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Development of Equipment to Estimate Momentum Shift in NEO Orbit Change by a Spacecraft Impact

Shohei KAGE[1*], Satoshi UENISHI[1], Masashi TANAKA[1],
Takao KOURA[1], and Yasuhiro AKAHOSHI[1]

[1]Department of Mechanical and Control Engineering, Kyushu Institute of Technology,
1 – 1 Sensui, Tobata, Kitakyushu, Fukuoka 804-8550, Japan

Abstract

For assessing the NEO orbit change by spacecraft impact, it is necessary to clarify the momentum shift at the impact time. Momentum shift is various amounts depending on the material of projectile and target, their shapes, and impact velocity. Currently, we have to collect more impact data by performing a simulated impact test on the earth because we do not have enough data to discuss design of a spacecraft impacter. Generally speaking, momentum shift is described at β (= about 1 ~ 10 in other institution's impact tests). We aim to get more efficient momentum shift by creating experimental conditions in which β is larger than 10. In this study, we developed a test equipment of pendulum type for measuring β, and performed impact tests after calibration of the pendulum equipment.
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Keywords: Hypervelocity impact, momentum shift, space guard

Nomenclature

M	pendulum mass
I	pendulum inertia
l_G	distance of axis of rotation and center of gravity
l_p	distance of axis of rotation and impact point
P_p	momentum of projectile
P_t	momentum of target
β	ratio of momentum projectile before impact and target is given by impact
θ_{max}	maximum deflection angle
g	gravitational acceleration

1. Experimental conditions

When achieving the NEO (Near Earth Object) orbit change by a spacecraft impact, it is necessary to clarify the momentum increase between pre- and post- impacts [4]. For this purpose, we have to collect more impact data at various conditions by performing simulated impact tests on the earth. Momentum change is usually represented by β. Because the ejecta is generated from the target by impact, β could be larger than 1 [1] [2] [3]. In this study, we have tried to clarify conditions that larger β can be obtained by adjusting an experimental environment.

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* Shohei Kage. Tel & Fax: +81-93-884-3151.
E-mail address: o344111s@mail.kyutech.jp

The most important factor in building the experimental environment is measurement of β. In this study, we have adopted a test equipment of pendulum in simulated impact test for β measurement method. As shown Figure 1, the experiment is collision of projectile and target that is placed in pendulum. From the equation of motion of the rotation and the law of conservation of mechanical energy, Equations (1) and (2) are derived. Then, Equation (3) is derived from the two equations. As shown in Equation (3), β is determined by measuring the maximum deflection angle θ_{max} of the pendulum. A similar device like a pendulum type was also proposed in other research institute [1] [5]. However, our experiment of the projectile momentum is about 100 times larger than others. In this study, we use a Two-Stage Light Gas Gun (TS-LGG) installed in Kyushu Institute of Technology to accelerate the projectile (shown in Figure 2). This gun has the ability to accelerate 14 mm diameter aluminium sphere (4 g) to 3.8 km/s. Our pendulum can perform experiments with a target attached to L300mm×W300×T200mm. Appearance of pendulum is shown in Figure 3, and its characteristic curve is shown in Figure 4. It is a line drawn by put the actual values in Equation (3). The horizontal axis is the pendulum swing angle, and the vertical axis is β. According to Figure 4, it can be shown that the pendulum swings 15 deg. at 1 km/s, 30 deg. at 2 km/s is required to obtain β =10.
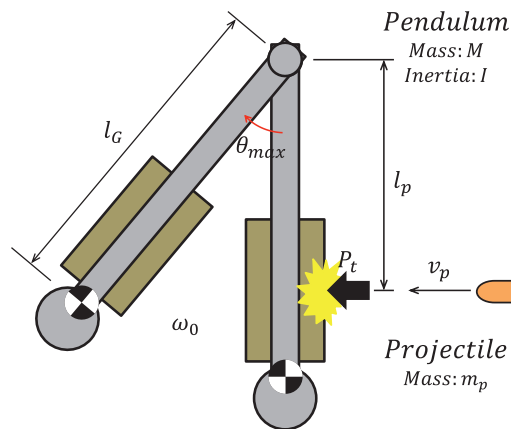

