Impulse Generation Using 300-J Class Laser with Confinement Geometries in Air

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Nomenclature

\[ a_0: \text{speed of sound in ambient air} \]
\[ C_d: \text{drag coefficient} \]
\[ C_m = I/E: \text{momentum coupling coefficient} \]
\[ D: \text{quasi-steady-state drag} \]
\[ d: \text{diameter of flyer disk} \]
\[ E: \text{laser pulse energy effectively incident on flyer disk} \]
\[ I: \text{impulse} \]
\[ m: \text{mass of flyer disk} \]
\[ t: \text{time elapsed after } U \text{ attains } U_0 \]
\[ U: \text{flyer disk speed} \]
\[ U_0: \text{peak value in } U \]
\[ U_{TOF}: \text{flyer disk speed determined by time-of-flight method} \]
\[ \Delta m: \text{mass reduction of flyer disk (or separate ablator) after laser pulse irradiation} \]
\[ x: \text{distance from initial location} \]
\[ \alpha: \text{constant, Eq. (4)} \]
\[ \rho_0: \text{density of ambient air} \]

Subscripts

1: sensor 1 for time-of-flight method
2: sensor 2 for time-of-flight method

Impulse generation using laser energy from a remote device has several advantages in aerospace propulsion, such as remote manipulation ability and vastly reduced onboard mass (along with accompanying cost). Moreover, the specific input energy is not limited by the inherent energy of the working fluid. After Kantrowitz proposed the concept of laser propulsion in 1972, impulse generation using laser pulse irradiation has been examined experimentally using various configurations, such as ballistic pendulum tests, flyer (including micro-airplane) launches, and vertical launches with repetitive laser pulses. This technology even holds promise for removal of space debris.

Since laser impulse generation has nonlinear characteristics, laser pulse energy is an important parameter to specify. For example, in order to obtain an impulse on the order of 100 J or more is required. To our knowledge, laser impulse generation under such conditions is not reported extensively in the open literature. The objective of this study is to obtain a large impulse using a 300-J class single-laser pulse and to examine the fluid dynamic confinement effects. All experimental data are obtained in air at atmospheric pressure.

1. Experimental Apparatus

This study used a transversely-excited atmospheric (TEA) CO\(_2\) laser with a wavelength of 10.6 \(\mu\)m. The power history of the laser pulse has two peaks; one with a full width at half maximum (FWHM) of 50 ns containing 12% of the total energy, and a second with a relatively-low peak power and long-duration tail; 90% of the total energy is output in 2.5 \(\mu\)s. The beam has a square cross-sectional area of 150 x 150 mm with the central 80 x 80 mm in the shadow of the mirror of the unstable resonator. The output laser beam was reflected onto plane and concave (focal length: 5 m) mirrors and then directed onto a flyer disk in the atmosphere. The effective laser pulse energy incident on the flyer disk was equal to 310 ± 20 J. The effective beam cross-section on the flyer disk was reduced to a 30 x 30-mm square. The average fluence over the flyer disk, excluding the shadow of the resonator mirror, was equal to 480 ± 30 kJ/m\(^2\).

The flyer disk was 42 mm in diameter and 0.5-mm thick, with a 0.5-mm thick, 4.5-mm long rim. Four flyer disk materials were examined: polyamide (PA), polyethylene (PE), polycarbonate (PC), and polyacetal (POM). Unless otherwise stated, the laser beam was directly incident on the flyer disk (the flyer disk itself was also used as an ablator). In other cases, a separate ablator layer made of cellophane (0.07 g) was mounted on the PC flyer disk.

The surface of a flyer disk irradiated by a laser incurs ablation due to the high laser beam intensity generating a high pressure field and propulsive impulse. Three flyer disk mounts (Fig. 1) were examined. In all cases, the flyer disk was launched horizontally. In Case A (Fig. 1a), the flyer disk was mounted in a 4.5-mm deep mount hole in a 5-mm thick aluminum holder plate. In Case B (Fig. 1b), the flyer disk was mounted in a 4.5-mm thick mount hole at
the exit of a 250-mm long duct shaped like a truncated cone. The 1.4° converging angle of the duct was 0.2° larger than the converging angle of the laser beam from the concave mirror. In Case C (Fig. 1c), the flyer disk was mounted in the same way as Case A, but a piece of 30-mm thick NaCl window, which is transparent to the laser beam, was attached to the periphery of the mount hole, and rigidly connected to the holder plate. In all mounts, the rim acted as a Bridgman seal, preventing the laser-powered gas leaking forward through the clearance between the flyer disk and mount hole. The clearance was on the order of 50 \( \mu \text{m} \).

