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Study of the Effects of Projectile Shape in the Asteroid Orbit Change by Spacecraft Impact

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Abstract

NEO (Near Earth Object) are the celestial bodies which pass near the Earth. One NEO deflection method is spacecraft impact. In order to estimate its results, it is necessary to clarify mechanism of momentum change of NEO. Generally, β is used as an evaluation index in this field and affected by various factors, so this study focuses on spacecraft shape. Five types of projectile shape were tested and compared in term of two aspects. In addition, we made comparison by using scaling law in order to compare the shape effect in the speed region which is assumed to using actual NEO deflection.

Peer-review under responsibility of the scientific committee of the 14th Hypervelocity Impact Symposium 2017.

Keywords: Hypervelocity impact; momentum shift; space guard

Nomenclature

M_t	Target mass
Δv_t	Target velocity increment
m_p	Projectile mass
v_p	Projectile velocity

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m_e	Ejecta mass
v_e	Ejecta velocity
α	Ejecta spread angle
β	Momentum ratio
ρ_t	Target density
ρ_p	Projectile density
Y_t	Target strength

1. Introduction

"NEOs" are asteroids and comets whose orbits pass near the Earth. One example of a NEO that actually hit the Earth is the Chelyabinsk meteor, which fell and exploded in southern Russia in 2013. It was the first case of damage which was clearly and unambiguously caused by an asteroid. It is also considered that the Tunguska event, and the extinction of many species about 65 million years ago, are due to asteroid impacts. In order to prevent these sort of damaging events, it is necessary to perform a deflection of a NEOs orbit before it hits the Earth. One efficient method of deflection is to use spacecraft impacts to change the NEOs orbit. This method does not require additional equipment to be attached to the NEO, rarely disrupts the asteroid, and ends quickly. Therefore, in this study we focus on spacecraft impacts as a deflection method.

Spacecraft impact is performed by transference of momentum from spacecraft to NEO and evaluated β which is defined by the ratio of momentum of spacecraft in (1).

$$M_t \Delta\overrightarrow{v_t} = m_p\overrightarrow{v_p} - \sum m_e\overrightarrow{v_e} = \left(1 - \frac{\sum m_e v_e \cos\alpha}{m_p\overrightarrow{v_p}}\right) m_p\overrightarrow{v_p} = \beta m_p\overrightarrow{v_p} \quad (1)$$

We need to estimate β when deflection method is carried out. However, it is difficult to estimate β because it is affected by a lot of factors. These factors have been investigated by many researchers. For example, studies have focused on the porosity of the target [1-3], the angle of incidence of the projectile [4], factors that influence ejecta generation [5], and so on. This study focuses on the effect of projectile shape from these factors. In field of hypervelocity impact on NEO, a few studies on projectile shape effect can be found even though the impact velocity and the characteristic of target are often focused. Based on these backgrounds, this study aimed to investigate the influence of the projectile shape on β.

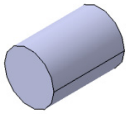
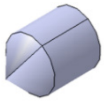
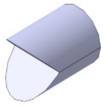
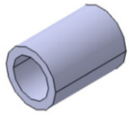
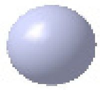
2. Instruments

Two stage light gas gun was used as a projectile launcher and a pendulum type testing machine for measuring the momentum [6].

2.1. Projectile

Five types of projectiles were tested as can be seen in Table 1. They are made of aluminum alloy for imitating spacecraft structure's material.

Table 1. Projectile

	Cylinder	Cone	Punch	Cup	Sphere
Shape					
Material	Al 2024-T4				Al 2017-T4

Four of these projectiles are made of Al 2024-T4 which is registered in the AUTODYN's library (numerical analysis software) in order to facilitate numerical analysis in future research. The sphere shape was used to test pendulum type testing machine in the previous study [6], so its material is different, this one is made of Al 2017-T4. Each projectiles diameter is 14 mm, and length is 20 mm except for the sphere shape. We usually should set the same mass of projectile in case of comparing these shape effects. But, the problem here is we used also a sphere shape projectile, and in this case, the limiting parameter would be the Length / Diameter projectile's ratio. Indeed, if we keep the same masses for every projectiles, it will cause instable projectile's posture during the launch. This is why we focused on the Length / Diameter ratio instead of the mass. The crater formation is mainly due to the projectile's length, this is why we kept the same dimensions for our study.

