Boundary Effect on the Laser-ablation Impulse Characteristics of a Flat-Head Cylinder*

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Nomenclature

- $C_m$: momentum coupling coefficient
- $d_a$: diameter of ablator rod
- $d_l$: diameter laser irradiation spot
- $m$: molecular mass
- $n$: integrated number of laser pulses
- $R_0$: universal gas constant
- $T$: temperature
- $x$: coordinate of ablator rod head
- $x_0$: ablator head position
- $\gamma$: specific heat ratio

1. Introduction

The amount of space debris is rapidly increasing due to growing space activities that are further accompanied even by satellite fragmentation due to mutual collisions. As a solution to this problem, a methodology for actively de-orbiting space debris must be developed. Laser-ablation propulsion is a promising aerospace propulsion method in which thrust is generated remotely, this method has a clear advantage in space applications, such as space debris.2) The amount of space debris is rapidly increasing due to growing space activities that are further accompanied even by satellite fragmentation due to mutual collisions. As a solution to this problem, a methodology for actively de-orbiting space debris must be developed. Laser-ablation propulsion is a promising aerospace propulsion method in which thrust is generated remotely, this method has a clear advantage in space applications, such as space debris.2) When a laser pulse is irradiated onto a target, the characteristic of the impulse, which is a time integration of the temporal thrust, should be affected by the geometry of the target. If the ablation area has sufficiently large dimensions, the impulse is obtained in a one-dimensional manner, and not affected by pressure waves from the boundary. If the ablation area has finite dimensions and is not surrounded by a wall, the pressure on the target is decreased by the formation of expansion waves.3) In contrast, if the ablation area is surrounded by a wall, the expansion waves are suppressed and the surface pressure is not decreased as long as the ablation lasts if its height is large enough. This physical issue is important in practical applications for de-orbiting space debris. The purpose of this study is to investigate the effects of surrounding boundary conditions around the flat-head of a cylinder on the laser-ablation impulse characteristics. We conducted two experimental campaigns: Experiment 1 (Exp. 1) and Experiment 2 (Exp. 2), using different laser pulse properties and ablator materials. In the former experiment, the laser pulse duration was 20 times longer than the latter experiment. In this paper, we discuss the relationship between the geometrical boundary conditions and the propagation of expansion waves.

2. Experimental Apparatus

2.1. Impulse measurement

The impulse induced by the laser ablation was measured using two different types of pendulum: a gravity pendulum and a torsion pendulum, in Exp. 1 and Exp. 2, respectively. Because the expected impulse in Exp. 2 was significantly smaller than that of Exp. 1, the torsion pendulum was utilized to improve sensitivity. Figure 1(a) shows a schematic of the pendulum and its calibration system used in Exp. 1. The pendulum consisted of a 381-mm-long pendulum arm, which was supported by two knife edges at the fulcrum (see Fig. 1(b)), an ablator and mounting, and an eddy current damper. The knife edges were made of stainless steel (iso: 4401-316-00-I) with a width of 10 mm and an apex angle of 60 deg. Each knife edge was mounted on a V-shaped groove with a full apex angle of 120 deg. Each groove was formed by two blocks made of stainless steel (iso: 4301-304-00-I) so that the bottom was not rounded. The displacement of the pendulum was measured using a linear variable differential transformer (LVDT) (LVDT1301-2, Shinko Electric Industries Co., Ltd.) with a resolution of 10 μm placed near the ablator. The natural oscillation period of the gravity pendulum was 1.0 s, which is much longer than the timescale for impulse generation.4) The pendulum was calibrated in the range of up to 320 μNs using an impact hammer (086ES80, PCB Piezotronics Inc.) supported by another knife edge. The level of impact was varied by changing the angle of rise using metal washers, a pulley, electromagnet, and a micro-stage. The impact point was set to 95 mm from the fulcrum. The eddy current damper was made of an aluminum plate, and a neodymium magnet dampened the pendulum’s oscillation. We utilized the same calibration procedure described in Tsuruta et al.5) The conversion factor calibration was 492 μNs/V and the regression

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correlation coefficient was 0.999.

