Impulse Vector Characteristics of Laser Ablation Thrusters

By Takumi OYAMA, Keiji HAGIWARA, Hideyuki HORISAWA and Kota FUKUDA

Department of Aeronautics and Astronautics, Tokai University, Hiratsuka, Japan

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This paper proposes direct focusing of repetitive high-power laser pulses on an arbitrary surface of a vehicle in the atmosphere to generate a blast wave at each pulse and push the vehicle along an impulse or thrust vector. Fundamental research was conducted on the interaction between a focused high-power laser pulse or blast wave and a surface with arbitrary curvatures. The characteristics of the impulse or thrust vector generation on the surface were numerically simulated. For simplicity, some fundamental shapes of the surface or vehicle were assumed for the simulation (i.e., planar and semicircular bodies) to examine shock–surface interactions. The impulse vector characteristics were also investigated experimentally. The results showed that the composition of the impulse vector (or each component) reached about 90% of the total impulse in the initial 10 μs. In this duration, a significant high-pressure region induced by the shockwave was localized near the laser irradiation spot; it acted on the surface vectors to induce a primary thrust. Based on these results, the directions of impulse vectors are primarily determined by the local surface vectors of the laser irradiation spots.

Key Words: Laser Ablations, Shock Wave, CFD, Thrust Vector, Impulse Bit

1. Introduction

Kantrowitz introduced the concept of propelling a vehicle by irradiating it with a remotely stationed high-power laser. In the atmosphere, the physics of the initial interaction between the high-power laser beam and a surface is strongly influenced by the presence of air above the surface. Before a jet of absorbing vapor can be obtained, the air above the surface may break down and initiate a laser-supported detonation wave. Air breakdown then occurs in the focal region of the parabola. With regard to the nozzle shape, Ageev et al. studied the influence of nozzle geometry on impulse generation using conical and parabolic nozzles and found the optimum nozzle length for a given laser pulse energy. Myrabo et al. found the optimum laser pulse energy for a given nozzle geometry. Mori et al. studied the aerodynamic transformation of the blast wave to impulsive thrust in a nozzle to derive a general scaling law. After Myrabo et al.’s first successful flight experiments, other countries reported similar investigations, including vertical free flights and horizontal wire-guided flights.

In contrast to the above previous studies, the present paper proposes direct focusing of repetitive high-power laser pulses onto an arbitrary surface of the vehicle in atmosphere to generate a blast wave at each pulse that propels the vehicle along an impulse or thrust vector. A fundamental study was conducted on the interaction between the focused high-power laser pulse or blast wave and a surface with arbitrary curvatures. The impulse or thrust vector characteristics generated on the surface were numerically simulated. For simplicity, fundamental two-dimensional shapes of the surface or vehicle were assumed for the simulation: concave, convex, and planar shapes with various curvatures.

2. Computational Method

The commercial computational fluid dynamics (CFD) code CFD++ (Metacomp Technologies) was utilized in the numerical simulation. This code solves unsteady compressible Navier–Stokes equations by using the total variation diminishing discretization scheme. The MUSCL (Modified Upwind Scheme for Conservation Laws) scheme with second-order interpolation was employed for higher spatial accuracies. The Euler implicit method was employed for time integration. The HLLC (Harten-Lax-van Lee-Contact) method was used to evaluate the flow flux.

The fundamental investigation concentrated on direct focusing of repetitive high-power laser pulses onto a vehicle surface with arbitrary curvatures in atmosphere to generate a blast wave with each pulse and push the vehicle along an impulse or thrust vector. The numerical simulation examined the interaction between the focused high-power laser pulse or blast wave and the surface with arbitrary curvatures.

Fig. 1 shows the schematic of a typical model and defines the radius \( r \) and virtual cone angle \( \alpha \) of a divergent nozzle. Table 1 lists the model parameters that determined the shapes of the models. Models 1 and 2 were concave shapes, and Models 1’ and 2’ were convex shapes. Model P was a planar plate with a width of 50 mm. Models 1 and 1’ had identical geometries of semicircles with a radius of 25 mm. Models 2 and 2’ also had identical geometries of quarter circles with a radius of 25 mm. In order to calculate the pressures, impulses,
etc., the depths of the two-dimensional bodies were assumed to be 25 mm.