The flyer disk launch speed was measured by the time-of-flight method. Combinations of a laser diode and a photodiode were arranged at \( x_1 = 15 \text{ mm} \) and \( x_2 = 65 \text{ mm} \), respectively. The signals from the photodiode were recorded to digital memory (DL1740, Yokogawa Electric Corporation) and processed using a personal computer. The motion of the flyer disk was observed using a high-speed framing camera (Ultra 8, DRS Technologies, 1 \( \times 10^5 \) frame/s max., 8 frames) in a Schlieren arrangement with a circular knife edge.

2. Results and Discussion

Figure 2 shows framing Schlieren images of the POM flyer disk material at launch speed of 31 m/s and exposure time of 0.2 \( \mu \text{s} \).

Figure 2. Framing Schlieren photographs.

POM flyer disk material at launch speed of 31 m/s and exposure time of 0.2 \( \mu \text{s} \).
sistent with the flyer disk motion in Fig. 2; even when the flyer disk accelerates to peak speed, $U_0$, the travel distance is still much shorter than the depth of the mount hole. Once detached from the mount hole, the disk flies at almost constant speed.

A weak shock wave was observed in front of the flyer disk for $t > 15.6 \mu s$. Such a shock wave may be caused by two mechanisms. First, gas leaking through the peripheral clearance between the flyer disk and mount hole drives a shock wave. Second, the impulsive motion of the flyer disk drives a shock wave in front of it. The former is presumably suppressed to a satisfactory level by the flyer disk rim functioning as Bridgman seal. The shock wave becomes weak enough to be neglected after the primary impulse generation terminates at $t > 50 \mu s$, and does not affect the accuracy of the launch speed measured by the time-of-flight method described below.

If we assume that after being detached from the mount hole, the flyer disk experiences a quasi-steady-state drag force, $D$, that is approximately given as a function of a flight speed, $U$, then

$$D = C_d \cdot \frac{1}{2} \rho_0 U^2 \cdot \frac{\pi}{4} d^2$$  \hspace{1cm} (1)

For a flat disk, $C_d = 2.0$. Solving the equation of motion of the flyer disk yields

$$U_{\text{TOF}} \equiv \frac{x_2 - x_1}{t_2 - t_1} = \phi U_0$$  \hspace{1cm} (2)

$$\phi = \frac{c}{\alpha x_2 - x_1} e^{\alpha x_2} - e^{\alpha x_1}$$  \hspace{1cm} (3)

$$\alpha = \frac{\pi C_d \rho_0 d^2}{8 m}$$  \hspace{1cm} (4)

Substituting the values of the present experiment, $\rho_0 = 1.2$ kg/m$^3$, $d = 4.2 \times 10^{-3}$ m, $m = 1.4 \times 10^{-3}$ kg (POM flyer disk), $\alpha$ and $\phi$ equal 1.2 and 0.95, respectively. For the PE flyer disk, $m = 0.8 \times 10^{-3}$ kg (lightest) and $\phi = 0.92$. This suggests that since the flyer disk loses speed due to the quasi-steady-state aerodynamic drag force, $U_{\text{TOF}}$ becomes smaller than $U_0$ by 5% to 8%. Since the difference in the speed decrement between the flyer disk materials was trivial, the launch performance can be properly evaluated based on $U_{\text{TOF}}$.

Table 1 summarizes the measurements of launch performance. When using cellophane as the ablator, a layer of film (37–38 $\mu$m in thickness) was mounted on the PC flyer disk. PC was selected as the flyer disk material due to its highest mechanical strength, although launch performance data were not obtained just for the PC flyer disk. Irradiating the laser pulse directly onto the PC flyer disk resulted in strong radiation emission, interfering with the time-of-flight measurement between $x_1 = 15$ mm and $x_2 = 65$ mm. In both Cases A and B, POM and cellophane had better impulse performance than PA and PE. The mass reduction of the former materials was at least one order of magnitude larger than that of the others. As seen in Fig. 2, the impulse was generated by the interaction between the laser-generated plasma and the ambient air. The laser-generated plasma comprised both ablated material and air that absorbed the laser beam. A mass of 10 mg corresponds to an air column of the flyer disk diameter and a length of 6 mm, so it is not negligible as the driver.

