Analytical Study on Flight Performance of an Air-Breathing RP Laser Launcher

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Abstract

An Air-breathing RP Laser Launcher has been proposed as the alternative to conventional chemical launch systems. This paper analytically examines the feasibility of SSTO system powered by RP lasers. The trajectory from the ground to the geosynchronous orbit is computed and the launch cost including laser-base development is estimated. The engine performance is evaluated by a cycle analysis and validated by CFD computations. The results show that the beam power of 1.6MW per unit initial vehicle mass is optimum to reach a geo-synchronous transfer orbit, and 4,000 launches are necessary to redeem the cost for laser transmitter.

INTRODUCTION

Schematic of a vehicle boosted by laser beams is shown in Fig. 1. When laser beam is transmitted from the ground and focused by the parabola nozzle, breakdown occurs near the focus, and plasma is formed. The plasma absorbs the following part of beamed energy and expands outward generating shock waves. The shock waves reflect on the nozzle surface, generating impulsive thrust. Because the energy is provided from the ground and the atmospheric air is utilized as a propellant, neither energy source nor propellant is loaded on the vehicle. Thereby, this type of launcher is expected to achieve a high payload ratio and a low launch cost.

Although many experimental and analytical studies have been carried out on beaming propulsion,1-4 feasibility studies of the system are quite few. We propose a launch system from the ground to a Geosynchronous Transfer Orbit (GTO) by RP laser propulsion. In the initial stage of launch, the vehicle closes the inlet and takes the air from the rear. This flight mode is called “pulsejet mode”. When ram-compression becomes available as vehicle velocity increases, the inlet is opened and the flight mode is switched to “ramjet mode”. When the vehicle cannot breathe sufficient air at high altitudes, the flight mode is switched to “rocket mode.” Through these three modes, the vehicle is accelerated to reach the orbital velocity.

BEAM TRANSMISSION

High power and large-scale lasers such as chemical, free electron and solid-state lasers are under development for directed energy systems, though there are obstacles in scaling up of a laser oscillator: In general, with the increase in power and size of a laser oscillator, it becomes quite expensive and difficult to oscillate in a single transverse mode to produce optimum beam collimation.

A phased laser array as shown in Fig. 2 is one of the solutions.5 It will reduce the development cost drastically. However, spatial coherence of arrayed transmitters would be degraded because the profile becomes inevitably a cluster of multiple beams without any overlapping between each other. Therefore, it would be important to know the combined diffraction patterns and their dependency on geometric parameters of the array.

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Computed far-field diffraction patterns were shown in Fig. 3. $z_F \equiv (nd)^2/\lambda$ is the boundary distance between Fresnel and Fraunhofer regions. Because its profile on the transmitter is almost flat, far-field profiles tend to consist of a main lobe and several side lobes. Since it would be disadvantageous to collect the power in side lobes from the viewpoint of receiver size, we assume to use only a main lobe for energy transmission.

The fractional energy contained in the main lobe is expressed in terms of the main lobe energy efficiency, $\eta_{\text{ML}}$. Computed $\eta_{\text{ML}}$ is plotted in Fig. 4. $\eta_{\text{ML}}$ is increased with the aperture fill factor $f \equiv 2w_0/d$. This relationship is valid for array number $n$ at $z > 2z_F$, and can be fitted using a following polynomial function as

$$\eta_{\text{ML}} = -0.241f + 2.54f^2 - 1.58f^3.$$  (1)

$\eta_{\text{ML}}$ of 0.72 will be attainable with $f \approx 1$.

**PROPOSED TRAJECTORY TO THE GEOSYNCHRONOUS ORBIT**

We propose a vertical launch to minimize the development cost of the laser base. The laser transmitter can be fixed on the base because it is free from tracking and pointing. The beam degradation due to the atmospheric turbulence is also minimized. Figure 5 shows the proposed trajectory: The vehicle is boosted by beaming propulsion to reach the orbit beyond the GEO. At the apogee point, the vehicle is kicked to a GTO by an on-board motor and decelerated at the perigee point as well.

Figure 6 shows the necessary velocity increment by an on-board motor assuming the Hohmann transfer. If the vehicle is boosted to have the velocity of 10.85 km/s, necessary velocity increment by the on-board motor is only 2 km/s,
which will be achieved by electric propulsion.

**THRUST PERFORMANCE**

Thrust performance during the pulsejet mode has been evaluated by means of ground tests. Schematic of our thrust measurement system is shown in Fig. 7. The focus of optics was set in the vicinity of the apex of nozzle cone, and the impulse imparted to the cone was measured using a ballistic pendulum. The pendulum displacement was measured using a laser distance measurement sensor. The cone angle $\alpha$, nozzle length $n_r$ and laser energy $E_i$ were varied. The inner wall of nozzle was made of aluminum, and each cone was encased in a cylinder so that the thrust force was not exerted on the outer surface of the nozzle.