For Model 1, various laser irradiation spots were examined with angles of $\theta = 90^\circ$ (center), 60°, and 30°, as shown schematically in Fig. 2. For Model 2, the angles were $\theta = 90^\circ$ (center), 75°, and 60°. For Model P, the angles were $\theta = 90^\circ$ (center), 76°, and 66°. The horizontal (x-axis) and vertical (y-axis) components of the thrusts or impulses induced by the motion of a shock wave were evaluated to predict the motion of the vehicle.

The initial blast wave with a circular shape was assumed to be a point explosion having a radius of 1 mm (with a width of 25 mm), pressure of 8000 MPa, and temperature of 5000 K on the model surface.

![Fig. 1. Schematics of typical models.](image)

![Fig. 2. Schematics of laser irradiation and thrust vector generation in Model 1.](image)

Table 1. Model parameters. Models 1 and 2 are concave shapes. Models 1’ and 2’ are convex shapes. Model P is a planar shape.

<table>
<thead>
<tr>
<th>Model number</th>
<th>1</th>
<th>1’</th>
<th>2</th>
<th>2’</th>
<th>P (Plate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle cone angle, $\alpha$: deg</td>
<td>90</td>
<td>135</td>
<td>180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radius, $r$: mm</td>
<td>25</td>
<td>25</td>
<td>25 (half width)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. Computational Results

3.1. Histories of thrust and pressure contours

Figs. 3(a) and (b) show typical examples of temporal thrust variations, where the instantaneous thrusts were obtained by integrating local pressures multiplied by the surface vectors of the local elements throughout the upper and lower surfaces. For convenience, typical events for $\theta = 90^\circ$ were denoted as follows: $t_0 = \text{laser irradiation}$, $t_1 = \text{when the } y\text{-component thrust reached the minimum value}$, $t_2 = \text{when the } y\text{-component thrust reached the second peak}$, $t_3 = \text{when the shock wave front reached the target edge}$, and $t_4 = \text{when the total thrust converged to zero}$. Because the $y$-component and total thrusts overlap in Fig. 3(a), the temporal variation in the $y$-component thrusts is invisible. On the other hand, these events differed for the different $\theta$ shown in Fig. 3(b) and are denoted as follows: $t_{0'} = \text{laser irradiation}$, $t_{1'} = \text{when the } x\text{-component thrust crossed zero}$, $t_{2'} = \text{when the } x\text{-component thrust reached the minimum value}$, $t_{3'} = \text{when the } y\text{-component thrust reached the second peak value}$, and $t_{4'} = \text{when the thrust converged to zero}$.

![Fig. 3. Typical temporal thrust variations of Model-1. Because of the overlap of $F_x$ and $F_y$ in (a), the temporal variation of $F_y$ is invisible.](image)

Figs. 4 and 5 show the thrust history and corresponding pressure contours, respectively, of Model 1 for $\theta = 90^\circ$; the full range of thrusts in Fig. 3(a) are replotted. For $\theta = 90^\circ$, the explosion started at $t = 0 \mu s$. The initial $y$-component thrust
was about 880 kN. Although the x-component thrusts stayed almost zero, small non-zero x-component thrusts appeared because of some asymmetric phenomena. However, the total x-component impulse was zero in this case, as discussed in the next section. Because the y-component and total thrusts overlap in Fig. 4(a), the temporal variation of the y-component thrusts is invisible. In Fig. 5(a), the y-component thrust reached the minimum value at \( t = 15 \, \mu s \). The shock wave reached the target edge at \( t = 17 \, \mu s \) (see \( t_{3}^{t} \) of Fig. 5(b)).

Figs. 6 and 7 respectively show the thrust history and corresponding pressure contours of Model 1 at \( \theta = 60^\circ \). At \( \theta = 60^\circ \) an explosion started at \( t = 0 \, \mu s \). Immediately after the laser irradiation, the x- and y-component thrusts were positive at about 760 and 440 kN, respectively. The shock wave reached the target edge at \( t = 13 \, \mu s \) (see \( t_{3}^{t} \) in Fig. 7(a)). The x-component thrust reached its minimum (negative) value at \( t = 28 \, \mu s \). The y-component thrust then increased to its second peak (see \( t_{3}^{t} \) in Fig. 7(b)).

