

results of Ref. 1 with a touchdown dynamics program that is in use at NASA Marshall Space Flight Center indicates that several assumptions made in Ref. 1 are questionable and lead to optimistic results.

One assumption made in the analysis is that the coefficient of friction is considered to be sufficiently high, for all landing conditions, to develop the external forces required to crush the energy-absorbing materials. This assumption is valid only as long as sliding is present. When a foot stops sliding, the force component acting along the surface is greatly reduced, and the lateral energy absorber stops crushing. In the example presented, the crushing force of the lateral energy absorber was taken to be half that of the vertical energy absorber. As the vehicle contacts a 15° slope on the uphill leg with the lateral velocity in the downhill direction (Fig. 5, p. 1122, Ref. 1), the force vector initially acting on the foot pad is inclined 26.6° from the vertical and thus 41.6° from the normal to the surface. Thus, a coefficient of friction of 0.89 or larger would be sufficiently high to develop the external force required initially to crush the lateral energy absorber. However, this condition exists for only a very short time. The foot stops sliding, and the component of force acting laterally is less than the crushing force and must be computed. At this point, the vehicle's leg is still crushing vertically but not laterally.

As the vehicle continues to rotate, the crushing rate of the vertical energy absorber reduces. At some point, the crushing rate changes sign. When this occurs, the time at which the vertical crushing rate goes to zero should be determined by interpolation. The vehicle may then rotate as a rigid body without any crushing. The vertical component of external force is then less than the crushing force of the vertical energy absorber and must be computed. Thus another assumption in the analysis of Ref. 1 is not valid, inasmuch as it is assumed that the vehicle's leg has lifted off the surface whenever the crushing rate has changed sign or, as stated in Ref. 1, whenever the amount of deformation decreases in magnitude. According to this assumption, after the downhill legs contact the surface and the amount of deformation decreases, the downhill legs would be considered to have lifted off the surface! This is incorrect, inasmuch as inelastic energy-absorption devices without rebound are considered. Actually, the crushing stops, and the vehicle then rotates on the downhill legs as a rigid body. It thus appears that the analysis of Ref. 1 fails to determine adequately the lateral and vertical forces whenever they are less than the respective crushing forces of the energy absorbers.

A comparison of the results from Fig. 5 of Ref. 1 with that obtained by the touchdown dynamics program in use at NASA Marshall Space Flight Center is shown in Fig. 1. The nomenclature of Ref. 1 is used. Exact duplication of the input data was not possible, since a lateral energy absorber crushing force is assumed in Ref. 1, whereas the program at NASA Marshall Space Flight Center assumes a value for the coefficient of friction. However, as the vehicle contacts on the two downhill legs, the legs are essentially normal to the surface so that the tangential force developed is half the normal force and corresponds to a friction coefficient of 0.5. Therefore, this value was used in the NASA Marshall Space Flight Center program to represent most accurately the lateral energy absorber.

As seen from Fig. 1, with a lateral velocity of zero, the vehicle tumbles by the procedure used at NASA Marshall Space Flight Center for a vertical velocity of about 1.9 m/sec or greater, whereas by the method of Ref. 1 the vehicle does not tumble until the vertical velocity exceeds about 3.1 m/sec. This represents an increase of over 60% in the permissible vertical velocity.

Up to a vertical velocity of about 4.3 m/sec, the uphill leg stops crushing but does not leave the surface. The vehicle rotates as a rigid body, and the vehicle's angular acceleration continues to increase the verticle's rotational

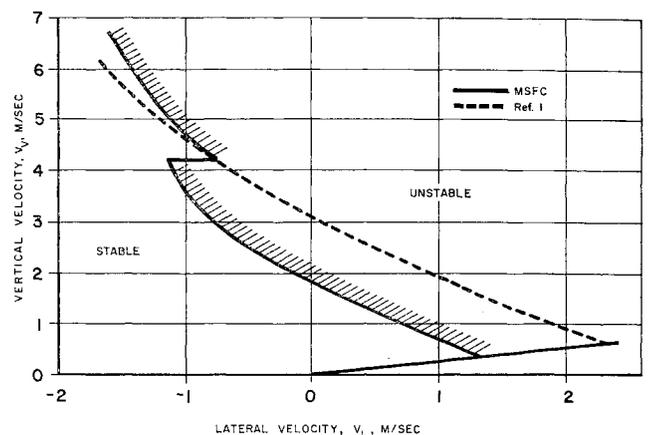


Fig. 1 Landing stability of vehicle impacting a 15° slope initially on one leg ($R_1 = 12$ ft, $R_2 = 10.4$ ft, $R_3 = 6$ ft, $I_x/m = 36$ ft², $DCG = 10$ ft, $nF_v/m = 386.4$ ft/sec², $A = 15^\circ$, $B = 0^\circ$, $\beta = 270^\circ$).

rate in the tumbling sense. At a vertical velocity slightly in excess of 4.3 m/sec, the uphill leg stops crushing and does leave the surface. The computed normal force required to hold the leg to the surface becomes negative. No negative normal forces are physically possible, so that the forces are set to zero and the leg leaves the surface. When in free flight, the angular acceleration is zero, and thus the rotational rate does not increase. This accounts for the increased stability effect seen in Fig. 1. The discontinuity on the stability curve occurs at the vertical velocity which results in a free-flight condition after the uphill leg stops crushing.

Reference

¹ Cappelli, A. P., "Dynamic analysis for lunar alightment," AIAA J. 1, 1119-1125 (1963).

Addendum to "Nonequatorial Launching to Equatorial Orbits and General Nonplanar Launching"

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ATTENTION is invited to the paper by Carstens and Edelbaum,¹ which gives data for optimum attainment of circular orbits from arbitrary launch points, considers nonapogee target orbit interception, and bears directly on the problem treated in Ref. 2. This reference was inadvertently and unfortunately omitted from the list of references given in Ref. 2.

References

¹ Carstens, J. P. and Edelbaum, T. N., "Optimum maneuvers for launching satellites into circular orbits of arbitrary radius and inclination," ARS J. 31, 943-949 (1961).
² Haviland, R. P. and House, C. M., "Nonequatorial launching to equatorial orbits and general nonplanar launching," AIAA J. 1, 1336-1342 (1963).

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