SMALL CARRY-ON IMPACTOR OF HAYABUSA-2 MISSION

Takanao SAIKI, Hiroshi IMAMURA, Hirotaka SAWADA and Chisato OKAMOTO
JAXA Space Exploration Center (JSPEC) / Japan Aerospace Exploration Agency (JAXA),
Email: saiki.takanao@jaxa.jp

Abstract

The study of the next asteroid exploration mission has been performed supposing a launch in 2014. The spacecraft is called HAYABUSA-2 and its design basically follows HAYABUSA. From the point of the scientific objective, 1999 JU3 which is the asteroid with the primitive composition (C-type) is chosen as the target and one of the most important scientific objectives of HAYABUSA-2 is to investigate chemical and physical properties of the internal materials and the internal structures. In order to achieve this objective a new component, small carry-on impactor, is planned to be equipped in HAYABUSA-2 mission and it is required to remove the surface regolith and create an artificial crater on the surface of the asteroid. This paper presents the overview of our small carry-on impactor system and impact operation of HAYABUSA-2 mission.

はやぶさ 2 の小型衝突装置

佐伯 孝尚，今村 裕志，澤田 弘崇，岡本 千里
宇宙航空研究開発機構 月・惑星探査プログラムグループ(JSPEC)

概要

はやぶさ後継機である「はやぶさ 2」は，小惑星の内部情報を知ることが，サイエンス目標の一つとなっている．そのため，小惑星表面にクレータを生成するために衝突装置を搭載する．衝突装置は爆薬を搭載し，金属体を高速で小惑星表面に衝突させることによって，クレータを形成するものであり，衝突装置の概要とその運用について概説する．

1. Introduction

The Japanese asteroid explorer HAYABUSA launched in 2003 arrived at its target asteroid ITOKAWA in September, 2005. HAYABUSA has made great amount of scientific discoveries and technological achievements during its stay at ITOKAWA. Although many troubles, it left ITOKAWA in December, 2005 and came back to the Earth on June 13, 2010.

Under this situation, the next asteroid exploration project started supposing a launch in 2014. The spacecraft is called HAYABUSA-2 and its design basically follows HAYABUSA in order to shorten the development time. From the point of the scientific objective, 1999 JU3 which is the asteroid with the primitive composition (C-type) is chosen as the target. C-type asteroids are rocky like ITOKAWA(S-type), but it is thought that their rocks obtain much more organic matters.

A small carry-on impactor (SCI) is one of the new challenges that were not seen with HAYABUSA. The observations by HAYABUSA discovered that ITOKAWA is rubble-pile body with the macro-porosity. However, we have no direct observational data as for their internal structures and sub-surface materials. One of the most important scientific objectives of HAYABUSA-2 is to investigate chemical and physical properties of the internal materials and the internal structures in order to understand the formation history of small bodies such as small, un-differentiated asteroids. In order to achieve this objective, the impactor is required to remove the surface regolith and create an artificial crater on the surface of the asteroid.

This paper presents the overview of our small carry-on impactor system and impact operation of HAYABUSA-2 mission.

2. Small Carry-on Impactor

There are many ways to observe the sub-surface materials of asteroid. The simplest way is to drill and mine inner materials from the asteroid. However, mining under small gravity is very difficult and long stay on the asteroid's surface is danger because of the high temperature. Using blast from explosive is good way to blow regolith away, but, the pollution of soil becomes problem for sampling. After considerable discussion, high speed carry-on type impactor is adopted to remove the surface regolith and create an artificial crater in the HAYABUSA-2 mission.
High kinetic energy (about 2km/s impact speed and 2kg impact mass) is required to make a meaningful crater. The biggest challenge of this high kinetic energy impactor system is how to accelerate the impact head. Although traditional acceleration devices like rocket motors can achieve the required speed, the acceleration force is small and it takes long time to achieve the final velocity. Consequently, the acceleration distance becomes large and it is difficult to hit the asteroid without guidance and control. As the weight and size of the impactor system is strictly restricted, it should be simple. To overcome this difficulty, the powerful explosive is adopted to accelerate the metal impact head. Fig. 1 shows the special type of shaped charge. Powerful explosive is filled in the metal case, and it has a liner in the shape of a shallow dish. The force of the blast deforms liner to bullet shape (cold forging). The velocity of the formed projectile is about 2000m/s. And the deformation and acceleration period is very short (less than 1 millisecond). Therefore, the acceleration distance can become very small. Additionally, the attitude disturbances during explosion do not influence the flight direction of the projectile due to the short deformation period. This means that the projectile flies out in the direction at the moment of ignition.