Fig.1 Schematic diagram of pendulum

$$l_p P_t = I\omega_0 \tag{1}$$

$$I\omega_0^2 = Mgl_G\left(1 - \cos\theta_{max}\right) \tag{2}$$

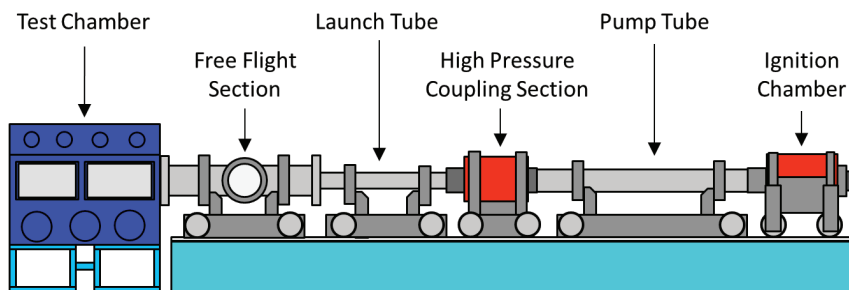$$\beta = \frac{\sqrt{2MIgl_G\left(1 - \cos\theta_{max}\right)}}{P_p l_p} \tag{3}$$

Fig.2. Images of acceleration part: TS-LGG using hydrogen and helium as a compressed gas and there is pendulum in test chamber

Fig.3. Images of our pendulum: left shows appearance of pendulum (about 400 kg); center shows bricks target (300×300×t140, 28.65 kg, 2.27 g/cm³) with wooden frame (plaster as other targets); right shows pendulum with target.
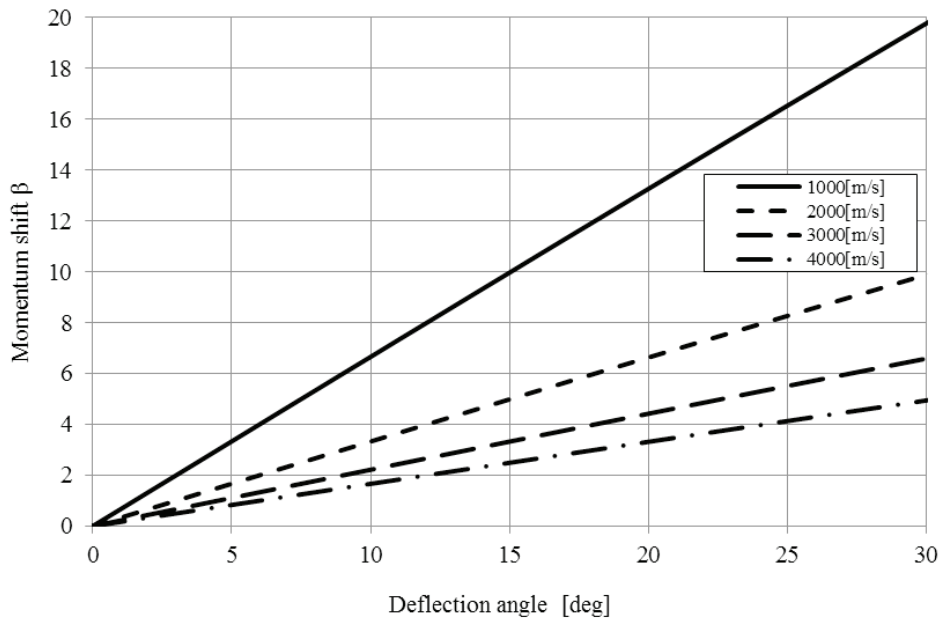

Fig.4. Proposed pendulum's characteristic curve with bricks target of 28.65kg; M=141.3kg, I=9.09kg·m/s, l_g=0.18m, l_p=0.31m.
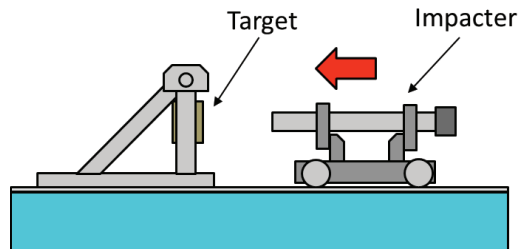

