The Effect of Surface Ejecta due to Ion Beam Impingement for an Asteroid Redirection Mission

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Abstract

The ion beam deflection (IBD) concept for asteroid deflection makes use of an electric propulsion system to provide a continuous thrust to alter an asteroid's trajectory and prevent Earth impact. The effect of surface sputtering by the beam has been previously mentioned as a source of momentum deposition enhancement; while this effect may play a role in the effectiveness of the overall concept, its effect has not been closely scrutinized. In this study, we consider some of the important forces which may play a role in surface sputtering and the resulting ejecta via analytic theory and numerical modeling using the discrete element method. We find that surface gravity plays a minimal role for the size of asteroids which this concept would target, while surface cohesion could play a primary role in the extent of particles sputtered from the surface.

Introduction

Ion beam deflection (IBD) is a conceptual asteroid deflection method for planetary defense [1]. In this concept, a spacecraft stationed at some standoff from the target asteroid fires an electric propulsion (EP) thruster, such as an ion thruster or Hall thruster, at the surface. Over time, this thruster alters the trajectory of the asteroid such that it will no longer impact Earth. With current technology, this method is capable of deflecting asteroids of the same size as kinetic impactor and gravity tractors concepts (O(10-100) m). A sketch of this concept is included as Figure 1.

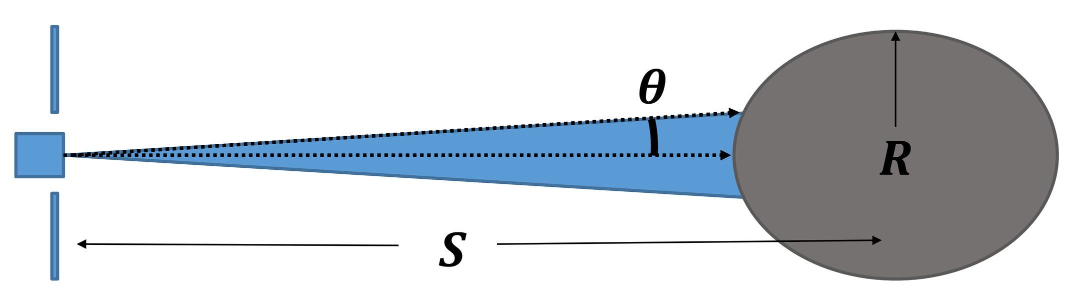

Figure 1: Sketch of the IBD concept.

In this concept, the satellite must remain at a large enough standoff distance, $\boldsymbol{S}$, such that the force of gravity ($\mathbf{F_g}$) at the spacecraft is far lesser than the delivered thrust ($\mathbf{F_g}(\boldsymbol{S}) \ll \mathbf{F_T}$). Conversely, $\boldsymbol{S}$ must be small enough such that the beam divergence (with half angle $\boldsymbol{\theta}$) does not cause the effective beam radius $\boldsymbol{r_b}$ to be larger than the asteroid radius **R**. This yields the expression:

$$\mathbf{S_{max}} = \mathbf{R}\left(\mathbf{1} + \frac{\mathbf{1}}{\mathbf{tan\theta}}\right).$$

Due to the large exhaust velocity of the ion beam, the mass efficiency of an IBD system is higher than that of a kinetic impactor. An IBD mission is more technologically complex, however; engineering challenges such as transport and storage of a large propellant mass and sufficient spacecraft power generation in deep space are key to mission success [2].

Problem Statement

Previous studies of the IBD concept have commented on the possibility of material being sputtered from the asteroid surface [1,2]. For those particles who are ejected with velocities in excess of the asteroid escape velocity, the consequences of this potential sputtering could be two-fold:

- Sputtering may result in an **enhancement of the momentum** transfer to the asteroid, benefitting the mission objective.
- Conversely, such sputtered material could **interact with the spacecraft** and possibly damage components or reduce the efficiency of solar panels through surface coating.

In both cases, it is important to understand the particle size and velocity distribution that may be sputtered from the surface of the asteroid. In this study, we aim to understand asteroid surface sputtering due to ion beam impingement from an ion beam deflector spacecraft.

Methods and Assumptions

To begin to understand IBD-induced surface sputtering, we utilize the Spheral code at LLNL; in particular, we utilize the new discrete element method (DEM) module which follows the approach in [3,4].

In general, the most mature EP technology with sufficiently small divergence angles to achieve this objective is the gridded ion thruster [2]. In particular, the NEXIS ion thruster has demonstrated small beam divergence and has seen extensive testing [5], and so we adopt this thruster for our study.