Figs. 8 and 9 respectively show the thrust history and corresponding pressure contours of Model 1 at \( \theta = 30^\circ \). At \( \theta = 30^\circ \), an explosion started at \( t = 0 \, \mu s \). The initial y- and x-component thrusts were about 430 and 750 kN, respectively, so the x-component was larger than the y-component. The shock wave reached the target edge at \( t = 9 \, \mu s \) (see \( t_{3}^{t} \) in Fig. 9(a)). At \( t = 27 \, \mu s \), the x-component thrust reached its minimum value. On the other hand, the y-component thrust reached the second peak (see \( t_{3}^{t} \) in Fig. 9(b)). When the shock wave turned around at the edge, a high pressure started acting on the upper side of the target. This pressure induced a negative thrust, and the x-component became negative.

Figs. 4, 6, and 8 show that the composition of the impulse vector (or each component) reached about 90% of the total impulse within the initial 10 \( \mu s \). Figs. 5, 7, and 9, show that, during this duration, a significant high-pressure region induced by the shockwave acted on the surface vectors; this induced a primary thrust that was localized near the laser irradiation spot.
3.2. Relationships between impulse bits and laser irradiation positions

The results of the thrust histories were used to obtain impulse bits through time integration of the thrusts for various cases of Models 1–P.

Fig. 10 plots the relationships between the impulse bits and laser irradiation positions: (a) the \( x \)- and \( y \)-components of the impulse bits for Models 1–P and (b) the total impulse bits for Models 1–P. For both Models 1 and 2, the maximum total impulse bits were obtained at \( \theta = 90^\circ \), where the \( y \)-component impulse bits were maximum while the \( x \)-components were zero.

When irradiated at the smallest \( \theta \) or near the right edges, the total impulse bits became minimized, where the \( y \)-component impulse bits were also minimized and the \( x \)-components were maximized. Since the local force induced by the shock wave was the product of the local pressure and the surface element vector, the force vector had the direction of the surface vector: +\( y \)-direction when \( \theta = 90^\circ \) and mostly +\( x \)-direction when \( \theta \) was at its minimum near the right edge.

In Model 2, the \( y \)-component impulses were much larger than the \( x \)-component impulses. Since Model 2 had a more planar shape, the smaller \( x \)-component surface vectors throughout the surface resulted in smaller \( x \)-component impulses.

Since there were no \( x \)-component surface vectors in Model P because of its planar shape, the total \( x \)-component impulse was zero. There were slight differences in the impulses: the impulse was larger when irradiated at the edge than the center. This was because of the longer duration of the laser-induced pressure acting on the lower surface than on the center in this case. Among the three models, Model 1 showed the largest impulse at \( \theta = 90^\circ \).

Mori et al.\(^8,11\) previously demonstrated that laser thrusters irradiating focused high-power laser pulses from conical or parabolic nozzles showed higher impulse characteristics with smaller cone angles. Similarly, Model 1 showed better thrust performances since it had smaller cone angles.

These results showed that the direction of an impulse vector is determined by the direction of the local surface vector of a laser irradiation spot. This is because (i) a force vector induced by a shockwave is the products of local pressures and local surface elements, (ii) the total impulse reached about 90% its value within the initial 10 \( \mu \)s, and (iii) during this duration, the pressure induced by the shockwave on the surface vector was localized near the laser irradiation spot.

4. Experimental Setup and Method

Fig. 11 shows a schematic of the experimental setup for the impulse vector measurement. Laser pulses from a TEA–CO\(_2\) laser (Lumonics, TE822HP, wavelength: 10.6 \( \mu \)m, pulse energy: 2 J, pulse width: 8 \( \mu \)s) were irradiated onto a target with a semicircular surface. A two-dimensional impulse vector generated with the laser ablation of the target was...
measured with a two-axis-pendulum thrust stand, as shown in Fig. 12.

This thrust stand could measure both the longitudinal (x-axis, parallel to laser beam) and transverse (y-axis) components of the impulse vector simultaneously. It consisted of an arm hung with two-stage knife edges that pivoted independently to measure each component of the arm displacement. To monitor each displacement component, an LED displacement sensor (OMRON, Z4W-V25R, spatial resolution: 10 μm) was used for each axis. Each measurement was calibrated by applying an arbitrary impulse vector through the perfectly inelastic collision of an aluminum ball hanging from a thin string with the target.