Figure 2 shows the torsion pendulum apparatus consisting of a pendulum arm, pivot at the rotation axis, ablator and mounting, balance weight, and an eddy current damper. To lighten the pendulum arm weight, a 1-m-long aluminum frame with a 15-mm square cross-section was used. A laser displacement sensor (IL-030, Keyence Corporation) with a resolution of 1 μm was used to measure the pendulum’s displacement. The displacement sensing point was 507 mm from the pendulum rotation axis. At the pendulum rotation axis, the pivot (E-10, C-Flex Bearing Co., Inc.) was mounted only on the lower side of the pendulum arm. The spring constant was 0.024 Nm/rad. The ablator and its mounting were fixed at one end of the pendulum arm. The eddy current damper was located at the other end of the pendulum arm. A brass balance weight was attached to suppress rolling and pitching. The pendulum had a moment of inertia of 0.062 kgm² and a natural oscillation period of 7.1 s. We used the same calibration method used in Exp. 1. Impulses up to 6.6 μNs were applied. A calibration factor of 171 μNs/V was obtained, and the regression line had a correlation coefficient of 0.994.

2.2. Ablator and mount configurations

Figure 3 shows the ablator and its mounting. The ablator consisted of a cylindrical rod placed in a hole on the flat surface of the mount. The ablator diameter \( d_a \) and its material were varied as presented in Table 1. The diameter of the hole allowed for a loose fit with the ablator rod. The ablator was set coaxially with the laser beam. The height of the ablator head is denoted by \( x_s \) in Fig. 2. This value is positive if the ablator head extrudes over the mount surface. If \( x_s \) is negative, the ablator head recedes from the surface. By changing the ablator length, the initial value of \( x_s \) was varied from \(-1 \) mm to 1 mm in Exp. 1 and \(-4.0 \) mm to 4.0 mm in Exp. 2. In Exp. 1, \( x_s \) was varied as irradiating laser pulses. The laser displacement sensor measured the value of \( x_s \) for every 10 shots when \( n \leq 200 \) and every 50 shots when \( n > 200 \).

In all experiments, \( d_b \) is larger than \( d_a \).

Table 1. Experimental conditions and measurement apparatus.

| Item                | Parameter       | Unit          | Exp. 1          | Exp. 2          |
|---------------------|-----------------|---------------|-----------------|-----------------|
| Ablator             | Material        | —             | POM             | Al              |
|                     | Diameter        | mm            | 2.0, 4.0        | 1.5             |
|                     | Ablator head height | —     | Variable (measured using laser displacement sensor) | Fixed |
|                     | Impulse range   | μNs           | 35–200          | 2.6–4.1         |
| Mount               | Material        | —             | Al              | PTFE            |
|                     | Ablation threshold fluence | J/cm² | 7⁶            | 10⁶            |
| Laser               | Type            | —             | TEA-CO₂         | Nd-YAG          |
|                     | FWHM            | ns            | 140             | 7               |
|                     | Wavelength      | μm            | 10.6            | 1.064           |
|                     | Total energy irradiated in spot | J     | 10.3            | 0.16            |
|                     | Spot diameter   | mm            | 12              | 1.7             |
|                     | Fluence         | J/cm²         | 5.7–6.2         | 8.3             |
| Pendulum stand      | Type            | —             | Gravity pendulum (Fig. 1) | Torsion pendulum (Fig. 2) |
| Measurement equipment of displacement | —     | LVDT          | Laser displacement sensor |
using a plano-convex lens with a focal length of 500 mm. FWHM irradiated the ablator. The laser beam was collimated for Exp. 1, a TEA-CO₂ laser with a 140 ns pulse width (full width at half-maximum: FWHM) was used. A ZnSe lens with a focal length of 1100 mm and F-number of 20 collimated the laser beam. The effective beam diameter on the mount (d_b) was 12 mm. Only the central section of the laser beam, where the intensity distribution was almost uniform, was used for the ablation. The total laser pulse energy in the spot was 10.3 J. Because of the collimator lens, the nominal fluence on the ablator surface was varied. When d_b = 2.0 mm, fluence changed from 6.0 J/cm² at x_s = 3.0 mm to 6.2 J/cm² at x_s = −5 mm. When d_b = 4.0 mm, fluence was 5.71 J/cm² at x_s = 3.0 mm and 5.91 J/cm² at x_s = −5 mm. For Exp. 2, a Nd-YAG laser with a 7 ns FWHM irradiated the ablator. The laser beam was collimated using a plano-convex lens with a focal length of 500 mm. The d_b was 1.7 mm, which was larger than the ablator diameter, d_a = 1.5 mm. The laser pulse energy was fixed at 0.16 J. The fluence was maintained at 8.3 J/cm² for different x_s by changing the position of the plano-convex lens. Table 1 also summarizes the ablator mount properties. Because the laser fluence on the ablator surface was smaller than the ablation threshold fluence of the mount material, it was confirmed that irradiating a laser pulse onto the mount without the ablator rod did not induce a measurable impulse.