For the momentum transfer, it is necessary to select projectiles that can generate more fragments with an opposite direction from the projectile. In addition, we chose a simple shape to examine the features of shape effect. The cylinder, cone and punch shape were chosen for their potential to increase the crater volume. These shapes were adopted because they are considered to be able to increase the volume of crater by making its depth deeper which will also increase β. The sphere shape have a particularly: if the impact velocity was increased, it was found out only the crater's diameter increased whereas the depth almost did not change. The cup shape was selected to control the direction of generated ejecta. We wanted to use also a pipe shape for our study, in that case, it is thought that the scattering direction of the ejecta can be controlled by it passing through the inner cavity. But it can not be accelerated, hence we preferred to select the cup shape. In NEO deflection by using spacecraft impact, it is important how much ejecta is generated in the opposite direction to the projectile. However, we need to take into account the momentum transfer, which will decrease when the spread angle of ejecta get wider.

2.2. Target

Firebrick was used as targets in this study. The reason for selecting firebrick is that the density is close to NEO's one (about 2.0 g/cm^3), so it can simulate deflection process. In addition, because firebricks are cut out from a homogeneous larger base material, then individual differences between each samples are considered to be small or nonexistent. In order to prevent collapsing the target and its crater by the impact, the target is surrounded by a wooden frame to protect it.

3. Consideration

3.1. Projectile shape effects for ejecta mass

The amount of ejecta is one of the most important factor in β calculation, so each shape was compared to show these effects by plotting impact velocity vs. ejecta mass. This comparison used a dimensionless number which is the ejecta mass divided by the projectile mass in order to avoid a variation of experimental results because of the projectile mass difference.

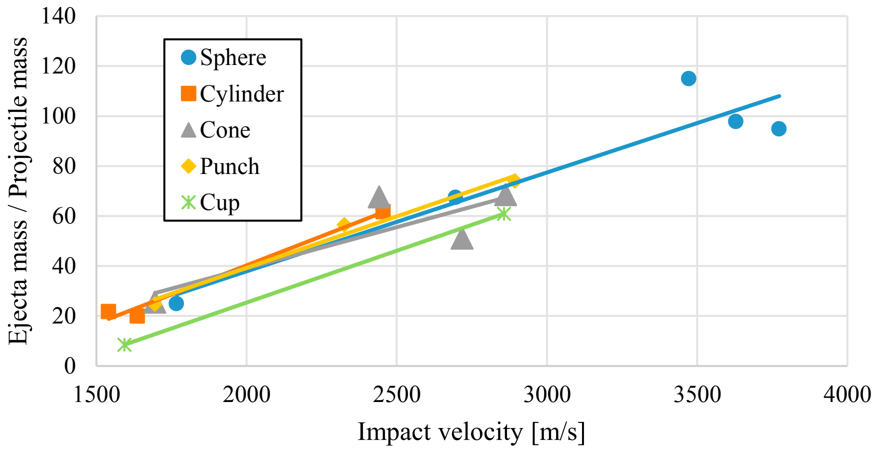


Fig. 1. Impact velocity vs. Normalized ejecta mass

In Fig. 1, we plotted points of each experimental data and used a method of linear regression. As you can see from Fig. 1, the slopes of each ejecta mass function is quite similar for every shape. Therefore, we can confirm for an impact velocity range from 1 to 4 km/s that the projectile shapes do not affect the ejecta mass. However, the cup shape got a bit different results because it can be due to its higher porosity than other shapes (mostly because of its hollow part). In other words, the density of the cup shape is smaller than the other ones. Projectile density is one of the factor which affects β, so this result was changed.

3.2. Projectile shape effects for β

The projectile shape effect will be compared by taking into account the efficiency of generated ejecta. We compared the momentum of projectile versus β (see Fig. 2) and also the projectile momentum versus Normalized ejecta mass (see Fig. 3). The same parameter (input momentum) was used on the abscissa in this comparison in order to compare the tendency of β and ejecta mass. Also, approximate line was drawn assuming that if input momentum equal 0, β equal 1 and the ejecta mass equal 0. If the input momentum is 0, ejecta are not generated by the impact. In this case ejecta's momentum ($m_e v_e$) in equation (1) equal 0. Also, we assumed that momentum is conserved before and after the impact, which means β minimal value will be 1.