The geometry of the target was identical to that of Model 1 in the numerical simulation; its surface consisted of polyoxymethylene (POM, or polyacetal), which is known to be the best material to obtain large impulses for pulsed CO₂ laser ablation in atmosphere.

5. Experimental Results and Discussion

Fig. 13 plots variations in the x- and y-components of the impulse bit vectors with the laser irradiation position. The y-component of the impulse vector became largest at the center (θ = 90°). As it approached the edge (i.e., decreasing θ) the x-components increased and the y-components decreased. The x-component of the impulse vector became largest at θ = 15° (near the edge).

A comparison of the experimental (Fig. 10) and numerical simulation results showed that the above tendencies were qualitatively similar. However, there were large discrepancies in the thrusts and impulses between the experimental and simulation results. Since the simulation thrusts were obtained under the assumption of two-dimensional calculation with a uniform distribution over a depth of 25 mm, the calculated values were too large for quantitative comparison to the experimental thrusts.

However, the decreases near the edge were more significant in the experimental results than in the numerical simulation results. This was attributed to the interaction between the incoming laser beam and the target surface, which reduced the effective beam energy on the target surface. Since the edge of the beam radius of the laser beam passed near the surface of the target, especially at θ = 15°, breakdown plasmas tended to form along the surface far before the focal point, as shown in Fig. 14; this reduced the effective energy at the focal point.

In previous studies on laser-boosted vehicles, various investigations including flight tests [12, 13], flight dynamics [12-19], flight trajectories [18-20], etc. were extensively conducted. In their studies, effects of laser-induced impulses and incoming airflows, including aerodynamics and flight dynamics, on vehicle’s attitudes and trajectories were discussed. In these studies, the axes of the vehicle and laser beaming were assumed to be one-dimensional, and the lasers entered into a center of the exhaust nozzle. In particular, to control the motions (translational and rotational) of the vehicle, passive pitching suppression and beam-riding characteristics for on- or off-axis beam were evaluated. Therefore, the passive control was primarily assumed and employed in these studies.

On the other hand in this study, the active control of the motion of the vehicle is our primary concern, which uses repetitive laser pulses (ex. 0.1 ~ 1 kHz) scanned and directed to various parts of the vehicle’s surface. From previous studies, the magnitude of laser-induced impulses was dependent on
combinations of laser fluence, target material and ambient gas. In addition, according to the results of this study, it was found that the direction of laser-induced impulse vector per pulse was determined by a local surface (element) vector of the lased spot.

Therefore, to achieve our goal of the control, firstly, it is necessary to rapidly scan and obtain the temporal variations of whole 3-D (dimensional) surface vector elements of the vehicle. Secondly, the surface element of the vehicle, which directs the targeted motions (translational and rotational), and pulse energy for the subsequent laser pulse are determined, and then irradiated to the surface spot. The continuous repetitions of the rapid 3-D scanning and laser pulse irradiation can give the targeted motions to the vehicle.

Under an assumption of high-speed flight, since influences of the drag and perturbations of the flow will be included in the resultant motions of the vehicle, these are namely taken into account. Subsequent repetitive laser pulses can successively compensate the deviations of the instantaneous motions from the targeted motions. For example, assuming a repetitive rate of laser pulses of 100 Hz and a hovering vehicle with negligible initial rotation, the deviations from the targeted motions during the pulse separation of 10 ms can be insignificant and their successive correction will be achieved with the repetitive pulses.

6. Conclusions

A fundamental investigation was conducted on the interaction between a focused high-power laser pulse or blast wave and a surface with an arbitrary shape. The characteristics of the impulse or thrust vector generated on the surface were numerically simulated. For simplicity, some fundamental shapes of the surface or vehicle were assumed, and the shock–surface interactions were investigated. An experimental investigation on the impulse vector characteristics was also performed. The following conclusions were drawn:

1) The impulse vector (or each component) reached about 90% of the total impulse within the initial 10 μs.
2) During this duration, a significant high-pressure region induced by the shockwave acted on the surface vectors to induce a primary thrust that was localized near the laser irradiation spot.
3) Since the impulse vectors induced by the shockwaves were the products of local pressures and local surface elements, the direction of an impulse vector is primarily determined by the direction of the local surface vector at the laser irradiation spot.

References