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Impulse calculation and characteristic analysis of space debris by pulsed laser ablation

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Abstract

Ablation by high-energy pulsed laser provides recoil impulse that results in the de-orbiting and atmospheric re-entry of space debris, which may be the best method of clearing space debris in the size range of 1–10 cm. Both the magnitude and direction of the recoil impulse depend on the shape and orientation of the target and serve as the foundation for studying orbital evolution and evaluating removal effects. However, how to calculate the recoil impulse and analyze the features of recoil impulse have not received sufficient attention in the literature. Based on certain assumed conditions, a general numerical method is proposed to calculate the recoil impulse of free motion debris under a set of laser pulses. Selecting cylindrical debris as the research target, we derive an analytical method to calculate the ablation-driven impulse. Moreover, the characteristics of single impulses changing over time and the total impulse are examined using analytical expressions. Finally, simulation experiments are conducted to validate both the numerical and analytical methods.

Keywords: Pulsed laser; Space debris; Impulse

1. Introduction

With the development of worldwide space activities, the quantity of space debris is increasing rapidly. The continuing accumulation of space debris not only poses a threat to functional space assets but also increases the risk of subsequent orbital collisions that will produce more and more debris, known as the Kessler Syndrome (Kessler and Cour-Palais, 1978).

As of April 2014, there are approximately 670,000 pieces of space debris in the size range of 1–10 cm (http://www.orbitaldebris.jsc.nasa.gov, 2014). These debris particles have high velocity and cannot be tracked and catalogued effectively. It is difficult for space assets to counter the threat through structural reinforcement or orbital maneuver, so removing the space debris actively is necessary. However, there are no easily applicable ways to clear up space debris (Kaplan, 2009).

Space debris removal using high-energy pulsed laser may be the most effective way to mitigate the debris problem (Phipps et al., 2012). Under laser irradiation, a thin surface layer is ablated to provide the debris particle with an impulse. When the impulse vector is appropriate, the perigee of debris orbit will descend and the debris will finally burn up in the atmosphere. Therefore, the feature of impulse vectors driven by pulsed laser deserves further investigation.

In concept studies of space debris removal, spherical targets are mostly invoked, which implies that the recoil impulse is precisely parallel to the laser beam (Bohn, 1999; Phipps and Reilly, 1997; Schall, 1998). Even in the project proposed by RIkagaku KENkyusho in Japan to validate the debris removal technique on the International Space Station, the effects of debris shape and its

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orientation with respect to the laser pulse direction were not considered (Ebisuzaki et al., 2015).

However, in recent years, researchers have become concerned about the effects of target shape and other factors on recoil impulse. Based on the assumptions that the impulse is precisely opposite to the ablation recoil whereas the ablation is parallel to the local surface normal, the Area Matrix Approach was proposed to calculate the recoil impulse by a single laser pulse in theory (Liedahl et al., 2010). The Area Matrix Approach is an effective means to analyze the shape effects of spheres, cylinders, cubes, and so on. A time-continuous force equation has been proposed to approximately describe the impulse driven by discrete laser pulses when debris is irradiated discretely by a set of laser pulses (Liedahl et al., 2013). The kinetic characteristics of spinning plate and cylinder around a fixed axis under continuous laser irradiation have also been studied.

In practice, pulsed laser with high energy and short pulse duration is often used to clear space debris because pulsed laser with high energy and short pulse duration has a better momentum coupling effect than continuous laser (Phipps et al., 2006; Uchida et al., 2000). Therefore, laser ablation events are discrete over time. Moreover, the attitude motion of space debris is fixed-point motion relative to its center of mass. Hence, the total impulse characteristics of free-motion space debris under a set of laser pulses is worthy of focus.

We provide a general approach to calculating the recoil impulse of space debris driven by a set of laser pulses in the article. Selecting cylindrical particles as the target, we analyze the characteristics of the cylindrical particles' motion under pulsed laser interaction, consequently avoid solving the differential equation of attitude kinematics, and derive an analytical solution of recoil impulse driven by a set of laser pulses. According to the analytical expressions, the characteristics of discrete recoil impulse over time are analyzed. Finally, some relevant simulation experiments are given to validate the analytical solution.

2. Method of calculating the impulse vector

2.1. Momentum coupling coefficient

The momentum coupling coefficient, denoted here by C_{m}, is often used to describe quantitatively the magnitude of the recoil impulse under per unit of laser energy (Phipps et al., 1988):

$$C_{\mathrm{m}} = \frac{m\Delta v}{E_{\mathrm{inc}}} \quad (\mathrm{N \cdot s/J}), \tag{1}$$

where m is the mass of debris, Δv is the velocity increment, $m\Delta v$ is the recoil impulse, and E_{inc} is the total laser energy incident on the debris.

