Engineering Notes

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Post-Ejection Impacts of the Space Shuttle Solid Rocket Booster Nose Cap

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THE parachute recovery of the space shuttle solid rocket booster is initiated by the separation of the nose cap from the solid rocket booster. After separation the nose cap pulls out (by means of a tether line) a pilot parachute and a drogue parachute stowed in the nose cap. The nose cap is 75 in. high and 67 in. in diameter and forms the top part of the solid rocket booster nose cone. The current baseline nose cap weighs 300 lb, and its moment of inertia about the pitch axis is 49.2 slug-ft^2. Flight environment at nose cap separation is represented by a dynamic pressure of 200 psf at an altitude of 19,000 ft, and a booster velocity of 558.3 fps at a large angle of attack (about 90°). The nose cap is ejected at a velocity of 80 fps by means of three pyrotechnic thrusters. It is required that the ejected nose cap should clear the drogue parachute pack without impact. Impact could however occur if due to some malfunctioning of the thrusters, the ejection velocity is low and the nose cap angle of attack is in some critical range characterized by the aerodynamic pitching moment. The purpose of this Note is to analyze the dynamics of the nose cap and parachute pack impacts, outlining the various possible impact conditions. A sample case is considered that simulates the impacts and is not intended to represent the baseline parachute deployment method. The analytical tool presented here can predict the ejection velocity at which the nose cap would separate from the solid rocket booster in a reasonable time, with some impact on the parachute pack permitted.

Impact Equations

Restricting the analysis to planar impact, with generalized coordinates q_r representing x, y, θ (see Fig. 1), the linear and angular impulses are obtained from the generalized impulse relation

$$I_r = V^Q,_{\dot{q}_r} \cdot (N_1 n_1 + N_2 n_2) \tag{1}$$

where $V^Q,_{\dot{q}_r}$ is the partial rate of change of position[1] of the impact point Q on the nose cap with respect to q_r, and N_1 and N_2 are magnitudes of impulses on the nose cap in the direction of the unit vectors $\boldsymbol{n}_1$, $\boldsymbol{n}_2$ fixed on the rocket (solid rocket booster). The basic impulse momentum relation at impact is

$$I_r = p_r(t_+) - p_r(t_-) \tag{2}$$

where p_r is the generalized momentum, and t_-, t_+ are instants of time just before and after impact. In Eq. (2) p_r is derived from the kinetic energy K as

$$p_r = K,_{\dot{q}_r} \equiv (\partial/\partial \dot{q}_r)[\tfrac{1}{2}m(\dot{x}^2+\dot{y}^2) + \tfrac{1}{2}I\dot{\theta}^2] \tag{3}$$

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with $\dot{q}_r = \dot{x}, \dot{y}, \dot{\theta}$, where m and I are mass and mass moment of inertia of the nose cap, respectively.

Considering the effect of the impulse to be negligible on the rocket because of its massive inertia, Eq. (3) can be looked at as 3 equations in 5 unknowns, $\dot{x}(t_+)$, $\dot{y}(t_+)$, $\dot{\theta}(t_+)$, N_1, N_2 Two assumptions are standardly made[1] to complete the solution. The first is the law of restitution, expressed as

$$V^{Q/P}(t_+) \cdot \boldsymbol{n}_2 = -eV^{Q/P}(t_-) \cdot \boldsymbol{n}_1 \tag{4}$$

where $V^{Q/P} = V^Q - V^P$, V^P being the velocity of the impact point P on the rocket, and e is the coefficient of restitution. The second assumption depends upon the friction behavior of the colliding surfaces and results in either a normal rebound or a sliding impact. Normal rebound, that is, no slip, is expressed as

$$V^{Q/P}(t_+) \cdot \boldsymbol{n}_2 = 0 \tag{5}$$

and is possible only if

$$|N_2| < \mu N_1 \tag{6}$$

where μ is the coefficient of friction.