The relation between the momentum coupling coefficient $C_m$ and the nozzle length is shown in Fig. 8. The nozzle scaling $\bar{r}_n$ is defined as $\bar{r}_n = R_n/R^*$. $R_n$ is an actual nozzle length and $R^*$ is a characteristic radius of shock wave defined as,

$$R^* = \left( \frac{E_i \sin^2 (\alpha/2)}{p_a} \right)^{\frac{1}{3}}$$

$p_a$ is an ambient pressure. $R^*$ is a measure of the strength of explosion, and this is equivalent to the radius of the shock wave $R_s$ when the pressure at the shock front decayed mostly to $p_a$. $C_m$ was found to take maximum value of about 350Ns/MJ at $\bar{r}_n = 0.3$.

**FLIGHT ANALYSIS OF RP LASER LAUNCH SYSTEM**

**Analysis method**

Thrust during the pulsejet mode can be estimated using the measured data of $C_m$. In the ramjet mode, the airflows inside the vehicle must be considered. Thrust was calculated by an engine cycle analysis similar to those for scramjet engines. The Humphrey cycle as indicated in Figs. 9 and 10 is assumed. Area ratios to vehicle cross-sections $S$ at Positions #0 $\sim$ #4 in Fig. 9 are listed in Table 1. An effective inlet area $A_0$ is defined as

$$A_0 = S \int_{s_{\text{inlet}}} \rho v \cdot dS / \int_S \rho v \cdot dS$$

$p_v$ is an ambient pressure. $R^*$ is a measure of the strength of explosion, and this is equivalent to the radius of the shock wave $R_s$ when the pressure at the shock front decayed mostly to $p_a$. $C_m$ was found to take maximum value of about 350Ns/MJ at $\bar{r}_n = 0.3$. 

![Fig. 6 Required velocity increment from GTO to GEO. Electric propulsion will serve as an upper-stage engine.](image)

![Fig. 7 Impulsive thrust measurement system using a 10J/pulse CO2 Laser](image)

![Fig. 8 Measured $C_m$ and dimensionless nozzle length](image)

![Fig. 9 Laser boosted ramjet engine cycle](image)
Fig. 10 Humphrey cycle with additional isentropic expansion #1 → #2.

Table 1 Area ratios of assumed vehicle configuration.

<table>
<thead>
<tr>
<th></th>
<th>$A_1/S$</th>
<th>$A_2/S$</th>
<th>$A_3/S = A_4/S$</th>
<th>$A_4/S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>0.6</td>
<td>0.38</td>
<td>0.75</td>
<td>1</td>
</tr>
</tbody>
</table>

From Position #0 to #1, air is ram-compressed as

$$
\frac{P_0}{P_t} = \left[1 + \left(1 - \eta_d \frac{\gamma - 1}{2} M_0^2\right)^{\gamma/\gamma - 1}\right]^{\gamma-1}
$$

where $t$ designates stagnation point, $\eta_d$ and $\gamma$ were assumed as 0.97 and 1.4, respectively. The air is isentropically expanded from #1 to #2 and isometrically heated from #2 to #3. Physical properties at #3 were calculated as

$$
\rho_3 = \rho_2, \quad u_3 = u_2, \quad T_3 = T_2 + \frac{\eta_\theta \eta_T P_1}{C_p m_p},
$$

$$
p_3 = \rho_3 R T_3, \quad M_3 = u_3/\sqrt{\gamma R T_3}
$$

where $\eta_\theta$ is the fraction of laser energy that is converted to blast wave energy and set to 40%. Finally, the air was again isentropically expanded from #3 to #4, and thrust was calculated as the following:

$$
F = \dot{m}_p |u_4 - u_0| + A_4 (p_4 - p_0)
$$

The mass flow rate taken from the inlet decreases with the altitude due to the decrease in air density. The flight mode is switched to the rocket mode just before thermal choking occurs. The inlet is closed and hydrogen propellant is injected between #1 and #2. The propellant is laser-heated from #2 to #3 and the flow is assumed to choke thermally at #3. Since the energy of flow before heating is negligibly small compared to the laser energy input, the following relations are derived from the energy conservation law and the equation of state:

$$
T_i = \frac{\eta_\theta P_1}{m_p} \left[\frac{2}{C_p (\gamma + 1)}\right]
$$

$$
p_s = \frac{\dot{m}_p}{A_p} \sqrt{\frac{RT_i}{\gamma}}.
$$

From #3 to #4, isentropic expansion was assumed.

