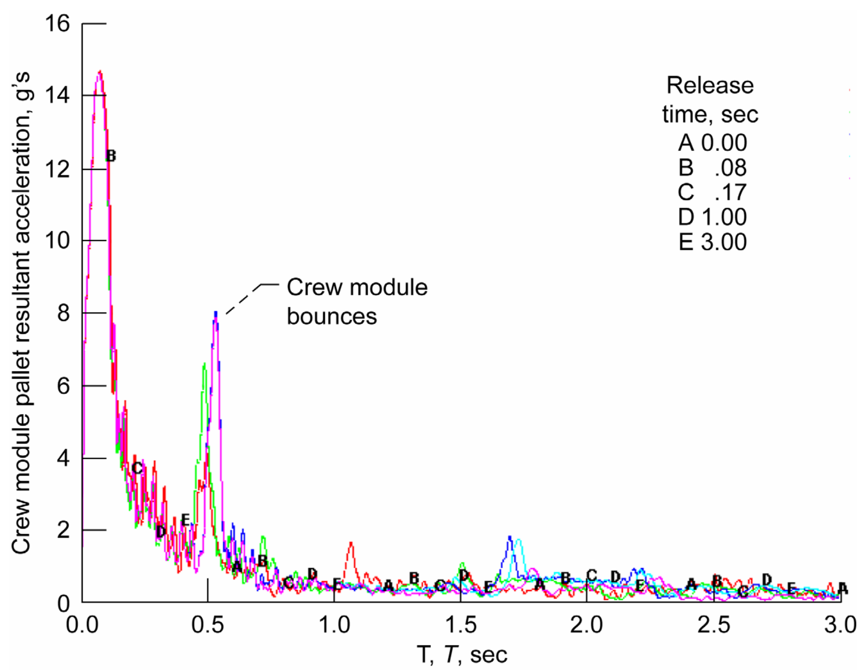

Figure 9.—Effect of parachute release time on pallet acceleration. Hang angle, θ_{hang}, 15°; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s.

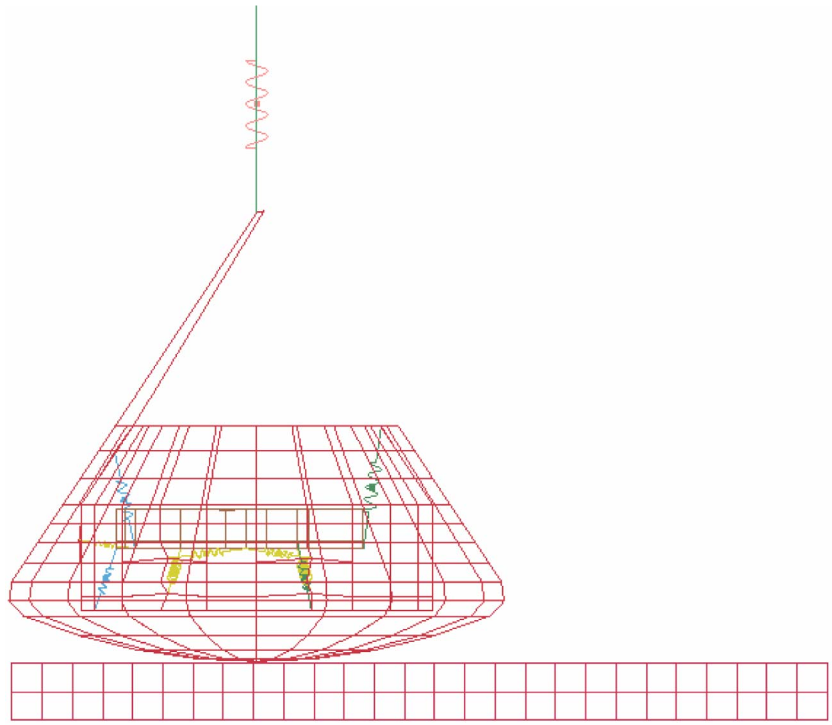

Figure 10.—Zero-degree hang angle (rigging attachment relocated to maintain hang angle).