By using this technology, the impactor system is able to be very simple and it becomes possible to crash into the asteroid without guidance and control system by separating SCI (small carry-on impactor) in the direction to the asteroid. In practice, spin for the attitude stabilization is given by the separation mechanism. This spin is for the attitude stabilization between separation and ignition not for stabilization during the explosion.

On the other hand, this system has one big problem. As the explosive is very powerful, the metal case is destroyed and many fragments are scattered when the explosive detonate (Fig. 2). As the velocity of broken pieces is very high like the formed projectile, they would damage the spacecraft when they hit it. To avoid this, the spacecraft should run away from SCI after the separation.

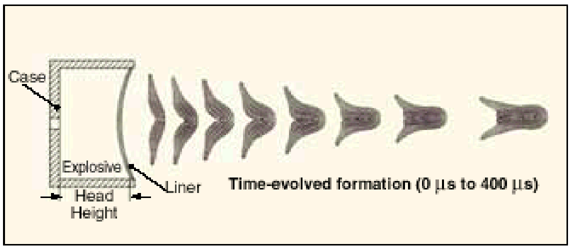

Fig. 1: Special type of shaped charge. The metal liner is deformed and accelerated by explosive blast.(http://en.wikipedia.org/wiki/Explosively_formed_penetrator)

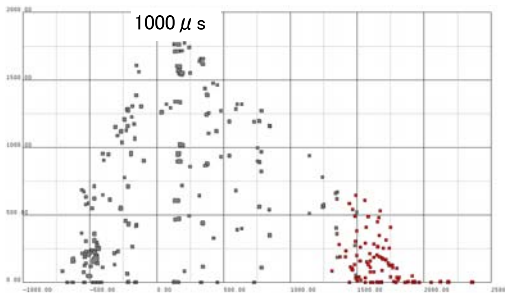

Fig. 2: Broken pieces of the case. As the velocity of the pieces is very large, they could damage the spacecraft, if they hit it.

3. Configuration of SCI

SCI is the spin type small spacecraft. It has cylindrical body and electric devices and explosive are fixed in it. Fig. 3 shows the configuration of SCI. The shape of the explosive part is circular cone and it is attached at the bottom of SCI. It can be removed easily for the safety of people and other devices. The explosive is ignited by the safe & arm device (SAD) which includes detonator. SAD separates the detonator form main explosive in safe status. Arming will be conducted after the separation from the main spacecraft. The length of SCI is about 300mm (incl. separation device) and the diameter is less than 300 mm. Total weight except for separation mechanism is about 15 kg. Fig. 4 shows the block diagram of SCI. The sequencer (timer) controls the arming and ignition. The sequence is installed to SCI from the mother spacecraft through the wired interface. The interface cables will be cut by the wire cutter before separation. Primary cells are used for the inner power supply.

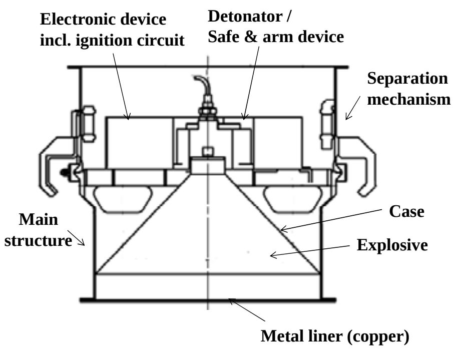

Fig. 3: SCI configuration. The shape of the explosive part is circular cone.

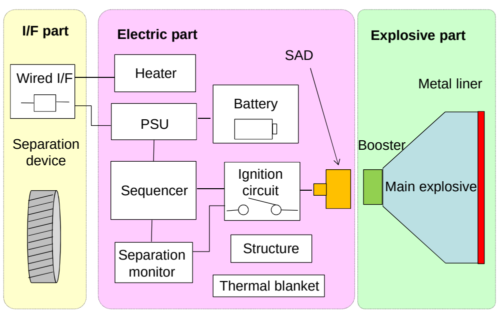

Fig. 4: Block diagram of SCI. Sequencer controls the arming and ignition.