The amount of the laser-ablated mass is determined through the combined effects of the ablator material, laser pulse characteristics, and condition of the ambient gas; the reason for the above-mentioned differences between the materials is not straightforward. In the present experiments, the interactions between the ablated gas, ambient gas, and laser pulse under different confinement conditions are complex. For a better understanding, time-resolved measurements of force (or pressure), laser beam absorption, etc., during the laser pulse period are required. Further quantitative analyses of these subjects are beyond the scope of the present study.

The impulse depends strongly on the confinement geometry. As seen in Table 1, the impulse increased from Case A to Case C. In order to save consumption of NaCl windows, the launch performance in Case C was examined only with POM and a cellophane ablator. In the POM case, the impulse increased by 2.4 times by introducing duct confinement (Case B). In this geometry, the laser-generated shock wave is reflected repeatedly on the duct wall, and high pressure is held longer than in Case A. With the NaCl window confinement (Case C), the impulse was 5.8 times larger than in Case A, because the ablated gas was confined between the NaCl window and flyer disk, enhancing the pressure.

In this Case, a 1.43-g POM flyer disk was launched at $U_{\text{TOF}} = 151 \pm 4$ m/s, corresponding to a ballistic efficiency of 5.3% ± 0.6%.

<table>
<thead>
<tr>
<th>Flyer disk (separate ablator)</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>$m$ (g)</td>
<td>$mU_{\text{TOF}}$ $(\times 10^{-3}$ Ns)</td>
<td>$\Delta m$ (mg)</td>
</tr>
<tr>
<td>PE</td>
<td>0.84 ± 0.01</td>
<td>25.4 ± 1.3</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>PA</td>
<td>1.19 ± 0.01</td>
<td>27.1 ± 0.8</td>
<td>1.4 ± 0.3</td>
</tr>
<tr>
<td>PC</td>
<td>1.22 ± 0.01</td>
<td>37.7 ± 0.4</td>
<td>14.9 ± 1.2</td>
</tr>
<tr>
<td>(Cellophane)</td>
<td>(0.07 ± 0.00)</td>
<td>37.1 ± 5.0</td>
<td>12.2 ± 1.6</td>
</tr>
</tbody>
</table>

Table 1. Values of $m$, $mU_{\text{TOF}}$, and $\Delta m$ for respective materials and confinement geometries.
3. Conclusions and Prospects

We have experimentally examined the impulse generation characteristics produced by a 310-J (effective value) single-pulse laser. The impulse enhancement owing to confinement effects was confirmed experimentally. In comparison with unconfined geometry, for a polyacetal (POM) flyer disk, the impulse increased by 2.4 and 5.8 times with duct confinement and NaCl window confinement, respectively. The 1.43-g flyer disk was launched at a speed of 151 m/s, corresponding to values of \( I \) and \( C_m \) of 0.22 Ns and 700 N/MW, respectively.

Figure 3 compares the operating conditions in previously published data and the present study. Note that the plotted data were obtained under different conditions with respect to the ablator material, dimensions and configuration of ablator, and laser pulse characteristics (wavelength, pulse duration, averaged fluence or spatial distribution, power history). Consequently, complete sensitivity analysis cannot be done, and the impacts of these important parameters on impulse characteristics require further systematic investigation. In the atmosphere, the impulse is enhanced by utilizing ablation. In the present study, \( C_m \) is highest among operations in the atmosphere. However, in other experiments, much larger values of \( C_m \) have been obtained in vacuum although the \( E \) level was much smaller. Therefore, the impulse performance at the present \( E \) level in reduced ambient pressures is an important subject for study from the viewpoints of basic physics and practical application. If the impulse level obtained in this study could be achieved in space, it will be a very useful method for remotely de-orbiting space debris.

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References