Fig.5 Schematic diagram of the calibration test

2. Calibration

At first we performed calibration tests of the developed pendulum with known β where impact velocity is very low. Because impact debris should not be generated. In that case, β is equal to 1. According to Figure 4, the deflection angle of pendulum is only 7 ~ 8 degrees under 4000m/s, 4g conditions. Therefore, it is necessary to increase the mass of impacter in order to obtain the same deflection angle at low speed impact. So, we calibrated by colliding the impacter (334.8 kg) with trucks (shown Figure 5). To get momentum equivalent to aluminium sphere (4 g, 3.8 km/s), it is sufficient to impact at velocity of 0.045 m/s (supposing residual velocity is 0). The results of the calibration tests are shown in Table 1 and Figure 5.

It can be said from Table 1 that the average of β is about 0.82. If the differences in each test follow a normal distribution (95 %), the error of β is about ± 0.04. Thus, calibrated β is shown in Equation (4).

$$\beta_{calibrated} = \left(1.221^{+0.067}_{-0.060}\right)\beta_{test} \tag{4}$$

Table 1 Results of calibration

Test No.	Initial velocity [m/s]*	Residual velocity [m/s]*	Input momentum [kg·m/s]	Maximum deflection angle [deg.]*	β test
C-1	0.1665	0.0874	26.49	7.6	0.76
C-2	0.1799	0.0929	29.14	8.7	0.80
C-3	0.1140	0.0650	16.40	4.9	0.80
C-4	0.1873	0.1110	25.53	8.6	0.90
C-5	0.1922	0.1016	30.32	10.9	0.96
C-6	0.1570	0.0830	24.77	7.2	0.77
C-7	0.1958	0.1060	30.06	8.9	0.79
C-8	0.1450	0.0797	21.87	6.7	0.82
C-9	0.1598	0.0852	24.98	7.3	0.78

*The velocity measurement is using high-speed camera, and the angle measurement is using rotary encoder.
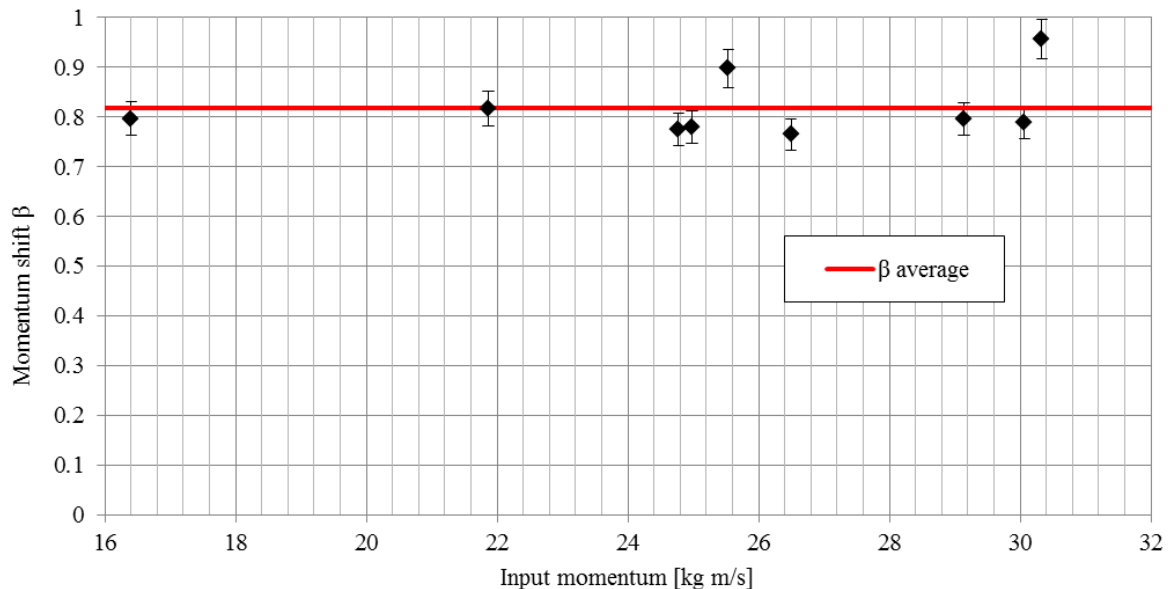