Assumptions:

- For our problem, we estimate the average particle size based on the gravity of the simulated body via the expression [6]:

$$\widehat{D} = 1{,}277\ g^{-0.32}\ \mu\text{m}$$

- To begin to understand the physics of the problem and the feasibility of applying DEM to it, we run a 2D bed of particles with a uniform gravitational force.
- Spheral cannot include particle charge effects (e.g. plasma effects). Therefore, we treat the thruster plume as a uniform pressure source.

Problem Setup:

Thruster:

- 446 mN of thrust from a 47cm exit plane.
- 3-degree divergence half-angle.
- 125 m standoff distance (~0.287 μg due to gravity).

Particle Bed:

- Uniform gravity of 100m, spherical, Bennu-like body (**g=1.8** $\boldsymbol{\mu g}$).
- Circular particles w/ varying radii (r_p), density **ρ=1.26 g/cc**.
- ~50% packing fraction by area.
- 15 m box with reflecting boundary conditions.

Methods and Assumptions (cont'd)

DEM requires the user input a variety of material property parameters for the simulation. We summarize these below:

- $\boldsymbol{k_N}$ (Normal spring constant): **10** $\boldsymbol{kg\ s^{-2}}$
- $\boldsymbol{k_T}$ (Tangential spring constant): $\frac{2}{7}\boldsymbol{k_N}$
- μ_S (Coefficient of static friction): **0.5**
- μ_D (Coefficient of dynamic friction): **0.5**
- μ_T (Coefficient of torsional friction): **1.3**
- μ_R (Coefficient of rolling friction): **1.05**
- $\boldsymbol{c}$ (Cohesive tensile strength): **10-100 Pa**
- **β** (Shape factor): **0.5**

Results

Effect of Particle Size

We derive an expression, dubbed the 'beam factor' ($\boldsymbol{\eta}$), to assess whether an average particle on the asteroid surface under the influence of gravity is dominated by the thrust force:

$$\boldsymbol{\eta} = \frac{\boldsymbol{F_T}}{\boldsymbol{F_g(R)}} = \frac{\boldsymbol{P_b \pi r_p^2}}{\frac{4}{3}\boldsymbol{\pi\rho g r_p^3}} = \frac{3}{4}\frac{\boldsymbol{P_b}}{\boldsymbol{\rho g r_p}}$$

where $\boldsymbol{P_b}$ is the thruster pressure. Using the expression for average regolith size, we find $\boldsymbol{\eta \sim 1.17x10^3}\ \frac{P_b}{\rho g^{0.68}}$. Indeed, for the setup of this problem, $\boldsymbol{\eta \gg 1}$, so the thruster force dominates gravity.

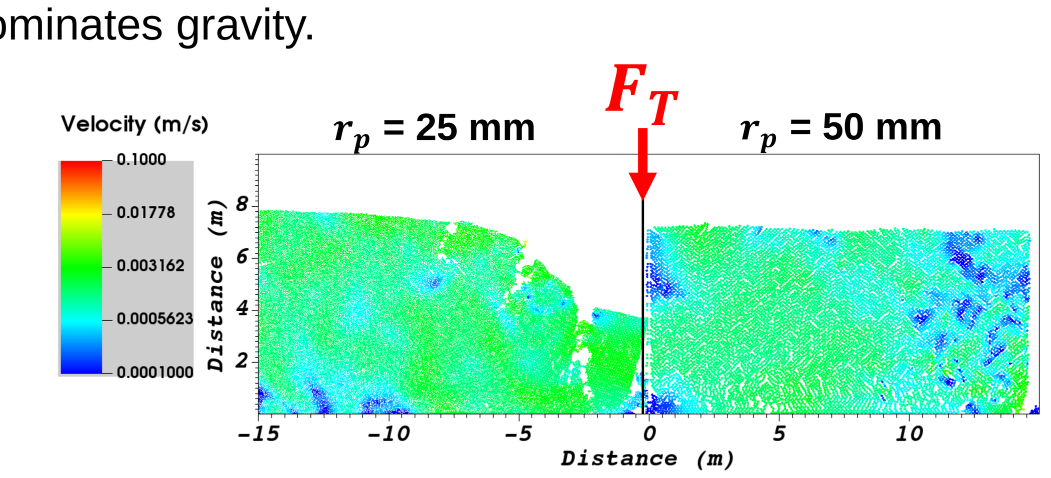

Figure 2: Uniform particle beds of various radii after 1000s of thrust.

