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Momentum Imparted to Double-Sheet and Tubular Structures by Hypervelocity Impact

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THE meteoroid impact of a spacecraft, besides causing structural damage, can impart momentum to the spacecraft. If the momentum is large, this could cause appreciable rotation of the spacecraft and consequent loss of stabilization.

Although some data are available for the momentum imparted to very thick targets[1] and thin aluminum sheets[2] by hypervelocity impact, very little is known regarding the momentum imparted to structures more representative of spacecraft, such as double sheets or tubes. Available data[2,3] suggest that the imparted momentum depends on the state of the material sprayed from the rear of the impacted wall into the structure's interior. Calculations based on the method of Ref. 4 and employing the meteoroid environment of Ref. 5 indicate that a meteoroid impact at a velocity of 20 km/sec for some low-density metals, would cause the spray material to be melted partially. Conceivably, the liquid spray could undergo multiple reflections and attendant shock-heating within the walls of the structure, become vaporized and jet through the original entry hole to add appreciably to the imparted momentum. Moreover, in the case of a tube, the surface of the rear wall, by virtue of its curvature, could concentrate the reflected spray such that any jet effect, and, therefore, imparted momentum would be enhanced. On the other hand, the spray material could rupture the rear wall and escape, and not impart all of its momentum. To settle some of these questions, impact tests were conducted to determine the qualitative effects of various structural configurations on the momentum imparted to a spacecraft by a meteoroid impact.

The targets and projectiles were of aluminum, since calculations indicated that, by impacting this material at 7.8 km/sec, some of the spray would be melted. Thus, the state of the spray material for a meteoroid impact of a spacecraft would be simulated. A number of thin-walled targets of various configurations were impacted to determine the effects of some of the target variables. Each target was impacted near center in a direction approximately normal to the surface by a spherical projectile with a diameter of 3.18 mm. Since the projectiles were larger than meteoroids typically expected, the structural dimensions also were scaled up. Each target was mounted on a ballistic pendulum that measured the final target momentum. Also measured, by a separate pendulum, was the momentum of the material ejected uprange from the target. (See Ref. 2 for the techniques by which the momenta were measured.)

The configurations tested are shown in Fig. 1. Three tests were made with the first configuration, Fig. 1a, and are designated A, B, and C. The second configuration, Fig. 1b, differed from the first only in that it was a "closed" structure, with an aluminum tube inserted between the spaced sheets to prevent material from escaping except through the original entry hole or through the rupture, if any, in the rear wall. Two such targets, designated D and E, were tested. The third configuration (Fig. 1c) was an open-ended tube. Two tests, designated F and G, were made with this configuration. In all cases, the thickness of the front wall was 0.81 mm. This thickness was chosen to be one-fourth of the projectile diameter in order that a large percentage of the spray material would be melted (Ref. 6). The thickness of the rear wall was chosen, however, such that for each configuration one target would be ruptured but at least one other would not. The 1.6-mm-thick rear wall of target F was obtained by reinforcing the rear wall of a tube of constant wall thickness with a curved aluminum sheet.

In Table 1, the measured target momentum $(MV)_T$ and ejecta momentum $(MV)_E$, normalized with respect to the projectile momentum mv, are listed. (These ratios of momenta are used traditionally, for convenience, to report the results of momentum tests, but do not imply a sole dependence of either target momentum or ejecta momentum on projectile momentum.) In the last two columns of the table, the target and ejecta momenta are compared as ratios to the corresponding calculated momenta for a similar impact of a nonrupturing closed double-sheet target designated by $(MV)_{T\text{CALC}}$ and $(MV)_{E\text{CALC}}$. The calculations are based on the conservation of momentum and a correlation equation from Ref. 2

$$(MV)_{T\text{CALC}} = mv + (MV)_{E\text{CALC}} \quad (1)$$

$$(MV)_{E\text{CALC}} = mc(v - v_0)^2 \quad (2)$$

It is assumed in this calculation that there is no jet emerging from the hole. Here, m and v are the projectile mass and velocity, and the constants v_0 and c are equal to 0.55 km/sec and 0.017 sec/km, respectively. The former value is given by Ref. 2, whereas the latter was found by extrapolating the data of Ref. 2 to the lower front-sheet thickness of the targets impacted in the present tests.

A comparison of these ratios of momenta permits an assessment of the effects of jetting and rear-wall rupture on target momentum. Thus, if the jet emerging from the structure's interior is important, it would tend to enhance the target momentum so that $(MV)_T/(MV)_{T\text{CALC}} > 1$; whereas rear-wall rupture with no jet would reduce it, and $(MV)_T/(MV)_{T\text{CALC}} < 1$.

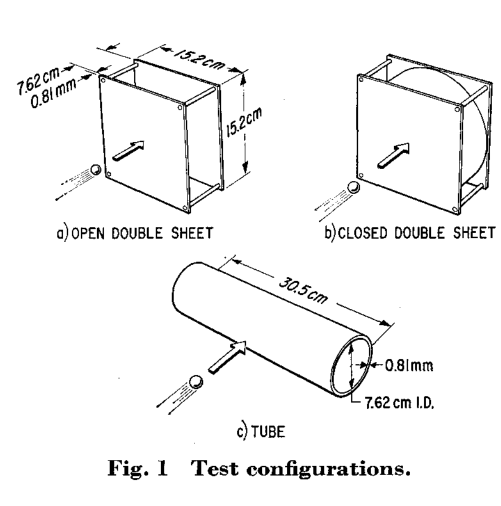

Fig. 1 Test configurations.