4. Impact Operation

4.1 Operation Outline

As described, SCI has no attitude and position control functions. Therefore the mother spacecraft should aim the asteroid and separate it at appropriate position. After separation, SAD switches from safe to arm state and it detonates during free-fall motion. The timing of the detonation is controlled by the sequencer (timer) on SCI. The mother ship should escape from the separation position because debris is scattered when the explosive detonate and ejecta from the asteroid comes flying from the impact point. Fig. 5 shows the outline of the impact operation. The mother spacecraft starts escape maneuver just after SCI separation and moves behind the asteroid. During the maneuver, the deployable camera (DCAM) is separated from the mother spacecraft and it transmit the impact image.

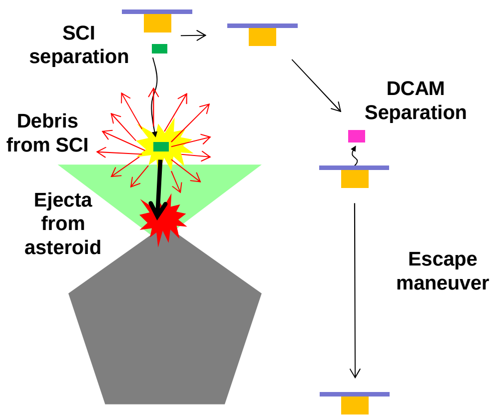

Fig. 5: Impact operation. The mother spacecraft should escape to avoid the debris and ejecta.

4.2 1999JU3

The target body of HAYABUSA-2 is a small asteroid, 1999JU3. It is classified as near earth asteroids (NEA) and its semi-major axis is about 1.19AU and eccentricity is about 0.19. HAYABUSA-2 will arrive at 1999JU3 in Jun, 2018 and it will leave in Dec., 2019.

The diameter of 1999JU3 is about 1 km (larger than ITOKAWA). The density is expected to be 500 - 4000kg/m3 and the gravity constant is estimated to be 11- 92 m3/s2. Fig. 6 illustrates the expected shape of 1999JU3. There are two models about the spin axis as follows,

Mueller model: [λ, β]=[73, -62]deg,

Kawakami model: [λ, β]= [331, 20]deg.

Fig. 7 shows the extimated acceleration of gravity, solar tide and solar radiation. This figure assume that GM=32m3/s2 and the non-spherical force is calculated on the assumption that the 1999JU3 is spheroid. This figure indicates that the non-spherical force have not a little effect on the motion of SCI.

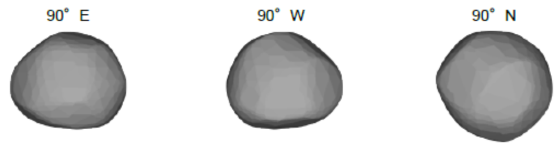

Fig. 6: Expected shape of 1999JU3. .

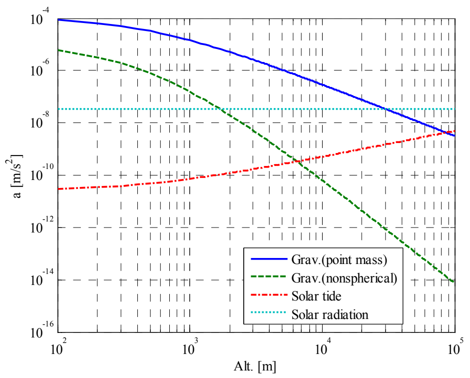

Fig. 7: Acceleration of gravity, solar tide and solar radiation

4.3 Separation Accuracy

The separation accuracy is the most important factor in the impact operation. If the separation accuracy is bad, the position error of SCI at detonation becomes large and the impact accuracy becomes worse.

The position and velocity error of SCI depends on the orbit control accuracy of the mother spacecraft and the separation accuracy of the separation device. Table 1 shows the separation accuracy of SCI. They are estimated by considering actual performance of HAYABUSA's landing operation and the separation device of the re-entry capsule. The sequence of the impact operation should be determined by considering this separation accuracy.

