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Technical Notes

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Moderate-Acceleration Launch Using Repetitive-Pulse Laser Ablation in a Tube

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Nomenclature

C_m = momentum coupling coefficient
E = laser-pulse energy
F_f = friction force on the projectile-launch-tube–wall interface
F_p = thrust
g = gravitational acceleration
m = mass of the projectile
N = number of laser pulses
t = time originated in initiation of laser-pulse irradiations
z = vertical coordinate along the launch tube originated in the initial projectile location
τ = duration of launch

Introduction

LASER propulsion [1] has large-payload capability because a vehicle can be propelled with power sent from a remote device. In the atmosphere, the air can be used as the propellant, as in the cases of bell nozzle engines [2,3] and the so-called lightcraft [4]. In vacuum, the propellant is usually supplied from laser ablation [5–11], and the impulse performance strongly depends on specifications of laser, ablative material, and engine configuration. Phipps et al. [5,6] integrated experimentally measured laser-ablation impulse performance of metals and polymers against various types of lasers in vacuum. When the ablation gas is confined in a narrow layer covered by a transparent solid or liquid substance, the laser-ablation impulse can be much enhanced [7,8,10,12]. Menezes et al. [12] applied this technique to drug delivery to human tissue. However, the pressure of the confined ablation gas can readily exceed the threshold value against damaging the substance; the device can only be used in disposable manner. It has been reported that an optimum fluence to maximize the momentum coupling exists [5]; irradiating a giant pulse with an excessively high fluence results in poor momentum coupling. With a given laser energy and irradiation area on the object, to maximize the impulse, laser pulses of the optimum fluence should be irradiated by a necessary number. When irradiating laser pulses in an open space, the enhancement of the impulse due to interaction among successive laser-pulse-induced flows cannot be expected. Yet, the impulse can be enhanced by *moderately* confining the driver gas in a tube. Sasoh et al. [13–15] demonstrated a projectile launch using repetitive laser pulses from a transversely excited atmospheric (TEA) carbon dioxide laser in a laser-driven in-tube accelerator (LITA), in which the launch tube was filled with inert gas such as xenon. However, in the LITA, both of the tube ends need to be plugged to prefill the driver gas; the projectile experiences an aerodynamic drag due to the gas ahead. These drawbacks can be eliminated by replacing the prefilled gas with the driver gas generated by laser ablation. In this study, we have developed a laser-driven in-tube accelerator using repetitive laser-pulse ablation, thereby realizing high impulse coupling with a moderate acceleration level on the order of the gravitation. The muzzle of the launcher can be open, even to vacuum.

Apparatus

The experiments were conducted using a 25-mm-inner-diam, 1-m-long acrylic cylinder as the vertical launch tube. The lower end of the launch tube was plugged by a piece of ZnSe window to send laser pulses through it; the upper end was by an acrylic window. The inner volume between the projectile at its initial location and the ZnSe window was 3.7×10^{-5} m^3. Near the upper end, a 16-mm-inner-diam duct is connected to a vacuum chamber of an inner volume of 0.8 m^3. Before a launch shot, the launch tube and the vacuum chamber were evacuated down to 20 Pa or lower using a rotary pump. Laser pulses were irradiated from a TEA CO_2 laser (ML205E, Selective Laser Coating Removal Co., with a wavelength of 10.6 μm and 12 J/pulse at 50 Hz, at a maximum), reflected from a concave mirror (focal length of 5 m) and two planar Mo mirrors. The power history of a laser pulse is composed of a primary power peak (the full-width at half-maximum: 170 ns) and a following tail for about 3 μs. The effective beam diameter in the launch tube was 20 ± 2.5 mm.

Figure 1 schematically illustrates the projectile in the launch tube. It is composed of an aluminum-alloy (A7075-T6) body and an ablator rod and its nut, the latter two of which are made of polyacetal homopolymer (Derlin). This material is known as a suitable volume absorber for 10.6-μm-wavelength light [15]. The collimated laser beam is focused by the projectile parabolic surface. Initially, the focus is located in the ablator rod at 2.0 mm in depth from its lower surface. The nominal fluence on the virgin surface was designed to be 20 ± 2 J/cm^2. The projectile has eight 0.5-mm-high fins (effective diameter of 24.9 mm), four around the parabola exit and the others around the upper disk so that its canting is suppressed up to 0.34%. Because the center of mass of the projectile exists in its upper half, the moment around the center of mass stabilizes the projectile axis toward the tube axis. The total mass of the projectile was 7.1 g.