### 3. Results and Discussions

All experiments were conducted in stainless-steel vacuum chambers that were evacuated using a turbomolecular pump, which was backed up by a rotary pump. In Exp. 1, the chamber had a diameter of 2.0 m and length of 4.0 m. In Exp. 2, the chamber diameter was 0.7 m and length was 2.2 m. During the experiments, the vacuum pressure was maintained at 2.0 mPa in Exp. 1 and 20 mPa in Exp. 2.

#### 3.1. Exp. 1: TEA-CO₂ laser pulse irradiation on a POM ablator

Figure 4(a) shows an example of recession history of the ablator head with d_a = 4.0 mm. Before the laser pulse irradiations, x_s was 3.08 mm and after 1200 shots, x_s was −4.96 mm. When n < 50, x_s quickly dropped, but when n ≥ 50, the rate of recession was constant. Therefore, the geometrical boundary condition was barely affected by the rate of recession. We fitted a linear regression, x_s = c₁n + c₂, using the least-squares method. The recession rate estimate c₁ was −6.6 × 10⁻³ mm and c₂ was 2.9 mm. Figure 4(b) shows the n dependence of C_m. Here, we define C_m as the ratio of the impulse measured against the laser pulse energy irradiated on the ablator head. In n ≤ 439, x_s ≥ 0 mm and C_m decreased as n increased. When n > 439, x_s became negative; namely the ablator head receded from the surface. Between 439 ≤ n < 742 (−2 mm < x_s ≤ 0 mm), C_m increased quickly from 212 μNs/J to 255 μNs/J as n increased. When the ablator head receded from the surface, the impulse was enhanced because the pressure reduction resulting from the expansion waves was suppressed by the side wall of the hole during the ablation period. Hereafter, we call this impulse enhancement the “confinement effect.” When n ≥ 742 (x_s ≤ −2 mm), C_m became saturated at 250 μNs/J. This saturation means that the effective length for the ablated gas confinement was on the order of 2 mm.

Figures 5(a) and 5(b) show the variation of C_m with respect to x_s for d_a = 2.0 mm and 4.0 mm, respectively. The different colors pertain to different initial x_s values. When d_a = 2.0 mm, initial x_s was 3.0 mm, 0.8 mm, 0 mm, and −1.1 mm. For d_a = 4.0 mm, initial x_s was every 1 mm from −3 mm to 3 mm. For both d_a values, C_m values overlapped and showed similar dependence on n regardless of the initial x_s.

Figure 5(c) shows the 40-point moving-average values for each data set. C_m exhibited three different dependences on x_s, as follows:

(i) x_s ≥ 0 mm: Between 0 mm ≤ x_s ≤ 3 mm, the average C_m was 195 ± 4.2 μNs/J for d_a = 2.0 mm and 225± 4.2 μNs/J for d_a = 4.0 mm. Because the ablator head was not surrounded by the wall, the expansion waves are generated at the peripheral of the head and propagated inward.
Therefore, the smaller $d_a$, the larger portion of ablator head area was affected by the expansion waves so that the ablation pressure and then the impulse decreased. 