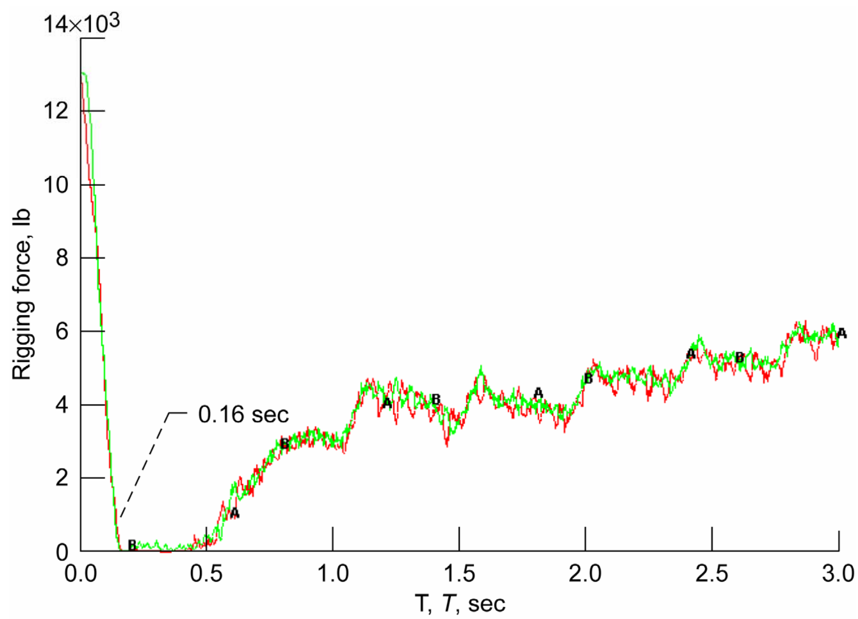

Figure 11.—Rigging force without chute release. Hang angle, θ_{hang}, 0°; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s.

Figure 10 shows a cross section of the vehicle for the 0° hang angle. For this hang angle, the parachute attachment point is moved to directly above the vehicle center of gravity while the vehicle is oriented at 0°. The center of gravity is close to the vehicle centerline so the attachment point appears to be centered in the figure. Figure 11 shows the transient rigging force for the case in which the parachute is not released. Similar to the 15° hang angle results, the force starts out at 13 046 lb and upon touchdown,

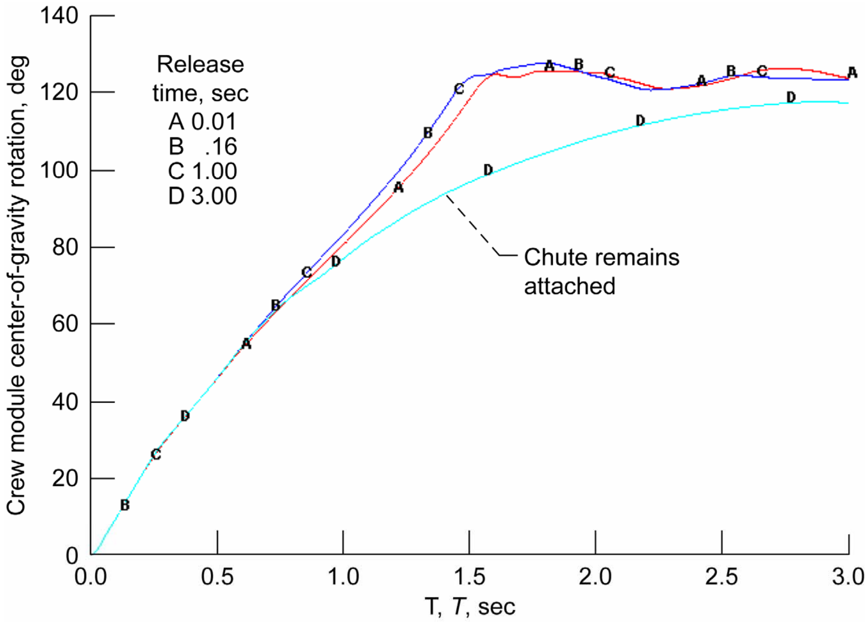

Figure 12.—Effect of parachute release time on vehicle roll. Hang angle, θ_{hang}, 0°; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s.

the rigging force quickly decreases and then the tension increases as the horizontal wind load drags the parachute. For the 0° hang angle, the parachute first becomes slack at 0.16 sec.

Figure 12 depicts the effect on vehicle roll of releasing the parachute at different times beyond the time when the vehicle touches ground. In general, the vehicle roll is very similar regardless of the release time. When the parachute remains attached for the duration, the vehicle roll is slightly less than that for the other cases for part of the response but converges to the same roll at the end of the simulation. All the cases converge to the same roll since the vehicle has rolled over at this time and is in a position resting on its top.

Figure 13 shows the resultant accelerations for the different release times, and similar to the roll profiles, the acceleration profiles are all very similar for each case with a peak acceleration near 0.20 sec followed by a second spike in the acceleration when the vehicle rolls over and the top of the vehicle strikes the ground.