Sliding impact occurs when $|N_2| = \mu N_1$, which is interpreted as

$$N_2 = \mu N_1 \tag{7}$$

or

$$N_2 = -\mu N_1 \tag{8}$$

Condition $N_2 > 0$ indicates backward slip for the nose cap, and $N_2 < 0$ denotes forward slip. The nomenclature "for-

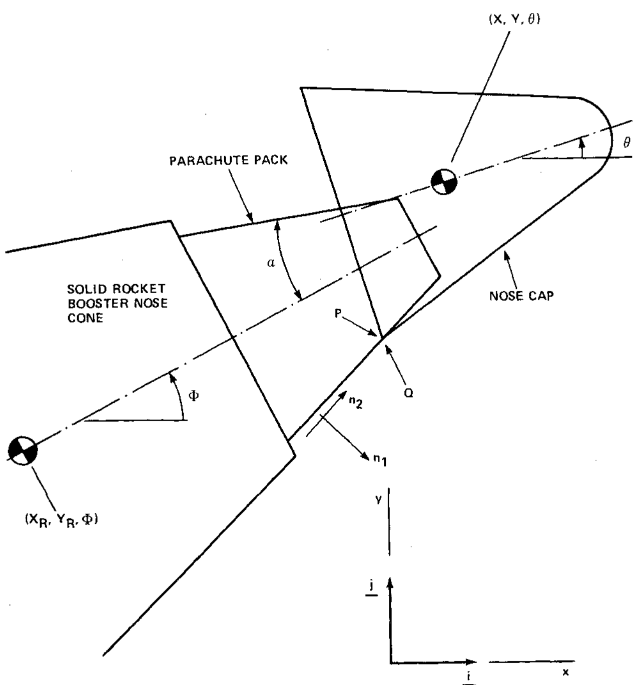

Fig. 1 Configuration of nose cap and rocket during impact.

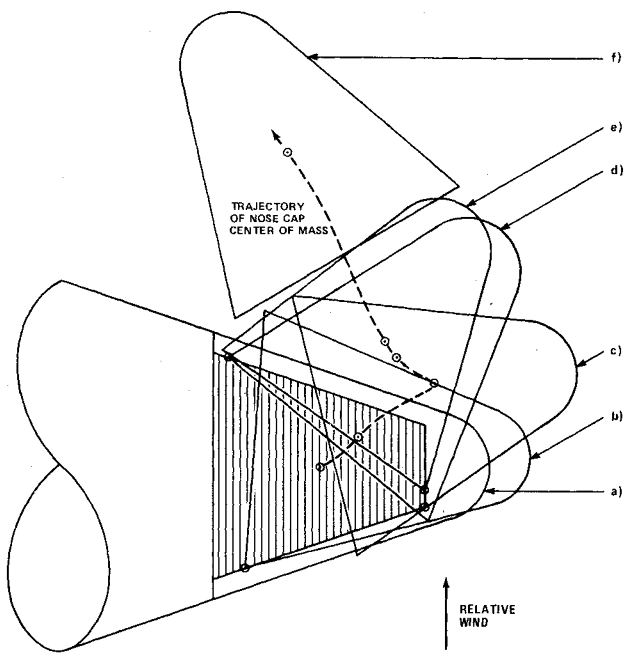

Fig. 2 Nose cap motion relative to rocket during successive impacts.