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Table 1 Momentum imparted to double-sheet and tubular structures, $m = 0.0459$ g

	Target configuration	Rear-wall thickness, mm	v, km/sec	Status of rear wall	$\frac{(MV)_T}{mv}$	$\frac{(MV)_E}{mv}$	$\frac{(MV)_T}{(MV)_{TCALC}}$	$\frac{(MV)_E}{(MV)_{ECALC}}$
A	Open double-sheet	2.3	7.754	Unruptured	1.11	0.166	0.995	1.5
B	Open double-sheet	0.81	8.006	Unruptured	1.10	0.162	0.987	1.4
C	Open double-sheet	0.41	7.761	Ruptured	1.06	0.151	0.947	1.3
D	Closed double-sheet	2.3	7.914	Unruptured	1.05	0.122	0.945	1.1
E	Closed double-sheet	0.41	7.698	Ruptured	0.99	0.104	0.890	0.92
F	Tube	1.6	8.085	Unruptured	1.05	0.115	0.936	0.97
G	Tube	0.81	7.553	Ruptured	1.07	0.110	0.963	1.0

For each target, it can be seen that the ratio $(MV)_T/(MV)_{TCALC}$ is less than one. This was the result even for target D, the unruptured closed double-sheet target, for which the ratio should have been one, at least. This result indicates that the measured target momenta may be low, with errors as great as 5%. It is concluded, however, that there was no significant jet effect for either the double-sheet configuration or the tube configuration despite the fact that the inside surfaces of the targets were found coated with a thin layer of aluminum, evidence that some aluminum had been melted and possibly vaporized by the impact. Apparently, most of the melted or vaporized spray material, instead of jetting through the original entry hole, deposited itself or condensed on the walls of the target in each case.

This result does not prove that there will be no significant jet effect for impacts of honeycomb or foam-filled double-sheet structures. These might enhance the jet either by confining the melted or vaporized spray material to a smaller volume, thus raising its pressure, and increasing the jet velocity or, in the case of the foam, by adding to the mass of the jetted material. Moreover, it is emphasized that these tests simulated meteoroid impacts that melt (rather than vaporize) the spacecraft material. If much vapor is produced, either because of the material used or because of a much higher meteoroid velocity than 20 km/sec, additional simulation tests will be required.

By comparing the ratio $(MV)_T/(MV)_{TCALC}$ for targets A, B, and C, or for targets D and E, the effect of rear-wall rupture for the double-sheet configurations is seen to be measurable, but small for these test conditions. For each of these configurations, the target momentum was reduced by about 5% by rupture, even though a large gaping hole was torn in the rear wall. Although it appears, by comparing the ratio for targets F and G, that the effect of rupturing the rear wall of the tube configuration was to increase the target momentum, this apparent increase is due to the fact that the unruptured tube was impacted slightly high, thus causing the ejecta momentum vector to be inclined at a small angle with respect to the flight axis. The axial component of the ejecta momentum was therefore smaller than it would have been had the projectile impacted normally. This caused the axial component of the unruptured tube's momentum, measured by the pendulum, to be smaller, too, since the axial target momentum is the sum of the axial ejecta momentum and projectile momentum. It should be noted, however, that the momenta of both the unruptured and ruptured tubes were nearly the same as that of an unruptured closed double-sheet target where there is no jet effect.

Rupturing of the tube's rear wall produced a large crack, but the hole was much smaller than for the ruptured double-sheet targets, which had a much thinner rear wall. However, the rear wall of the tube was ruptured, whereas the same thickness rear wall for the double-sheet configuration (target B) was not, even though the impact velocity for the latter target was higher.

The calculated ejecta momentum, on the other hand, was within 10% of that measured for all the targets except the open double-sheet targets (A, B, and C). For the latter targets, the measured ejecta momentum was as much as 50% greater than that calculated. This indicates that, for the open configuration, spray material reflected from the rear wall, escaped through the open peripheral area between the two sheets with a velocity component uprange, and because of the experimental setup hit the outer portions of the ejecta pendulum, thereby increasing its momentum. This escape of spray material also increased the target momentum, by ~5% over that of the closed configuration, as may be seen by comparing the ratio $(MV)_T/(MV)_{TCALC}$ for targets A, B, and D or for targets C and E.

These results indicate that the momentum imparted to a spacecraft by a meteoroid impact that produces solid or melted spray can be estimated from Eq. (1). For use in Eq. (1), a relation for $(MV)_{ECALC}$, as a function of impact velocity, must be established for impacts of the spacecraft material by projectiles that simulate meteoroids. The relation has yet to be established for materials other than 2024-T3 aluminum, but can be determined experimentally by the method of Ref. 2. For other materials, the relation is probably different from that given by Eq. (2), since it is expected that the ejecta momentum is dependent upon material properties. However, any empirically obtained relation probably will have to be extrapolated to the meteoroic velocity of interest, since laboratory velocities are much lower than meteoroid velocities.

The primary conclusions regarding the tests for momentum imparted to thin-walled structures by hypervelocity impact are as follows: 1) Neither jetting of spray material through the impact hole nor rupture of the rear wall has a significant effect on the imparted momentum. 2) The momentum imparted to a spacecraft by a meteoroid impact that produces melted or solid spray can be estimated by Eq. (1). 3) The momentum imparted to a thin-walled tube of diameter much larger than the size of the impacting particle is nearly the same as that of an unruptured closed double-sheet target.

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