Figures 14 and 15 show the effect of horizontal landing velocity and parachute release time on vehicle rollover for hang angles of 0° and 15°, respectively. In the presence of a horizontal landing velocity, the 15° hang angle is more stable than the 0° hang angle. Although the vehicle with a 15° hang angle can accommodate a horizontal landing velocity of close to 65 ft/s, the vehicle with a 0° hang angle rolls over when the horizontal velocity is only 30 ft/s. (Note that these rollover threshold velocities are relative, and additional study is needed to determine values that are more absolute.) As depicted in the figures, parachute release time has a minimal effect on vehicle rollover. For the 15° hang angle, the release time has no effect on rollover so long as the parachute is released before 0.18 sec. For the 0° hang angle, the allowable horizontal velocity before rollover occurs is slightly higher when the parachute is released at touchdown (time = 0.0); however, similar to the 15° results, the release time does not significantly affect rollover. Release times past 0.18 sec were not examined because the parachute rigging loses tension near 0.18 sec and beyond 0.18 when the rigging goes back into tension, the tension is a result of the horizontal wind, which always has a detrimental effect on rollover. Thus, the parachute should always be released before the rigging regains tension.

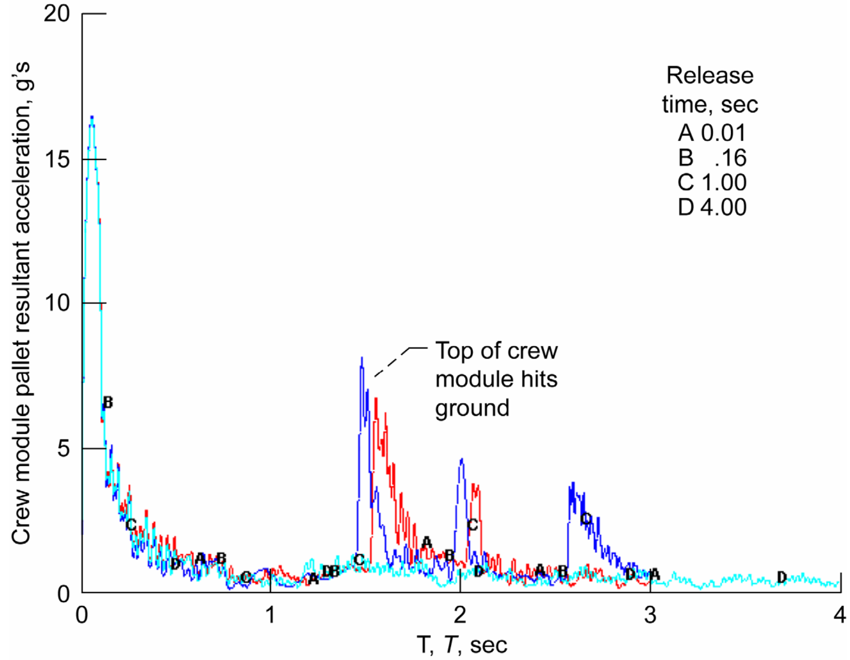

Figure 13.—Effect of parachute release time on pallet acceleration. Hang angle, θ_{hang}, 0°; vertical velocity, V_v, 26 ft/s; horizontal velocity, V_h, 37 ft/s.

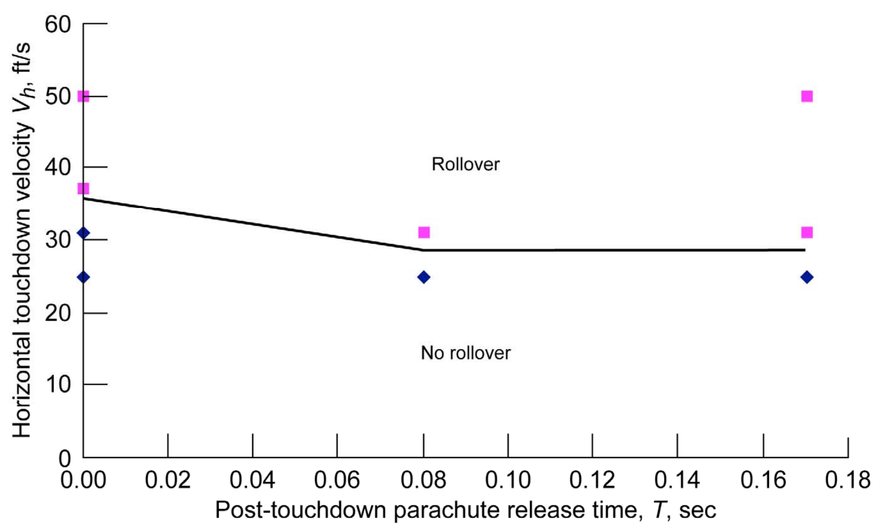

Figure 14.—Effect of horizontal velocity on rollover. Hang angle, θ_{hang}, 0°; vertical velocity, V_v, 26 ft/s; no roll.