Vertical launch trajectories are calculated by solving the following equation of motion by the 4th order Runge-Kutta scheme:

$$
m_c \frac{dU}{dt} = F - \frac{1}{2} \rho_s U^2 S C_d - m_c g
$$

where $m_c$ and $U$ is the vehicle mass and flight speed, respectively. Herein, flight conditions were decided by tracing the trajectory. Drag coefficient $C_d$ is a function of $M$.

Validation by CFD analysis

In order to validate the results of engine cycle analysis, computed $C_m$ of the ramjet mode was compared with our CFD computations. Figure 11 shows the pressure contour and thrust at 20µs after an explosion. The result is shown in Table 2. The performance at high Mach number is somewhat under-estimated in the engine cycle analysis.

Fig. 11 Pressure contours at $t=20\mu s$ at $H=20km M=5$.

<table>
<thead>
<tr>
<th>$H$, km</th>
<th>$M$</th>
<th>$C_m$(CFD),Ns/MJ</th>
<th>$C_m$(ECA),Ns/MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>5</td>
<td>66.0</td>
<td>58.4</td>
</tr>
<tr>
<td>30</td>
<td>8</td>
<td>41.0</td>
<td>22.7</td>
</tr>
</tbody>
</table>

Flight Trajectory and Payload Ratio

A payload ratio $\lambda$ is estimated using the results of engine cycle analysis, which is a conservative estimation.

$$
\lambda = \frac{m_c - \frac{\dot{m}_p}{1-\epsilon}}{m_c}
$$
The structure weight ratio $\varepsilon$ is assumed as 0.1 because of its simple structure. The final vehicle is set at 10.85 km/s.

Figures 12 and 13 show the boosting trajectories and payload ratios for several beam power. $\lambda$ decreases with the beam power per initial vehicle mass $P_L/m_0$. The period of the ramjet mode also decreases with $P_L/m_0$, and the ramjet mode is unavailable at $P_L/m_0 < 1.5$ MW/kg. Beam transmission of up to 300-400 km and duration of 60-160 s are requested.

Fig. 12 Flight Mach number and flight altitude

Fig. 13 Flight Mach number vs. flight time

Figure 14 shows the vehicle acceleration for the case of $P_L/m_0 = 1.6$ MW/kg. The vehicle is transiently almost stationary in the pulsejet period due to the equilibrium between the aerodynamic drag and the thrust. The acceleration impulsively increases at the mode starting of the pulsejet and ramjet. The acceleration gradually increases with a decrease in the fuel during the rocket mode. The maximum acceleration is about 27 $g$.

Fig. 14 Vehicle acceleration history.

Figure 18 shows payload mass per unit beam power vs. $P_L/m_0$. The optimum payload mass per unit beam power is 0.148 kg/MW at $P_L/m_0 = 1.6$ MW/kg. In other words, this is the optimum condition minimizing the development cost of laser base facilities.

Fig. 15 Payload mass per unit beam power

LAUNCH COST

The costs for laser base facilities, electricity and vehicle fabrication are considered. Table 3 shows the expected costs for beam transmitters. The other costs are tabulated in Table 4.
Table 3  Cost for beam transmitters

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Cost, $/W</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>10</td>
<td>30%</td>
</tr>
<tr>
<td>Microwave</td>
<td>0.1</td>
<td>90%</td>
</tr>
</tbody>
</table>

Table 4  Other costs

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.06 $/kWh</td>
</tr>
<tr>
<td>Vehicle fabrication</td>
<td>4,000 $/kg</td>
</tr>
</tbody>
</table>

Figure 16 shows the relationship between the launch cost and launch count. The cost for beam transmitters is predominant when the launch count is few. The launch cost decreases with the launch count, and the beam transmitter cost will be redeemed at 4,000 launches compared with that for chemical launchers.

For example, for the construction of a 100-ton space solar power satellite in GEO, chemical launchers can deliver it with 50 launches. Instead, laser beaming propulsion with the capability of 10kg payload/launch can deliver it with 10,000 launches and the cost is going to be half of chemical propulsion. A 100MW-output laser facility is required.

If microwave beaming launchers with the capability of 100kg payload/launch is available, 1,000 launches are necessary and cost is almost one-tenth of chemical rockets’ cost. A 1GW-output microwave facility is required.

**SUMMARY**

The beam power of 1.6MW per unit initial vehicle mass is optimum to reach GTO trajectory, and 4,000 launches are necessary to redeem the cost for laser transmitter facility.

**REFERENCES**