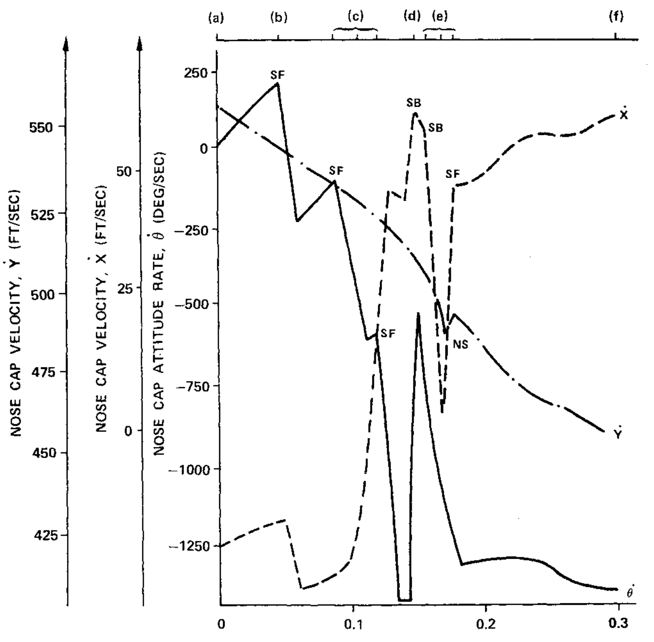

Fig. 3 Nose cap inertial velocities and angular rates during successive impacts.

ward" and "backward" is related to the fact that the tangential component of separation velocity is opposite in sense to tangential impulse $N_2 n_2$. Thus Eqs. (7) and (8) hold only if

$$N_2[V^{Q/P}(t_+)\cdot n_2]<0 \tag{9}$$

Analysis of an actual impact is started using Eqs. (2, 4, and 5). If the test in Eq. (6) fails, Eq. (5) is replaced by Eq. (7) and the test in Eq. (9) is applied to the resulting solution. If this too fails, the only possible solution is that given by Eqs. (2, 4, and 8).

Impact Detection

To use the preceding equations appropriately, positions of both bodies and their velocities at the exact instant of impact are required. Usually free flight equations of both bodies are integrated forward in time from a nonimpact configuration until time (t) at which an interpenetration of their geometric boundaries is indicated. Noting the penetration depth d of the point Q normal to the surface, a time interval $\Delta t = t - t_-$ is calculated from

$$d = -V^{Q/Q'}\cdot n_1\Delta t - a^{Q/Q'}\cdot n_1(\Delta t)^2/2 \tag{10}$$

where $V^{Q/Q'}$, $a^{Q/Q'}$ are the relative velocity and acceleration of Q with respect to Q', an image point of Q (after penetration) in the rocket R. Position and velocity of the impact point Q, just before impact, are obtained by backward integration as

$$q_r(t_-) = q_r(t) - \dot{q}_r(t)\Delta t - \ddot{q}_r(t)[(\Delta t)^2/2 \tag{11}$$

$$\dot{q}_r(t_-) = \dot{q}_r(t) - \ddot{q}_r(t)\Delta t \tag{12}$$

The quantities $\dot{q}_r$, $\dot{q}_r$ are obtained from the equation of motion and its first integral.

Steady-state aerodynamic coefficients based on unpublished wind tunnel test data on the nose cap (obtained from NASA Marshall Space Flight Center) were used in the equations of motion before and after impact. Consideration of the dynamic coefficients would be advisable because of the wide variation in angle of attack and velocities of the nose cap. Also, use of the interference aerodynamics data would be highly desirable.

Simulation Results

A typical case of separation with multiple impacts was obtained for the nose cap ejected at a velocity of 20 fps normal to the direction of the air flow. Coefficients of friction ($\mu = 0.25$), and restitution ($e = 0.85$) were selected. Seven successive impacts were detected and simulated. The motion of the nose cap relative to the rocket is shown on Fig. 2, where successive configurations are indicated. At separation, configuration (a), the cap takes a nose down motion relative to the rocket and impacts the parachute pack in (b). This impact causes the cap to bounce backwards and collide in diverse configurations (c-e) before going in free flight, (f). Inertial velocities and nose cap angular rates are plotted vs time on Fig. 3. All three types of impacts, slip forward (SF), slip backward (SB), and no slip (NS) actually happened in this case and are identified in this figure. The present analysis is applicable to impacts involving three-dimensional motion; the problem of locating the impact points, however, then becomes extremely cumbersome.

Reference

[1]Kane, T.R., *Dynamics*, Holt, Rinehart and Winston, New York, 1968, pp. 222-235.

Effects of Nosetip Shape Change on Re-entry Vehicle Dispersion

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Nomenclature

C_A = axial force coefficient
C_D = drag coefficient

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