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Numerical simulation and experiments of ground-based laser irradiating small scale space debris

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ABSTRACT

This article investigated the effects of ground-based laser irradiating small scale space debris by numerical simulation and experiments. A dynamic model of ground-based laser irradiating small scale space debris was established, and the waveforms and arriving position of shock wave propagation with different laser pulses width were analyzed, the interaction relationship of jet velocity with different laser energies was discussed, and the distributed rules of impulse coupling coefficient with different laser pulses width and power densities were also described. As a result, the removing effect of the small scale debris was described to evaluate the cleaning influence. This paper provides analyses for establishing removing schemes of small scale debris and selecting suitable parameters ground-based laser system.

1. Introduction

There are a lot of small-sized bodies by space activity since October 1957, such as space debris and space dusts. Especially, the space debris is artificially originated fragments upon rockets launch, etc. By the year 2014, there were about 670 thousand space debris with dimension of about 1–10 cm or more according to NASA [1–3]. It is rather difficult to monitor the space debris with small dimension of 1–10 cm level by conventional means. Hence, these centimeter-scale debris are called small scale space debris. At present, the amount of small scale space debris is increasing due to the increase of space activities in low-earth orbits [4]. The small scale space debris is one of the most dangerous environment factors to spacecraft because their velocities are 10 km/s or so, they are threatening the security of the orbiting space vehicles, and the impact damage will result in degradation and/or failure of space materials, leading to the decrease of stability and life of spacecraft [5,6]. Hence, research the removing technology of small scale space debris is very important to safely develop and utilize space resource for long.

A commonly used technique for removing small scale space debris is multi-pulse laser irradiation technology, and it is regarded as a feasible approach to clean scale space debris, and the clean core is that space debris obtains reversed velocity increment to realize orbit maneuver by laser irradiation. Sakai et al. analyzed the interaction mechanism of laser with target and vaporized target material, and discussed impulse generation on aluminum target irradiated with Nd: YAG laser pulse in ambient gas [7]. Sinko et al. presented a alternate model to address CO_2 laser ablation impulse of polymers in vapor and plasma regimes [8]. Phipps et al. presented an orion plan to remove space debris by using a 20 kW, 530 nm, pulse laser, and discussed the feasibility for laser removing space debris. Furthermore, Phipps et al. given an analytical model for calculating laser ablation impulse coupling coefficient, and discussed an alternate treatment of the vapor–plasma transition [9,10]. Lee et al. investigated the measurement method of freely-expanding plasma from hypervelocity space debris and space vehicle impacts [11], and Schall discussed the feasibility and basic principle for cleaning space debris from lower earth orbits by laser radiation [4]. An given a velocity model for predicting debris clouds produced by hypervelocity impacts in space by the two-stage light-gas gun impacting 6061-T6 aluminum sheets [12]. Jin et al. analyzed removal method of elliptic orbit space debris using ground-based laser, and the simulation results showed that the high power pulse laser can be considered as a feasible method to clean space debris [13]. In general, most researches have shown that high power pulse laser can clean space debris efficiently, but little attention has been focused on the discussion removal effects for laser irradiation small scale space debris. Hence, further studies on the effects of laser irradiating small scale space debris with different laser parameters are very important.

At present, no matter using space based or ground based (including air based) laser irradiating method, neither of them has absolute advantage to remove small scale space debris. Especially, the action mechanism of high power laser removing small scale space debris still lacks of understanding further. Hence, the aim of this article

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is to discuss the effects of ground-based laser irradiating small scale space debris with different laser parameters by numerical simulations and experiments, and it has very important theoretical significance and practical value for selecting suitable ground-based laser parameters and efficient removal schemes.

2. Analysis of removing method

According to the NASA's ground experiments of high speed collision disaggregation on satellites, space debris have various shapes, in which debris with the shape of flake, block, rod and irregular shape take up most of the debris. There are three main space debris removal methods proposed in and abroad, namely tethered dragging, trapping and laser irradiating. Based on the existing technology, laser irradiation technology is the most promising method to remove space debris, and it is the emphasis of current researches. At present, the main removal method of space debris includes based-space system and based-ground system by laser irradiation.