Table 1: Separation accuracy of SCI

Mother spacecraft	
Position	50m(horizontal dir.) 30m(vertical dir.)
Velocity	0.02m/s (horizontal dir.) 0.03m/s(vertical dir.)
Separation device	
Velocity	0.05m/s (separation dir.) 0.02m/s (orthogonal dir.)
Pointing	<20deg

4.4 Time to detonation

The timing of the detonation is one of the most important parameters of the impact operation. If the time to detonate is short, the required delta-V of escape maneuver becomes large. On the other hand, if it is long, SCI free-falls and reaches the asteroid surface. Moreover, the accuracy of impact reduces because the variation in the position of SCI at the detonation becomes large. Fig. 8 shows the SCI positions in Monte Carlo simulation. The separation altitude of this simulation is 500m. The variability of the position spreads with time. After 3600sec from separation, SCI of many cases reach the asteroid's surface. It is unacceptable for making crater. To avoid this, SCI should be separated at higher altitude. But it is not good solution because the impact accuracy becomes worse. So, we should choose the appropriate timing of detonation. In this paper, 2400sec is chosen.

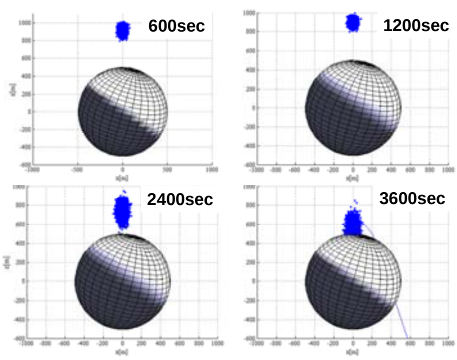

Fig. 8: Variation in SCI position. It spreads with time.

4.5 Impact Accuracy

As described, impact accuracy depends on the accuracy of position and velocity of mother spacecraft and separation velocity of separation device. And it also depends on the attitude of SCI. If the tip-off rate is large at separation, the nutatoin motion of SCI becomes large and the impact accuracy becomes worse. Fig. 9 shows the results of impact simulation. This result shows that the error of the impact point is about 200m in radius.

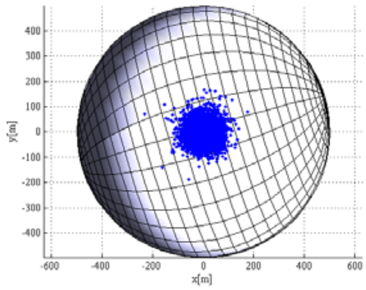

Fig. 9: Results of impact simulation.

4.6 Escape Maneuver

The escape maneuver should be determine to minimize the escape delta-V. In particular, the time to DCAM separation point is chosen to minimize total delta-V of escape maneuver. Fig. 10 shows an example of escape maneuver. The total delta-V is less than 10m/s in this example. To reduce the delta-V, the maneuver distance in horizontal direction should be small, but it is chosen appropriately considering the accuracy of the control force of thrusters. In this example, 1000m is chosen.

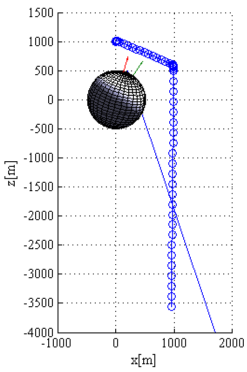

Fig. 10: An example of escape maneuver.

The accuracy of the given delta-V is also important factor of the escape maneuver. Fig. 11 shows the mother spacecraft positions after escape maneuver. If the thrust error is large, the horizontal escape distance should be large to avoid the collision with the 1999JU3 and the vertical escape distance should be large to avoid the collision with the debris from SCI. It is expected that the thrust error is less than 5 % in HAYABUSA-2 by using the accelerometer.

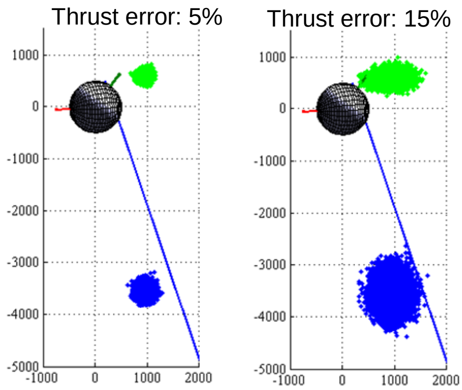

Fig. 11: Mother spacecraft position after escape maneuver. Left-hand figure shows the result when the thrust error is 5 % and right-hand figure shows the result when the thrust error is 15 %.