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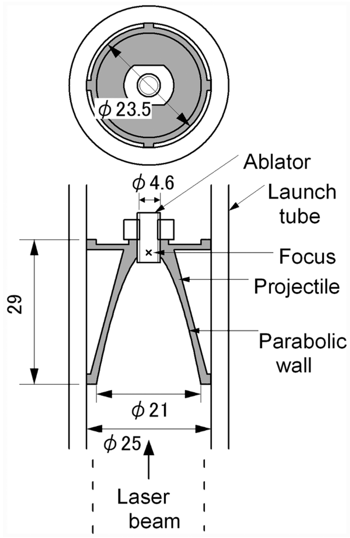

Fig. 1 Projectile in the launch tube (length is in millimeters).

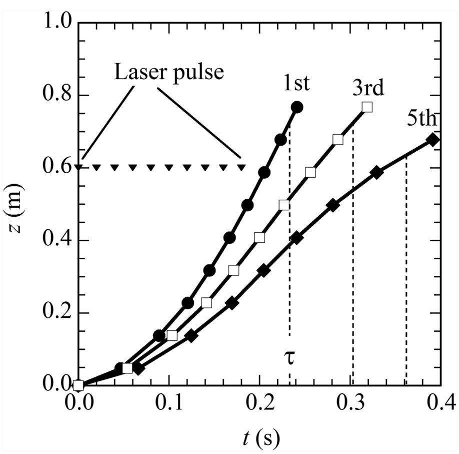

Fig. 2 Examples of the projectile trajectory with laser energy of 3.78 ± 0.05 J/pulse; times of laser-pulse irradiation are indicated with downward triangles.

Results and Discussion

In each series of experiments, a virgin ablator rod was initially inserted in the projectile at the location shown in Fig. 1. In the beginning, for cleaning, three laser pulses were irradiated on the lower surface with an interval of about 3 s each. Then the projectile was launched with 10 laser pulses irradiated at a repetition frequency of 50 Hz. This 10-pulse launch shot was repeated 5 times using the same ablator rod. The projectile trajectory was determined from the method of time of flight sensed by nine sets of a diode laser and a photo diode. Figure 2 shows examples of measured projectile trajectories. The time origin $t = 0$ corresponds to the initiation of the first laser pulse, and z denotes the vertical distance along the launch-tube axis measured from the initial location of the projectile. Although the projectile continued to be accelerated even after terminating the laser-pulse irradiations, we limited the number of laser pulses up to 10 to avoid damaging the projectile and upper window. The launch performance was evaluated only to this limited number of laser pulses. In Fig. 2, when the laser-pulse irradiation was terminated, the projectile reached at $z = 0.47$, 0.34, and 0.25 m in the first, third, and fifth launch shots, respectively. In all of the series of experiments, the launch performance degraded with accumulating numbers of launch shots. This performance degradation should be attributed to the erosion of the ablator rod. Figure 3 shows the cross section of the ablator rod observed after a series of launch shots: three cleaning laser pulses and five 10-pulse launch shots. The length of the ablator rod became shortened by 0.7 mm, and a 3.0-mm-diam,

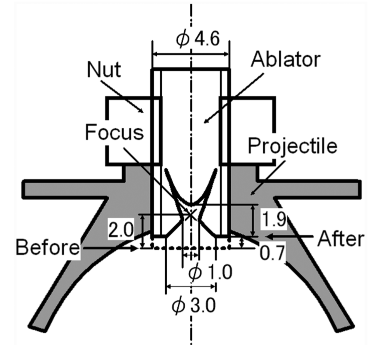

Fig. 3 Ablator shape before (broken lines) and after three laser-pulse irradiations and five 10-pulse launches with energy of 3.78 ± 0.05 J/pulse; before and after correspond to the respective lower-surface locations; ϕ indicates the diameter (length is in millimeters).

