MOMENTUM TRANSFER IN HYPERVELOCITY COLLISIONS. K.R. Housen[1] and K.A. Holsapple[2], [1]Applied Physics, MS 2T-50, The Boeing Co, PO Box 3999, Seattle WA 98124 kevin.r.housen@boeing.com, [2]Aeronautics and Astronautics, Univ. Washington, Seattle WA 98195 holsapple@aa.washington.edu.

Introduction: Aside from the obvious effects that impact events have on the surfaces of planetary bodies, cratering and fragmentation events impart momentum to the impacted body. This transfer of momentum affects the collisional evolution of planetary ring particles, the rotational states of asteroids, and is an important part of strategies to mitigate the threat of potentially hazardous objects [1]. This abstract describes the first steps in an experimental and theoretical program to improve our understanding of momentum transfer in hypervelocity collisions.

Scaling: The fundamental physics for the effects of an impact into an asteroid or comet is simply the balance of momentum. If the projectile has mass m and initial velocity, U, relative to the asteroid, then the velocity change of the asteroid (whose mass is M) is $\Delta v = \beta mU/M$ where β, the *momentum multiplication factor*, is ≥ 1. If the projectile just buries itself in the target and no material is thrown out, the event is 'perfectly plastic' and β=1. However, a hypervelocity impact into a geological material usually blasts out a crater many times the size of the impactor. The volume of the crater is a few orders of magnitude greater in volume than the impactor. In the cratering process, material is ejected at fairly large velocity, with a substantial component of that velocity being normal to the local surface. Therefore the total impulse imparted to the target body has two parts: the “primary” component from stopping the projectile, with β=1, and the additional component from the ejected material, which gives β>1 (normal to the surface). Depending on the mass and speed of the ejecta, the total transferred momentum can be significantly greater than the direct momentum of the projectile, i.e. β can be significantly larger than 1.

The dependence of β on the impact conditions is determined from the scaling theory of hypervelocity impacts. The scaling relies on the fact that the projectile is very small and transmits its effects very rapidly in comparison to the subsequent outcomes, such as the crater and the late ejecta, so the process can be approximated as a point source deposition of energy and momentum. In that case, all of a projectile’s defining parameters: its radius a, velocity U and mass density δ, combine into a single power-law combination $aU^{\mu}\delta^{\nu}$ that determines the outcome. The applicability of that assumption is well documented from experiments [1]. The scaling theory says that the value of the exponent μ must be between 1/3 and 2/3. Experiments in relatively non-porous materials such as rocks show μ is about 0.55. For moderately porous materials, e.g. dry sand, μ is 0.4, but is expected to approach the limit of 1/3 for highly porous materials.

If the crater produced by an impact on an asteroid is determined by the strength of the surface material, then the point source assumption gives the following scaling relation for β:

$$\beta \propto \left(U\sqrt{\rho / Y}\right)^{3\mu-1} \qquad (1)$$

where ρ and Y are the density and strength of the asteroid material. In the limiting case of μ =1/3, β is independent of impact speed. At the other extreme of μ =2/3, β increases linearly with U. Real geological materials fall somewhere between these limits. In any case, the momentum multiplication for an impact into as asteroid at 10 or 20 km/s could be much higher than measured in the lab at lower impact speeds.

If the asteroid were a strengthless "rubble-pile" then material strength would be irrelevant and the surface gravity g would determine the cratering. The scaling theory for this gravity-dominated regime is

$$\beta \propto \left(U^2 / ga\right)^{(3\mu-1)/(2+\mu)} \qquad (2)$$

In the limiting case of μ =1/3, β is again independent of impact speed, while for μ =2/3, β is proportional to $U^{3/4}$. As in the strength regime, gravity-dominated impacts into geological materials will show an increase of β with increasing impact speed. Another important aspect of gravity-dominated impacts is that β will also increase as gravity decreases. Physically this is due to the greater mass of ejecta associated with the larger craters produced in low-gravity environments. Applications of experimental results to asteroids must take this into account.

Experiment: The suite of planned experiments will include target materials spanning a wide range of strengths and porosities. In our initial experiments, the target is dense quartz sand, a gravity-dominated material. The experimental apparatus consists of a container of dry sand (density ~1.8 gm/cm^3) suspended in a test chamber by four steel springs whose attachment points are equally spaced around the perimeter of the cylindrical target container. In the single experiment reported here, the projectile was a polyethylene cylinder (12.1 mm dia and height, mass=1.34 gm) that impacted the sand target at normal incidence with a speed of 1.53 km/s. The chamber was evacuated prior to the test.

The impact was recorded by two high-speed video cameras, one to measure the projectile speed and one to record the frequency, ω, and magnitude, H, of the vertical oscillations of the target container after impact. The impulse delivered to the target is $H\omega M/2$, where M is the mass of the target. Therefore, the total impulse delivered to the target can be determined by recording the oscillations of the target container. That impulse, divided by the initial projectile momentum, gives the value of β for the experiment.

Results: The figure below shows the value of β measured in the present experiment in sand, along with literature data for other materials The data from Ref. 2 for aluminum targets currently provides the most information on how β depends on impact velocity. At the lowest speeds, the impact does not produce ejecta; the projectile simply rebounds from the target, and approaches the elastic rebound limit (with a given coefficient of restitution). Deformation of the projectile increases as the impact speed goes up, approaching the limit (β =1) of a perfectly inelastic collision at U~1 km/s. With further increases in impact speed, more and faster ejecta are produced, reflected by an increase in β. At speeds above U~5 km/s, the data follow the point-source power law slope expected for a non-porous material (Eq. 1 with μ=0.55), as indicated by the black dashed line. The data for basalt [3, 4] are much less extensive, but hint at a trend similar to that for aluminum. The basalt curve is shifted about a factor of 3 to the left of the aluminum data, consistent with the factor of 10 difference in their tensile strengths. That is, if the data were plotted in terms of $U/Y^{0.5}$, the two materials would collapse onto a single curve. Stated another way, at a given speed, the weaker basalt liberates more ejecta than an aluminum target, resulting in larger values of β for basalt.

The blue dashed line through the sand point shows the slope expected for a gravity-scaled impact in a moderately porous material (Eq. 2 with μ=0.4). The question of whether sand follows this power-law scaling line will be addressed in future experiments.

An important difference between the sand and basalt experiments is that part of the ejecta for a sand target returns to the surface and therefore does not contribute to momentum multiplication. Only the material that escapes the target container contributes. Similarly, only the ejecta that escapes an asteroid can contribute make β >1. The "escape velocity" for the sand container was ~1 m/s, which corresponds to the escape speed of a ~2 km asteroid. In that sense, the sand experiment reported here mimics the case of a strengthless asteroid a few km in diameter.

Validation of the scaling laws for β will be addressed in experiments with a variety of target materials and impact conditions. The anticipated results will provide insights into the collisional evolution of asteroid rotation rates and mechanisms for mitigation of potentially hazardous objects.

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