A vehicle employing airbags for landing load attenuation has conflicting requirements with regard to a vehicle configuration that strives to minimize rollover potential. Airbags are most effective for a flat (0° hang angle) landing and are less effective when there is a horizontal landing velocity or when the vehicle lands with a hang angle. However, in situations when there is a horizontal landing velocity and a vehicle hang angle of 0° to optimize the airbags effectiveness, the vehicle will be more prone to rollover than if its hang angle were 15°.

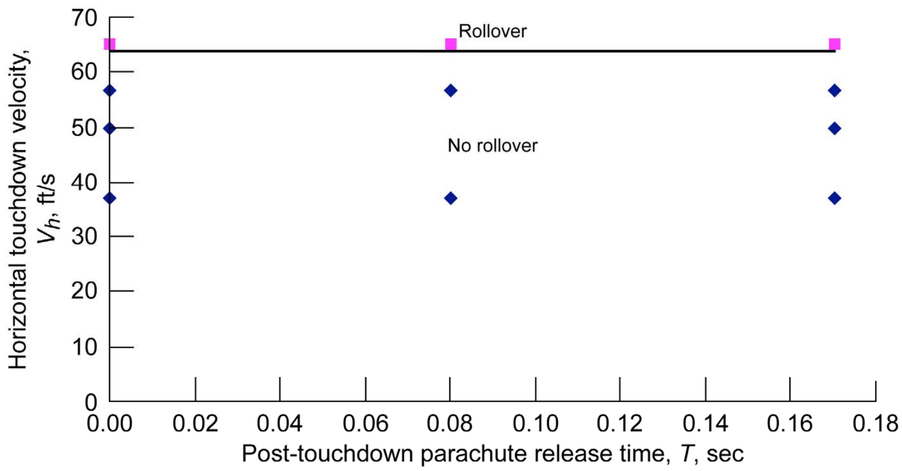

Figure 15.—Effect of horizontal velocity on rollover. Hang angle, θ_{hang}, 15°; vertical velocity, V_v, 26 ft/s; no roll.

Conclusions

A collection of representative landing conditions was used to assess the post-touchdown parachute release effect. In general, it was determined that there is no significant advantage or disadvantage to releasing the parachutes past the time when the vehicle touches ground. For landing conditions in which there is a high horizontal wind, retaining the parachutes has a detrimental effect on vehicle rollover because the drag force on the parachutes pulls the vehicle over. Some form of automated parachute release should be a requirement since in the presence of high horizontal winds, an attached parachute may cause the vehicle to roll over. An automated system is necessary because the release has to occur within 0.50 sec of touchdown (at the time when the parachute regains tension), which is not enough time for a crew-operated manual release.

The effects of rigging and parachute flexibility are minimal on the acceleration and roll response so that the trends reported herein should be applicable to most parachute system designs. Peak accelerations occur early at touchdown when the parachutes have negligible effect. Rollover that occurs after touchdown is not significantly affected by the parachutes because they are either slack or have minimal tension, thus applying little or no forces on the vehicle.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The effects that the Orion parachutes have on the vehicle response once the vehicle lands on the ground are examined in this report. A concern with the Orion landing is that structural accelerations will cause vehicle and/or crew injuries or that the vehicle may roll over. The parachute effects are thought to have the potential of pulling the vehicle over during conditions such as higher winds or in some cases stabilizing the vehicle by preventing its motions after touchdown. A collection of representative landing conditions is used to assess the post-touchdown parachute release effect, and it was determined that, in general, there is no significant advantage or disadvantage to releasing the parachutes past the time when the vehicle touches ground. For landing conditions when there is a high horizontal wind, retaining the parachutes has a detrimental effect on vehicle rollover because the drag force on the parachutes pulls the vehicle over. Under this condition, some form of automated parachute release should be a requirement given that an attached parachute may cause the vehicle to roll over. An automated system would ensure that the release occur within 0.50 sec of touchdown (time when parachute regains tension), which is not enough time for a crew-operated manual release.

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