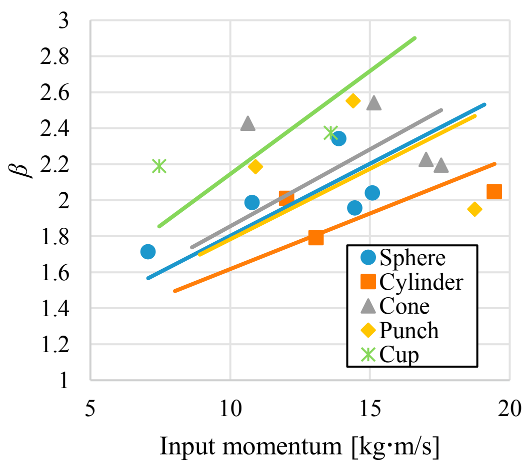


Fig. 2. Input momentum vs. β

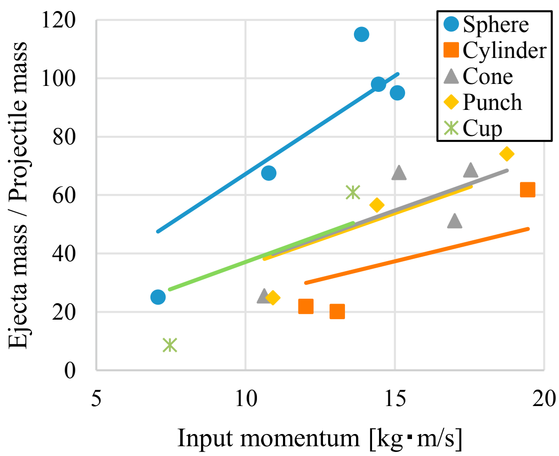


Fig. 3. Input momentum vs. Normalized ejecta mass

As shown in Fig. 2, for all the shapes, β increases when the input momentum get bigger. This behaviour occurs because of the previous effect we described in Fig. 1. For the same input momentum value, β of the cup shape was maximal, followed by the cone, sphere, punch and finally, cylinder. On the other hand, the largest ejecta mass was first the sphere shape. As mentioned above, we said β increases when the ejecta mass get bigger, but the influence of ejecta mass on momentum transfer for each shape is possibly different. It is presumed the β difference was caused by the spread direction of ejecta emission even if the amount of ejecta stays the same. For a larger spread angle, the ejecta will scatter more widely, which will make β smaller. In Fig. 5, the relationship between the ejecta amount and β for each shape was compared. In this graph, the larger the inclination, the more efficient the momentum transfer become because of the ejecta release.

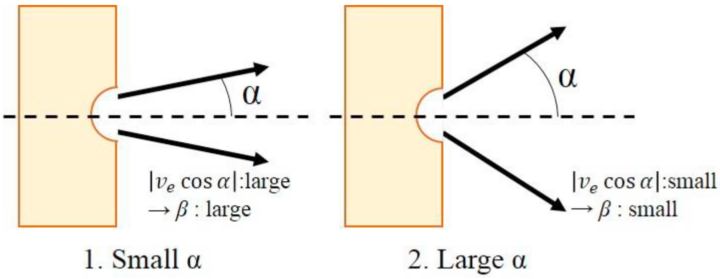


Fig. 4. Spread angle and β

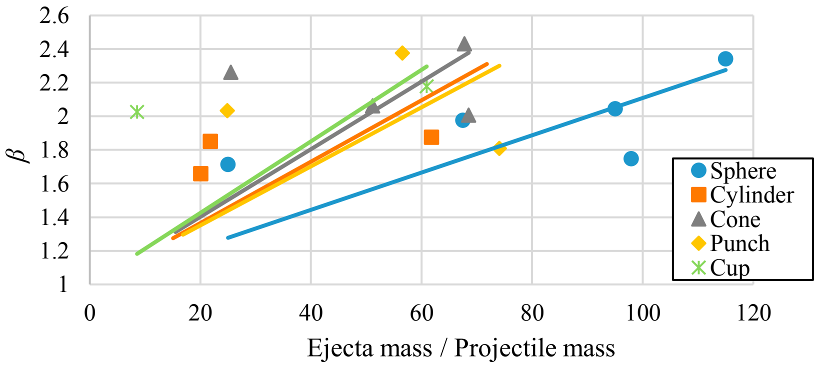


Fig. 5. Normalized ejecta mass vs. β

From Fig. 5, it can be seen that the cup shape is the most efficient projectile for momentum transfer in terms of ejecta mass. There is a cavity inside the cup shape, and it has a possibility that ejecta passed through it and the ejecta scattering angle did not become large like Fig. 6.

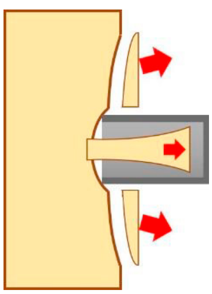


Fig. 6. Ejecta scattering direction (cup)

3.3. Comparison of projectile shape using scaling law

In this section, each shape were compared with a scaling law which does not have to consider the mass difference of projectiles and targets [7].
From this scaling law and the experimental data, β on the actual scale is given by:

$$(\beta - 1)\cdot\left(\frac{\rho_t}{\rho_p}\right)^{1-3\nu} = C\left(v_p\sqrt{\frac{\rho_t}{Y_t}}\right)^{3\mu-1} \quad (2)$$

We used ν equal to 0.4 in this calculation because lots of material has the same characteristic [8]. C and μ were used as parameters of the projectile shape. Both sides of previous formula were obtained from the results of the experiment, and Fig. 7 shows the tendency. In addition, the equation of the power approximate expression was found for each shape and C and μ were determined. In order to use the scaling law, NEO density and compressive strength are required. From the meteorite on which was investigated in [9], we selected those with both known strength and density and used their average value. For the projectile, we used Al 2024-T4 density. The table 2 shows each value used in this calculation and the table 3 shows each shapes parameter of equation (2) from Fig. 7.