Based-space laser monitoring and removing system is closer to the debris, and the problems of atmosphere transmission and control is no longer serious. However, the cost to launch the laser monitoring and removing system to LEO is about $20/g based on the NASA, and the problems of based-space debugging, replenishment are also complex, which would cost more than 2 times than developing based-ground system [14,15]. In addition, power density of continuous wave lasers irradiated on debris can hardly reach the breakdown threshold. Under this condition, space debris will be melted into more small parts and the target of removing cannot be effectively achieved. Therefore, various of countries pay attention to based-ground pulse laser monitoring and removing technologies, the most noted research is the Orion plan supported by NASA and USAF. Solid laser with pulse width of 10 ns is well developed in 1990s, hence Orion system choose based-ground Nd: lasers with average power of 30 kW (pulse width 10 ns) as a laser source. Accurate position of space debris is first monitored and detected by laser, and then high power laser is irradiated to the surface of space debris (power density larger than breakdown threshold) through tracing and aiming transmitter and self-adaption optical system. Space debris with small size can be totally ablated. For space debris with large size, during the process of laser impulse coupling, the debris can obtain a speed increment, and the debris will fall into aerosphere and burn off when the increment meets a certain condition [16,17]. Namely, the irradiated debris can be captured by atmosphere when the debris enter into the critical orbit altitude of 200 km or so. Finally, the semi-minor axis height of debris orbit is decreased by decreasing debris orbital speed through laser irradiation. Fig. 1 shows the basic removing principle based on high power laser.

3. Dynamic model of irradiating debris

In order to establish a dynamic model of laser irradiating small scale space debris, assumption conditions are given as follows. The pulse width of ground-based high energy laser is ns-level

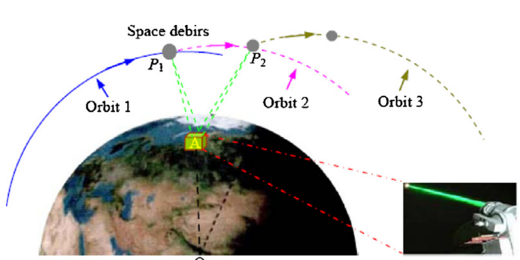

Fig. 1. Basic removing principle based on high power laser.

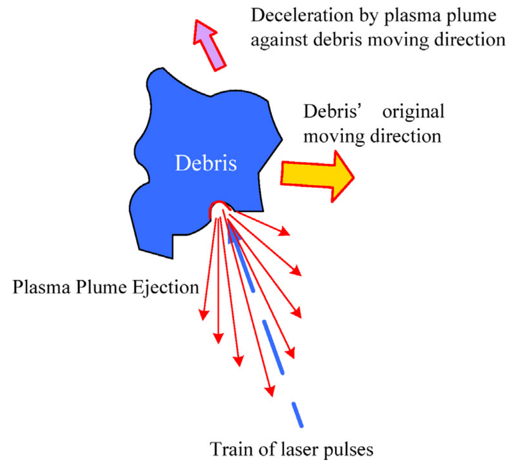

Fig. 2. The sketch map of laser irradiating small scale space debris.

generally. Hence, ground-based laser is assumed to be on the sub-track of space debris [18]. The velocity increment of debris is assumed to gain instantly, and the debris orbit changes are neglected during laser pulse, but the orbit changes in the pulse interval can't be ignored. At the same time, let the shape of space debris be a sphere, the spin of debris be ignored. So, the direction of achieved velocity and laser irradiation is always same. Based on literatures [19], a sketch map of laser irradiating small scale space debris was given, as shown in Fig. 2.

According to Fig. 2, let S be the area of light spot on the target, φ be energy density on the target, ε be transmission coefficient, W be pulse energy, and the following equation is obtained.

$$\phi S = W\varepsilon \tag{1}$$

Assuming S completely fall on the target, then

$$S = \frac{1}{4}\pi d_S^2 \tag{2}$$

Let C_m be impulse coupling coefficient, μ be the rate of debris mass and area, η be velocity change factor, the velocity change of the debris is given by

$$\Delta v = \eta C_m \frac{\phi}{\mu} \tag{3}$$

Substituting Eqs. (1) and (2) in Eq. (3), the velocity increment Δv is expressed as follows

$$\Delta v = \eta C_m \frac{W\varepsilon}{\mu S} = \eta C_m \frac{4W\varepsilon}{\mu\pi {d_S}^2} \tag{4}$$

According to Eq. (4), C_m is target impulse gained from the unit incident laser energy. Impulse coupling coefficient is a parameter that directly relates target impulse to laser energy, and its value reflects the energy utilization in the process of laser ablation in a certain extent. It is influenced by parameters of incident laser, laser energy distribution on the target, and target surface material and target surface structure. The following will discuss the calculating method of C_m.

According to the definition of impulse coupling coefficient, C_m is expressed as follows:

$$C_m = \frac{mv_0}{E_1} = \frac{P}{I} \tag{5}$$

where E_l is the laser energy, m is the quality of target, v_0 is the achieved target velocity, P is peak pressure on target surface, I is incident laser power density.