Fig.6. Graph of pendulum calibration by low-speed impact

3. Impact experiments

Based on the results of calibration, the experiments were conducted using three different targets. Targets are two bricks

and a plaster. The experiments results are shown in Table 2. Also, the targets after the experiment are shown in Figure 7. Craters produced in the target show different characteristics depending on the material. In plaster, peeling of surface seems to be spall destruction. This can be observed in bricks, but the peeling range is smaller than that of plaster. β of plaster is larger than bricks, because the amount of plaster's ejecta was larger than bricks. This trend can be explained by definition of the index β of momentum shift. Because such trend was also obtained from the experiments, we can conclude that our pendulum has the validity to measure β.

Table 2 Results of experiments using aluminium spherical projectile (Φ14, 4g)

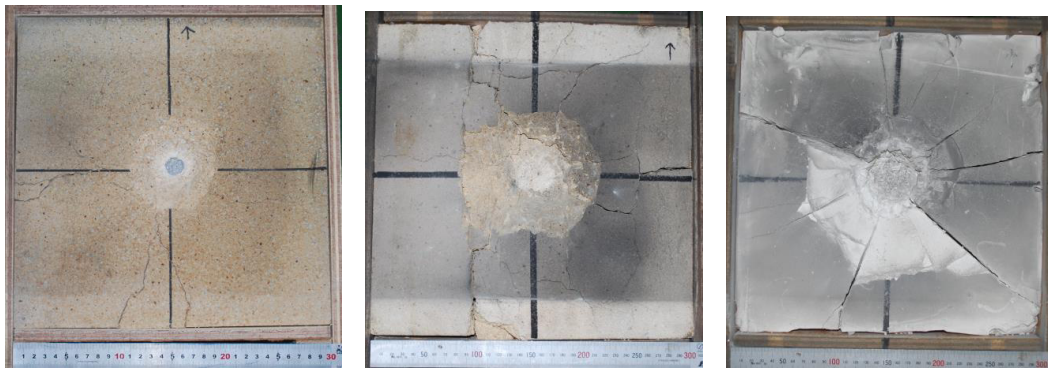| Test No.	Material	Target Thickness [mm]	Density [kg/cm³]	Impact velocity [km/s]	Maximum deflection angle [deg.]	β test	β calibrated
LTS14-052	Bricks	140	2.24	1.64	3.8	1.55	1.89
LTS14-053	Bricks	200	2.16	3.04	7.4	1.84	2.25
LTS14-054	Plaster	180	1.12	2.89	9.7	1.98	2.42

Fig.7. Images of targets after impact: left shows target of LTS14-052 (L300mm×W300mm×T140mm, 28.26kg, crater diameter is 100mm, crater depth is 13.91mm, ejecta* is 190.0g); center shows target of LTS14-053 (L300mm×W300mm×T200mm, 38.84kg, crater diameter is 145mm, crater depth is 29.48mm, ejecta* is 51.0g); right shows target of LTS14-054 (L300mm×W300mm×T180mm, 17.87kg, ejecta* is 168.8g); * only collected.

At the present, the validity of our pendulum is only shown by these experiments. We can obtain the trend of β differences due to the target materials. In the future, we should confirm whether there is a same tendency by repeating experiments at various velocities. In addition, our experiments use spherical projectiles, but it is thought that better impacter is a non-spherical spacecraft. If we can control the generating direction of the ejecta by changing the shape of projectile, we can obtain more efficiently β. In further study influence of impacter shape on β should be investigated. Because we have experience of experiments using non-spherical projectile by our TS-LGG, we can conduct experiments that aim to investigate the projectile's shape effect for β [6] [7].

4. Summary

We have designed a test machine of pendulum type as a device for measuring the momentum shift β. By carrying out the calibration, the reliable measuring results can be determined by calibration equation of $1.276 \times \beta_{test}$, which is obtained from the pendulum. Calibration can increase the reliability by performing experiments. In this study the developed pendulum can measure up to about $\beta = 2.5$. In the future, we want to investigate the projectile's shape effect for β by performing experiments changing the shape of projectile (ex. cylinders and hollow cylinders).

Acknowledgements

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