(ii) $-2 \text{ mm} \leq x_3 < 0$ mm: $C_m$ increased with decreasing $x_3$ because of the confinement effect. The side wall suppressed generation of the expansion waves, and the ablated gas was expected to expand one-dimensionally.

(iii) $x_3 < -2$ mm: $C_m$ was saturated at approximately 250 $\mu$Ns/J regardless of $d_a$. Because the effective length for the ablation gas confinement was on the order of 2 mm, a side wall longer than 2 mm had no effect on the pressure field on the ablator head.

3.2. Exp. 2: Nd-YAG laser pulse irradiation on an Al ablator

Figure 6 shows the dependence of $C_m$ on $x_3$. Each operating condition was repeated at least seven times. Symbols indicate the average value for each operating condition, and the error bars represent the standard deviation ($\pm \sigma$) of the means. Because of surface contamination, the magnitude of the impulse changed as $n$ increased. We confirmed that when $n \geq 3$, the impulse varied less than 4% as $n$ increased. In Fig. 6, $C_m$ at $n = 10$ are presented. After $n = 10$, the surface recession of the Al target is expected to be at the $\mu$m level,\(^7\) which is negligible for initial $x_3$. The $C_m$ values were approximately one-tenth of those in Exp. 1 and showed three characteristic ranges in $x_3$ variation, similar to those observed in Exp. 1. When the ablator head extruded over the surface ($x_3 \geq 0$ mm), $C_m$ remained constant (16 $\pm$ 0.3 $\mu$Ns/J). Between $-2$ mm $\leq x_3 < 0$ mm, $C_m$ quickly increased with decreasing $x_3$. In $x_3 < -2$ mm, $C_m$ gradually saturated to 24 $\pm$ 1.0 $\mu$Ns/J.

3.3. Effects of expansion waves on $C_m$ variation

Both Exp. 1 and Exp. 2 showed similar $C_m$ characteristics. $C_m$ decreased quickly as $x_3$ increased, and then gradually saturated. For Exp. 2, assuming the ablated Al gas was a calorifically perfect gas and had a temperature of 30000–80000 K,\(^8\) the propagation speed of the expansion waves ($\approx (\gamma R_0 T/m)^{1/2}$, $\gamma = 5/3$, $m = 27 \times 10^{-3}$ kg/mol) was 4.0–6.4 km/s. Within the impulse generation period of 50 ns,\(^5\) the expansion waves cover 45% to 67%, respectively, of the ablator surface area with $d_a = 1.5$ mm. Hence, the impulse, which is the time-integration of the thrust, is expected to decrease 26–41%, which agrees with the experimental value of 33% in Exp. 2. When $x_3 = 0$ mm, reduction in impulse should depend on $d_a$ and $d_b$. If $d_a$ and $d_b$ have large values, the propagation area of the expansion waves is relatively small with respect to the ablator surface area, and the reduction in impulse is limited. It is assumed that the same expansion wave effects also dominate the $C_m$ characteristics in Exp. 1.

4. Conclusion

We have demonstrated that laser-ablation impulses on the flat-head of a cylinders are affected by the surrounding boundary conditions. $C_m$ had an almost constant value when the cylinder extruded over the flat, non-ablative surface ($x_3 < 0$). However, it increased when the flat head receded from the surface ($x_3 > 0$) and then became saturated. In the present experiments, the saturated value was 11% to 50% larger than that with $x_3 > 0$. Such results are consistent with the discussion on unsteady pressure wave behavior: when the flat head is extruded over the surface, expansion waves are generated at the periphery of the head and propagate inward so that the ablation pressure and then the impulse decreased. If the periphery is surrounded by a wall with a sufficient height, the generation of expansion waves is suppressed during the ablation period, thereby the impulse is enhanced. This scenario is consistent with the results of different $d_a$. The impulse characteristics obtained in this study are important for estimating the laser ablation impulse in space applications, including motion control and even the de-orbiting space debris.

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Fig. 6. The $x_3$ dependence of $C_m$, $d_a = 1.5$ mm, $n = 10$. 

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