CONCEPTUAL STUDY OF LASER DIRECT LAUNCH

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ABSTRACT

A clean energy launch system using laser propulsion is studied. The concept essentially provides an air-breathing vehicle of which propellant is the atmospheric constituents. The vehicle receives the laser radiation energy from the ground station and finally becomes a 1 ton orbiter in a 500 km LEO (Low Earth Orbit). The technological problems are surveyed and most of them are found within the state-of-the-art of space engineering.

NOMENCLATURE

\[ A_w \] : air intake area
\[ C_L, C_D \] : aerodynamic coefficients

\[ F \] : thrust

\[ g_0 \] : gravity acceleration at sea level \((9.80665 \text{ ms}^{-2})\)
\[ h \] : altitude

\[ I_{sp} \] : specific impulse
\[ m \] : vehicle mass

\[ \dot{m} \] : mass flow rate
\[ P \] : laser power

\[ q \] : aerodynamic heating flux

\[ Q_{max} \] : aerodynamic pressure limitation

\[ R_0 \] : Earth's radius
\[ R \] : leading edge radius

\[ S_w \] : wing area

\[ T_w \] : wall temperature (leading edge)

\[ u, w \] : velocity component

\[ V \] : vehicle velocity

\[ \alpha \] : attack angle

\[ \gamma \] : velocity angle

\[ \delta \] : attitude angle

\[ \epsilon \] : emissivity

\[ \eta \] : thrust efficiency

\[ \phi \] : longitudinal angle

\[ \rho \] : atmospheric density

\[ \rho_0 \] : atmospheric density at sea level \((1.225 \text{ kgm}^{-3})\)

\[ \sigma \] : Stefan-Boltzmann constant \((5.67051 \times 10^{-8} \text{ Wm}^{-2}K^{-4})\)

INTRODUCTION

Toward the 21st century our space development activities will progress more extensively unless the financial support is fairly
slowed down during this decade. A great deal of construction material as well as accommodations for manned activities will be repetitively launched into LEO (Low Earth Orbit) for the space station and other space infrastructure. These massive transportation consume rocket propellant of a few ten times of the payload weight. This value cannot be ignored if we imagine the future environment of our planet. It seems that the situation is not improved even if we start to take advantage of the lunar-base and lunar resources. In order to relax the heavy pollution of the Earth's environment, it is worth-while investigating a clean-energy system of laser direct launch from now.

**CONCEPT DEFINITION**

The merit of laser propulsion is defined as the absence of propulsive energy source onboard the vehicle. It is a kind of external combustion rocket ejecting the propellant by absorption of laser transmitted energy from the ground station. By virtue of the removal of power source from the vehicle, one can increase the lift-off weight by more payload. In the recent literature A. R. Kantrowitz originally recommended the usage of solid LiH as the propellant for laser direct launch because LiH is expected to give good thrust performances because of its low molecular weight (Ref. 1). Unfortunately this recommendation was not a clean launch system.

In this study we describe a laser direct launch system employing solar radiation as the clean energy source and using the constituents of the Earth's atmosphere as the clean propellant. Figure 1 exhibits a drawing of our conceptual study "Clean Energy Launch System" revised from the A. R. Kantrowitz's original idea.

![Catapult Assist Laser Direct Launch at Uchinoura](image)

**Figure 1** Concept of laser direct launch using electromagnetic catapult and air-breathing vehicle (revised from Ref. 2).
(Ref. 2). In the daytime solar energy can primarily be directly converted into the electricity by photovoltaic cells or by more primitive method of oceanic water-power generation. For the nighttime we must accumulate the solar energy into the heat absorber or the water level of the dam. The stored energy is supplied to both the laser power station and the electromagnetic catapult. After the vehicle is accelerated to a transonic speed, air-breathing jet is driven by laser beam irradiation until the stored liquid air is used for the rocket phase. We begin with launching 1 ton orbiter into LEO but in contrast, this system may also be capable of retrieving the Earth's reentry vehicle. Figure 2 shows the constituents of the upper atmosphere. In the figure, STS is the Space Shuttle cruising at 300 km altitude and SFU is a free-flying platform at 500 km.

![Diagram](attachment:image.png)

**Figure 2** Constituents of upper atmosphere and typical operational altitudes of Earth's orbital spacecraft.

![Diagram](attachment:image.png)

**Figure 3** Thrust performances of laser rocket propulsion with the parameter of incident laser power.

**TECHNOLOGICAL SURVEY**

It should be kept in mind that the technological problem concerning the laser direct launch ranges almost all over the astronautics and aeronautics. Primary problems are reviewed from three aspects:

1) Feasibility of laser propulsion,
2) Navigation, guidance and control,
3) Availability of laser light source.

**LASER PROPULSION**

Firstly we must notice that a liquid rocket booster of 100 ton thrust generates 10 GW in terms of electrical power output. Even in the small-scale system by two orders of magnitude, 100 MW, such intensive power must be received by the launch vehicle. Therefore the laser rocket propulsion is required thermal efficiency as high as the conventional rocket engines. A fundamental research of laser propulsion using the air was already started in the laboratory (Ref.
A group in the University of Illinois presented an intermediate report of 10 kWe CW (Continuous Wave) CO\(_2\) laser propulsion experiment in 1990 (Ref. 4). They achieved 80% thermal efficiency at 3.53 atm hydrogen supplying pressure and confirmed that higher pressures give rise to this efficiency toward asymptotic value of 100%. Figure 3 shows the expected thrust performance of laser propulsion. The typical values are 1,000 sec in specific impulse with thrust efficiency of 50%.