1.9-mm-deep crater was formed on the receded surface. The apex of the crater was located at 0.6 mm up from the nominal focus of the projectile parabola. Beyond the crater apex, a conical groove was formed. The average erosion rate was 580 ± 80 μg/J. If we assume that the effective beam diameter equaled the crater diameter, then the effective fluence was increased by a factor of 2.4. According to Watanabe et al. [16] and Anju et al. [17], the optimum fluence to maximize the momentum coupling coefficient with polyacetal against a TEA CO_2 laser pulse was on the order of 20 J/cm^2. In the present experiments, the initial value was set to the same order. With the ablator-rod surface receded with accumulated numbers of laser pulses, the effective fluence exceeded the optimum value and continued to further increase.

The momentum coupling coefficient (the ratio of the propulsive impulse exerted on the projectile to the irradiated laser energy) is determined from the measured projectile trajectory. The effective friction force at the interface between the projectile and the launch-tube wall, which was estimated from in-tube free-fall trajectories, was equivalent to a deceleration of 0.29 ± 0.03 m/s^2. The gross force induced by the laser pulses (i.e., the thrust F_p) was determined by superimposing the gravitational and effective friction terms onto the measured acceleration. From the equation of motion of the projectile, F_p is determined by

$$F_p = m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2} + mg + F_f \tag{1}$$

The momentum coupling coefficient is obtained by integrating Eq. (1) such that

$$C_m \equiv \frac{\int_{t=0}^{\tau} F_p \,\mathrm{d}t}{EN} = \frac{m(\mathrm{d}z/\mathrm{d}t)|_{t=\tau} + (mg + F_f)\tau}{EN} \tag{2}$$

We evaluated the momentum coupling coefficient C_m given by Eq. (2) from time-of-flight data; τ is given as the mean passage time between the uppermost two sensor locations reached by the projectile. For example, in the first and third launch shots in Fig. 2, the projectile reached the ninth sensor location at $z = 0.76$ m; τ was given as the mean passage time between the eighth and ninth sensor locations. In the fifth shot, however, the projectile reached up to the eighth sensor at $z = 0.68$ m; the seventh and eighth sensor locations were used to obtain τ. It should be noted that in many of shots, the projectile continued to be accelerated even at the upper end of the launch tube; the present C_m was evaluated with this limited tube length.

Table 1 summarizes the measured values of C_m. Within the tunable range, three laser energies were examined. As seen in Table 1, the nominal fluence (which is estimated by dividing the laser energy by the cross-sectional area of the ablator rod) ranged from 18.5 to 22.7 J/cm^2, which was of the same order as the optimum condition obtained in previous studies [16,17]. In the first shot, C_m was 1310 ± 80 μN $\cdot$ s/J, on average. In the fifth shots, C_m was

Table 1 Measured momentum coupling coefficients

E, J/pulse	3.08 ± 0.02	3.47 ± 0.03	3.78 ± 0.05
Nominal fluence, $\mathrm{J/cm^2}$	18.5 ± 0.1	20.9 ± 0.2	22.7 ± 0.3
C_m (first shot)	1480 ± 10	1310 ± 30	1270 ± 60
C_m (third shot)	1230 ± 10	1010 ± 40	1020 ± 80
C_m (fifth shot)	1120 ± 10	900 ± 30	900 ± 40

decreased by $28 \pm 3\%$. The time-averaged pressure over a duration of τ was modest, ranging by 370 ± 40 Pa in the first shots and by 210 ± 10 Pa in the fifth shots. Anju et al. [17] measured the pressure–time variation on the ablator surface with the same ablator–laser combination as in this study at a fluence of 17.9 $\mathrm{J/cm^2}$ and an ambient pressure of 10^{-2} Pa. The pressure peak was higher than 300 MPa, with the full-width at half-maximum of 170 ns, and then a 60-MPa plateau for 1.5 μs followed. The momentum coupling coefficient was about 400 $\mu\mathrm{N \cdot s/J}$. In the present method, the ablative pressure was modulated to a moderated level, about a fifth-order-of-magnitude lower; the effective duration time was longer by more than five orders, obtaining a higher C_m by a factor of 3.

The lower the nominal fluence, the slightly better C_m became. From the aforementioned discussions related to the crater formation, the larger the nominal fluence, the further the effective fluence should deviate from the optimum value.

Conclusions

The presented method of launching an object using repetitive laser pulses backed by the moderately confined space in the tube is useful for obtaining a large impulse with a moderate acceleration level. The impulse performance can be increased by further increasing the launch-tube length.

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