4.7 Influence of Spin Axis Model

As mentioned, there are two models about asteroid's spin axis, Mueller and Kawakami model. It is expected that one model is adopted after the future observation from the earth, but we should consider both two models at this moment. Fig. 12 shows the spin axis of two types. As this figure shows the directions of spin axis are quite different between two types. This difference has little influence on the impact operation itself, but it has a considerable impact on the timing of impact and touch down operation. Then, the influence of spin axis model is summarized here.

Fig. 13 shows the rate of spin axis movement. As this figure shows, the rate of Kawakami model is larger than Mueller model. Both Fig. 12 and Fig. 13 indicate that the spin axis direction of Mueller model does not move drastically. Therefore the restriction on the timing of the impact operation is not severe. This means that the impact operation should be performed early on the impact phase (ex. in Jul, 2019) in the Mueller model to ensure the long observation time on the impact point. On the other hand, in Kawakami model, the spin axis moves fast and timing of the impact operation is restricted. For example, if the impact head hits the south area of the asteroid in the impact operation, it is difficult to observe the impact point after the impact operation. Fig. 14 shows the spin axis direction of Kawakami model. This figure indicates that the north pole can be seen from the earth direction between Sep. and Oct., 2019. Therefore, the impact should be performed in Sep. 2019. By doing this, more than one month observation can be ensured.

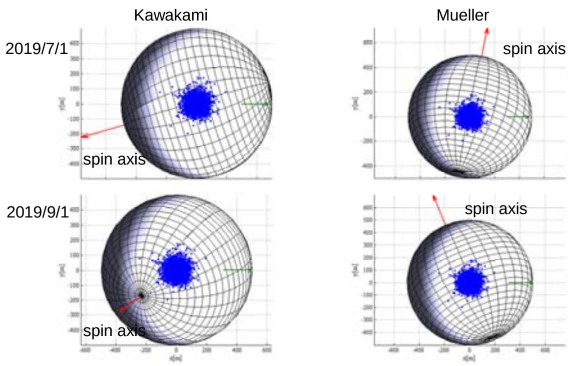

Fig. 12: Spin axis of two models. Left-hand figures show Kawakami model and right-hand figures show Mueller model.

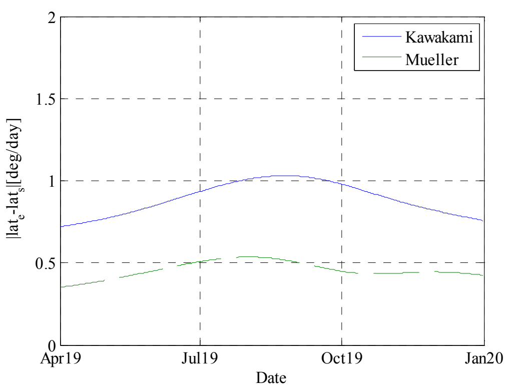

Fig. 13: Rate of spin axis movement. The rate of Kawakami model is larger than Mueller model.

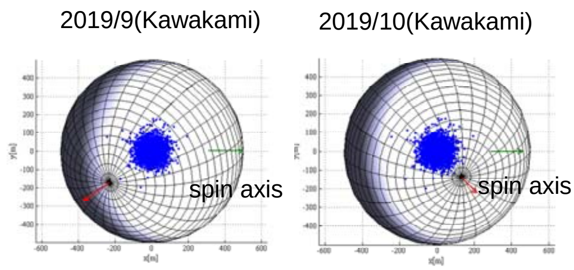

Fig. 14: Spin axis direction of Kawakami model in Sep. 2019 and Oct. 2019.

5. Conclusion

This paper presents the overview of the small carry-on impactor system and impact operation of HAYABUSA-2 mission. By controlling the separation accurately, it is possible to hit the asteroid although SCI is very simple sub-system. One the other hand, the escape maneuver after separation is required for the safety of mother spacecraft because SCI scatters many fragments when it detonates.

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