When a laser beam vertically irradiates a plate, the incident energy is determined by incident laser fluence F_{inc} and the illuminated area A: $E_{\mathrm{inc}} = F_{\mathrm{inc}}A$. After substitution into Eq. (1), the recoil impulse is

$$m\Delta v = C_{\mathrm{m}} F_{\mathrm{inc}} A. \tag{2}$$

2.2. The impulse vector

In fact, the recoil impulse is a vector whereas Eq. (2) is written in scalar form. We should recast Eq. (2) by taking the direction of impulse into account.

When laser irradiates an irregularly shaped target, the surface may be divided into two parts: the illuminated region and non-illuminated region, denoted by S and $\tilde{S}$, respectively, as shown in Fig. 1. Based on the assumption that the ablation vector is parallel to the local normal regardless of the laser incident direction (Liedahl et al., 2010), the impulse element on the area element dA can be expressed as

$$\begin{aligned} d(m\Delta \boldsymbol{v}) &= C_{\mathrm{m}} F_{\mathrm{inc}} |\boldsymbol{e}_{\mathrm{inc}} \cdot \boldsymbol{n}| dA(-\boldsymbol{n}) = C_{\mathrm{m}} F_{\mathrm{inc}} (\boldsymbol{e}_{\mathrm{inc}} \cdot \boldsymbol{n}) \boldsymbol{n} dA \\ &= C_{\mathrm{m}} F_{\mathrm{inc}} \boldsymbol{e}_{\mathrm{inc}} \cdot (\boldsymbol{n}\boldsymbol{n}) dA, \end{aligned} \tag{3}$$

where $\boldsymbol{n}$ is the unit normal vector of dA and $\boldsymbol{e}_{\mathrm{inc}}$ is the unit vector along the incident direction of laser beam. $F_{\mathrm{inc}}|\boldsymbol{e}_{\mathrm{inc}} \cdot \boldsymbol{n}|$ is the laser fluence incident on dA. Because $\boldsymbol{e}_{\mathrm{inc}} \cdot \boldsymbol{n} < 0$ in the illuminated region S, $|\boldsymbol{e}_{\mathrm{inc}} \cdot \boldsymbol{n}| = -(\boldsymbol{e}_{\mathrm{inc}} \cdot \boldsymbol{n})$.

To obtain the sum impulse of all element impulses, we should integrate Eq. (3) on the entire illuminated surface:

$$m\Delta \boldsymbol{v} = \int \int_S C_{\mathrm{m}} F_{\mathrm{inc}} \boldsymbol{e}_{\mathrm{inc}} \cdot (\boldsymbol{n}\boldsymbol{n}) dA. \tag{4}$$

As for the debris in free motion, the attitude of the target and the illuminated region relative to the laser beam vary with time. For the convenience of describing the relative attitude, we introduce two coordinate systems whose origins are both the mass center of target, as seen in Fig. 2: (1) the fixed coordinate system $Ox_by_bz_b$ (hereinafter referred to as *b-system* for short), which is fixed to the target; and (2) the inertial coordinate system $Ox_oy_oz_o$ (hereinafter referred to as *o-system* for short), in which the direction of each axis is spatially invariant.

Ignoring the effects of laser ablation on the target shape, the surface and the normal vector, denoted by $\boldsymbol{n}_b$, are constant in the *b-system*. If the attitude matrix of *b-system* with respect to *o-system* is $\mathbf{R}_{ob}(t)$ at time t, the normal vector in the *o-system* can be expressed as $\boldsymbol{n} = \mathbf{R}_{ob}(t) \cdot \boldsymbol{n}_b$.

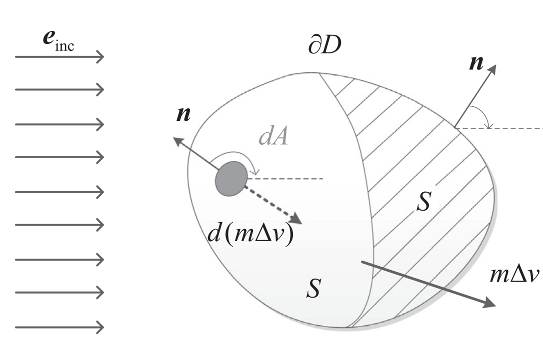

Fig. 1. Schematic of laser irradiates an irregularly shaped debris.