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Review

Brief review on pulse laser propulsion

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A B S T R A C T

Pulse laser propulsion (PLP) is an advanced propulsion concept can be used across a variety of fields with a wide range of applications. PLP reflects superior payload as well as decreased launch costs in comparison with other conventional methods of producing thrust, such as chemical propulsion or electric propulsion. Numerous researchers have attempted to exploit the potential applications of PLP. This paper first reviews concepts relevant to PLP, including the propulsion modes, breakdown regimes, and propulsion efficiency; the propulsion targets for different materials with the pulse laser are then discussed in detail, including the propulsion of solid and liquid microspheres. PLP applications such as the driven microsatellite, target surface particle removal, and orbital debris removal are also discussed. Although the PLP has been applied to a variety of fields, further research is yet warranted to establish its application in the aerospace field.

Contents

1. Introduction

Laser propulsion is an advanced concept with 45-year research history [1]. Laser propulsion can divide into pulse laser propulsion and continuous wave (CW) propulsion [2]. In the PLP process, a pulse laser impinges the target material surface, generating ionized vapor which forms plasma. The momentum transition occurring during PLP is thus dominated by the laser-induced plasma's counterforce exerted on the surface of the target material [3–5]. Therefore, it reveals that the nature of PLP is an interaction of pulse laser interaction with target material [6]. For PLP, represents a promising propulsion technology instead of chemical fuels propulsion,

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its target not required to carry additional fuels or propellant sources-the propellants can be acquired from the target itself or surrounding environment, thus drastically enhancing the propulsion efficiency [7].

PLP has an advantage beyond any propulsion methods, which it has potential to improvement the payloads of rockets and significantly decrease launch costs [8,9]. PLP has been investigated under several conditions including vacuum [10], air [11], and liquid [12]. In vacuum conditions, the PLP process is powered solely by evaporation and plasma expansion at the target surface. In air, if pulse laser energy density exceeds a certain threshold of air ionization, power originates not only from evaporation at the target surface but also from shock wave expansion, which including laser-air induced and laser-matter induced [13,14]. In liquid, the propulsion efficiency is more higher compared with the first two experiment environments, due to the addition of yet another power source, bubbles in the liquid environment.

There has been a wealth of research on the PLP process and conditions to date. Kantrowitz [15] first proposed the laser propulsion concept in 1972, as a replacement for chemical propulsion in sending the spacecraft to near earth orbits. Ultra-high laser systems appeared in the literature shortly thereafter and were quickly applied in practice in laser propulsion [16]. For example, Leik Myrabo et al. [17] used a pulse laser with power of 10-KW successfully strike a craft with a mass of 50 g and diameter of 12.2 cm to a height of 71 m. Prospective developments in PLP-based technology have garnered a great deal of research interest. Such as Klein et al. [18] demonstrated the pulse laser's ability to impinge (e.g., displace and deform) liquid particles. Another experiment is investigated by Zhang Nan et al. [19], it explored the femtosecond (fs) pulse laser impinging of microbeads, during which a channel forms; due to the balance between self-focusing and de-focusing, a microbead can run steadily in the channel. In a similar experiment, Zheng et al. [20] called this channel the "plasma channel". With the development tendency of PLP, which is a promising propulsion technique and have plenty of advantages compared to other propulsion techniques [21,22].

PLP has demonstrated numerous advantages and potential applications in the many fields of propulsion-especially utilize in the military, aerospace industry [23,24], cultural heritage cleaning, and contaminate particle cleaning fields [25–27]. For military application, for example, is possible to estimate the max destruction in a certain location based on the dynamic evolution of shock waves as a target is irradiated by a pulse laser. Pulse lasers can also be utilized to remove stains and debris from the surfaces of delicate cultural and historical relics via air ionization and shock wave formation. For protection of cultural relics has great significance.

Below, we first review the PLP theory including pulse laser propulsion modes, breakdown regimes, and propulsion efficiency. We then describe several notable experiments conducted by previous PLP researchers. To conclude the paper, we discuss several challenges and potential solutions to the applications of PLP in driven microsatellite, removal particles from the surface of targets [28] and orbital-debris-removal [29,30], which the earliest laser space debris removal was reported by Phipps et al. in 1996 [31].

2. Theory of pulse laser propulsion

As discussed above, PLP has garnered a great deal of attention due to its numerous advantages over other propulsion methods [4,15,32–34]. One should be notice that the real PLP is a very complex propulsion process, and involving many regimes at each interaction stage [35]. In this section, several mechanisms and propulsion efficiency of PLP have been described [36,37].

2.1. Pulse laser propulsion mode

PLP has attracted widely attention due to high coupling coefficient (C_m) and impulse specific (I_{sp}) [38,39]. It has two propulsion modes: Ablation [40] mode and air-breathing mode [41]. The two modes produce high-temperature [42,43], high-pressure plasma. The difference between them is that the air-breathing mode has no mass dissipation whereas the Ablation [44] mode target has to carry propellants [45]. For the former, the target does not need to carry fuels and the air serves as the propellant [46]. The different between two modes are demonstrated in detail below [47].

In ablation mode propulsion, the target material either itself acts as the propellant or carries other propellants (gas, liquid, or solid). Pulse laser with high power is directly focused on the propellants within the environment [48–50] and form gas, including vapor, from the target material surface and surrounding environment (i.e., air). Gas ionization quickly occurs and generates high-temperature, high-pressure plasma. The plasma generates thrust as it expands [51,52]. Different pulse laser system irradiation materials reflect different interaction mechanisms. For long time-scale pulse laser system such as millisecond (ms) pulse laser and nanosecond (ns) pulse laser [53,54], the plasma formation can be described by classical laser-matter interaction, as shown in Fig. 1 (a). The plasma evolution process can be divided into three stages [55–58]:

(1) Heat conduction, melting, and evaporation process: The surface of solid targets is irradiated by the pulse laser and its surface temperature increases until melting and vaporization. The temperature distribution can be calculated by the following heat conduction equation:

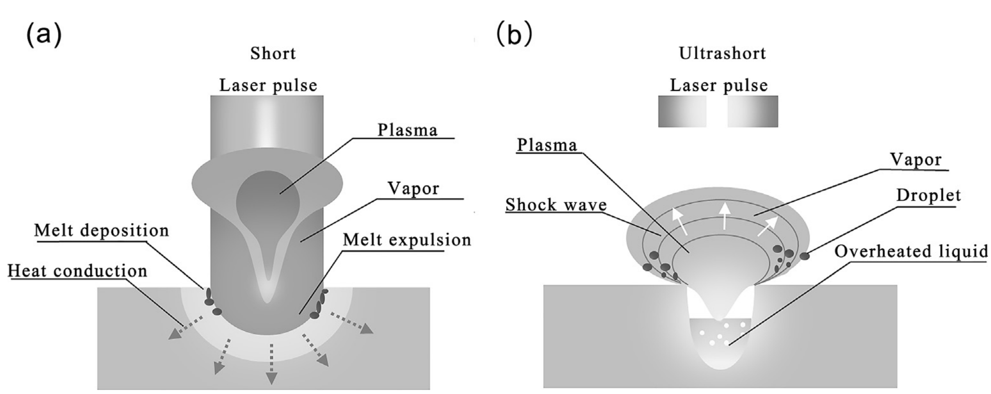

Fig. 1. Pulse laser beam-matter interaction. (a) Classical laser-matter interaction. (b) Ultrafast beam-matter interaction [64].