Table 2. Property

	Average
Compressive Strength [MPa]	191.15
Target Density [kg/m^3]	3430
Projectile Density [kg/m^3]	2698.4

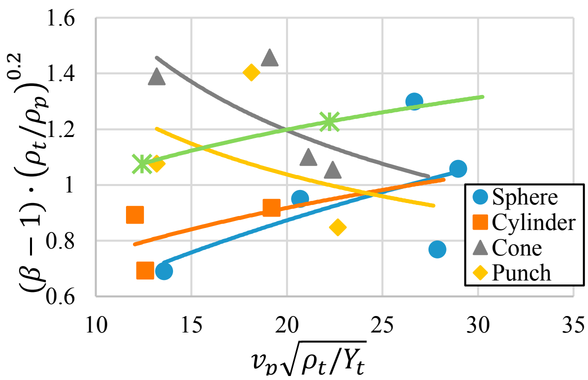


Fig. 7. β-scaling

Table 3. Parameter of (2) from Fig. 7

Shape	C	3μ-1
Sphere	0.1997	0.4924
Cylinder	0.3698	0.3034
Cone	4.9397	-0.4730
Punch	2.9801	-0.3520
Cup	0.6083	0.2264

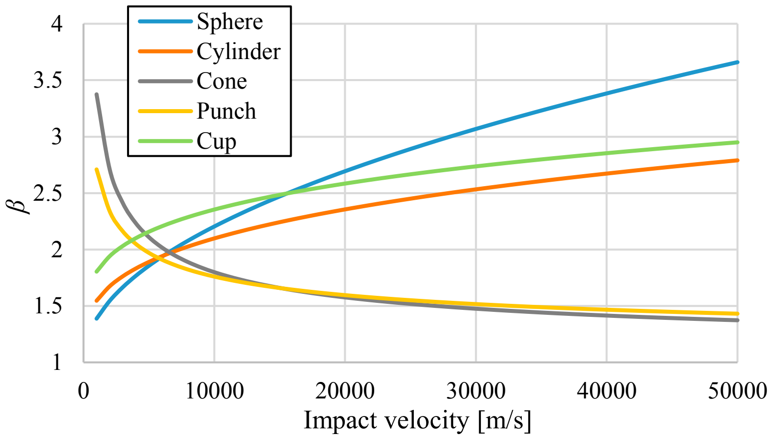


Fig. 8. Impact velocity vs. β (β-scaling)

In Fig. 8, the relation between impact velocity and β which is obtained with equation (2) and shape parameter from Fig. 7 is shown. In the velocity range of 5 km/s or more, which is assumed by actual deflection, β became larger as impact velocity increased for the cup, cylinder and sphere shape. Also, it is found that the cup shape is the best when the velocity is less than 15 km/s. In the speed range beyond that, the sphere shape takes the first position. This result proves that the sphere is the best and is consistent with what was pointed out in the previous study [5]. The cylinder shape is smaller than the two other shapes because ejecta were not generated in the opposite direction to the projectile as much as others, which will make them less efficient for the momentum transfer. On the contrary, the cone and punch shape show high β in low impact velocity, but then decreases as the impact velocity increases. This is because of the sharp tips on these shapes which can be deformed easily. By the deformation of the tip, momentum transfer to the target is decreased and the crater size is reduced, which is logical because generally β changes with the amount of ejecta coming from the crater. In order to obtain a large momentum at low velocity, it is necessary to increase the mass of projectile. As the mass increases, it becomes more difficult to launch it, so it can be said that it is not realistic to use the cone and punch shapes in these conditions.

4. Conclusion

We tried to estimate the momentum of an asteroid after the impact in the case of deflecting situation. But principally, we chose to focus on projectile shapes. During our study, first we found out the projectile shape does not affect the ejecta amount. Whereas, it affects the ejecta emission direction and the crater shape. In actual NEO deflection, the cup shape is the most efficient when impact velocity is less than 15 km/s. On the other hand, the sphere shape is when impact velocity is more than 15 km/s. In contrast, projectiles with sharp tips are sharp is not adequate to actual deflection application.

Acknowledgement

It is noted that the present experiments were done at Laboratory of Spacecraft Environmental Interaction Engineering, Kyushu Institute of Technology.

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