Effect of Cohesive Tensile Strength

Figure 2 demonstrates that, although the beam force dominates gravity, the particles remain on the surface of the asteroid. We have found that this can be attributed to the cohesive force ($\boldsymbol{F_C}$) between the particles, controlled by our parameter **c**. An expression derived in [7] gives this cohesive force as a function of $\boldsymbol{r_p}$ and surface cleanliness, **S**:

$$F_c = 3.6 \times 10^{-2} S^2 r$$

Taking **S=1**, this force can be comparable to the beam force ($\boldsymbol{F_C \sim F_T}$), so the particle response may be very sensitive to the choice of **c**. Asteroids have **c** in the range of 10 Pa – 1 kPa [7], so we look at two values in this range here.

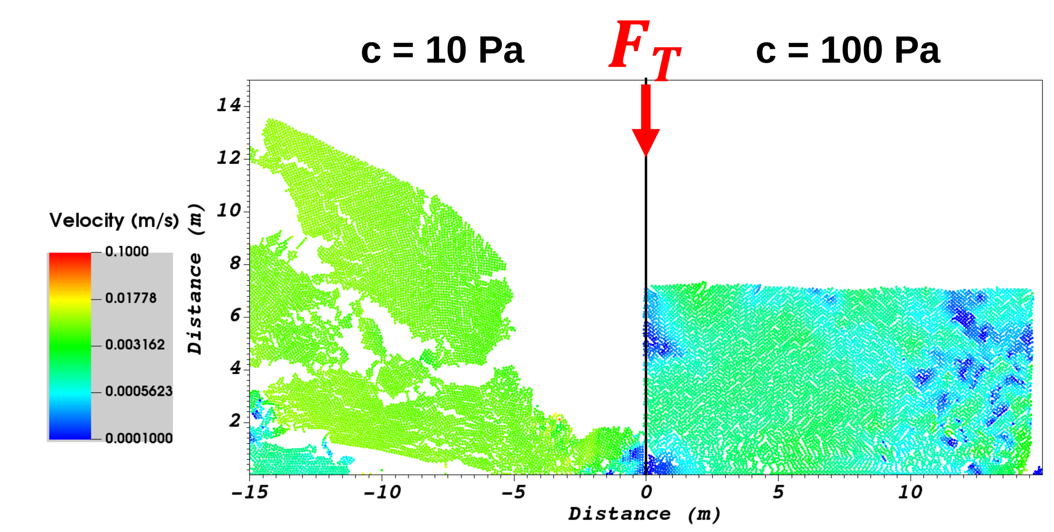

Figure 3: Uniform particle beds (r_p = 50 mm) of differing cohesive tensile strength after 1000s of thrust.

We find that by lowering **c** to 10 Pa, the particles are ejected from the surface, whereas for 100 Pa, they remain in place.

Conclusions

In this study, we have begun to consider the role of surface sputtering in the ion beam deflection (IBD) concept for asteroid redirection through analytic theory and numerical modeling. We have found that **surface gravity likely plays a minimal role** in the sputtering process, while **particle cohesion may dominate it**. Further analysis of the sputtering process via a circular (2D) or spherical (3D) geometry, as well as addition of particle charge effects, will further elucidate the important physical processes to IBD and whether particle sputtering plays an important role.

References

[1] Bombardelli, C. P., Jesus (2011). "Ion Beam Shepherd for Asteroid Deflection."

[2] Brophy, J., et al. (2018). "Characteristics of a high-power ion beam deflection system necessary to deflect the hypothetical asteroid 2017 PDC." Journal of Space Safety Engineering **5(1): 34-45.**

[3] Schwartz, S. R., et al. (2012). "An implementation of the soft-sphere discrete element method in a high-performance parallel gravity tree-code." Granular Matter **14(3): 363-380.**

[4] Zhang, Y., et al. (2018). "Rotational Failure of Rubble-pile Bodies: Influences of Shear and Cohesive Strengths." The Astrophysical Journal **857(1).**

[5] Snyder, J. S. G., Dan M.; Polk, James E.; Schneider, Analyn C.; Sengupta, Anita (2005). "Results of a 2000-Hour Wear Test of the NEXIS Ion Engine."

[6] Metzger, P. T. and D. T. Britt (2020). "Model for asteroid regolith to guide simulant development." Icarus **350.**

[7] Scheeres, D. J., et al. (2010). "Scaling forces to asteroid surfaces: The role of cohesion." Icarus **210(2): 968-984.**

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