Secondly we must touch the major problem how the laser beam is oriented to the engine. A single-port engine and two-port engine are considered as shown in Fig. 4 (Ref. 5). In the single-port engine a laser-collecting mirror also serves as the rocket thrust chamber and nozzle. The laser beam is focused into the thrust chamber where the propellant is heated up to plasma state by laser energy absorption. This method is the simplest but it suffers from stringent limitation of laser incident angle. In order to avoid this problem one must separate the absorption chamber from the focusing mirror. This method requires an aerodynamic window which is the only way to orient the laser beam into absorption chamber without passing through a solid transparent window. There is no existing material permeable to such high power laser beam without damage. This sort of aerodynamic window is valid as long as the flowing Mach number keeps 2.6 or higher (Ref. 6).

![Figure 4 Configuration of beam orientation to the laser propelled vehicle (Ref. 5).](image)

![Figure 5 Laser range versus laser wavelength with the parameter of a product of transmitter/receiver diameters (Ref. 7).](image)

**NAVIGATION, GUIDANCE AND CONTROL**

There are three phases of vehicle acceleration, an electromagnetic catapult pushing to a near transonic speed, laser powered air-breathing ramjet during the lower atmosphere flight, and laser rocket propulsion through the upper atmosphere. For this purpose, an optimal flight path calculation should be conducted.
including the max Q (maximum dynamic pressure) and the allowable aerodynamic heating. Surprisingly the long range laser beaming technology seems to be easier than anticipated, because the sufficient accuracy of beam orientation is expected by simply tracking a small guide-laser beam from the vehicle.

However, as shown in Fig. 5, the product of laser transmitting and receiving diameters has an upper limit due to the beam divergence (Ref. 7). To the contrary, this value should be smaller than $10^3$ from the realistic demands of the vehicle dimension as well as the scale of laser transmitter facility. In general the short laser wavelength is advantageous for transmission in the vacuum space. But it is not necessarily correct answer to choose ultraviolet or visible wavelength when the laser beam is transmitted from the ground station to the vehicle in the upper atmosphere. We must pay attention to the absorption by the cloud, the fog, the rain-fall, Mie-scattering by the floating dust, Rayleigh-scattering by the molecules, and even potentially the induced lightning along the laser beam path. From the optical point of view the reflective index of the receiving mirror is superior in the longer wavelength. Figure 6 shows the laser transmittance through the atmosphere versus wavelength (Ref. 8).

Based upon these discussions, it is found important for the laser direct launch that the down-range of flight path should be shorter than 3,000 km. In this flight-path calculation we used a typical winged-body vehicle as shown in Fig. 7 of which aerodynamic coefficients are known (Ref. 9). A standard atmospheric model shown in Fig. 8 was adopted for the temperature and density prediction as a function of flight altitude. The following assumptions are also incorporated.
a) Laser power is 200 MW,
b) Thrust efficiency of laser propulsion is 50 % constant,
c) Lift-off weight is 2 tons,
d) Target orbit is 500 km circular one,
e) Electromagnetic catapult is 3 km in length and capable of injection Mach number unity with the lift-up angle 5°,
f) Basic equations are summarized below.

\[ C_L = 0.6 \times 9 \alpha / \pi \]  
\[ C_D = 0.0076885 + 1.2312 C_L^2 \]  
\[ \alpha = \delta - \gamma \]  
\[ \gamma = \tan^{-1} \left( \frac{w}{u} \right) \]  
\[ V^2 = u^2 + w^2 \]  
\[ \frac{dh}{dt} = u \]  
\[ \frac{d\theta}{dt} = \frac{u}{r_o + h} \]  
\[ \frac{dn}{dt} = \rho A_w V \cos \alpha - \dot{m} \]  
\[ F = \left( 2 \eta P \dot{m} \right)^{1/2} \]  
\[ \dot{m} = \max \left( \rho A_w V \cos \alpha, \frac{2 \eta P}{\left( \frac{g_0 \text{Isp}}{2} \right)^2} \right) \]  
\[ \frac{du}{dt} = -\frac{S_w}{2n} \rho V (C_L u + C_D w) - w \frac{d\theta}{dt} n \cos \delta \]  
\[ \frac{dw}{dt} = \frac{S_w}{2n} V \left( C_L u - C_D w \right) - g_0 \left( \frac{r_o}{r_o + h} \right)^2 + u \frac{d\theta}{dt} n \sin \delta \]  
\[ Q_{\text{max}} = \left( \frac{1}{2} \rho V^2 \right) \max \]  
\[ q = 1.1 \times 10^9 \text{ R}^{-1/2} \left( \frac{\rho}{\rho_0} \right)^{1/2} \left( \frac{V}{7.925 \times 10^3} \right)^{3.15} = \epsilon \sigma T_w^4 \]  

Figure 8 Assumption of model.

Figure 9 shows the results for a long down-range (3,000 km) and a short down-range (1,500 km). In both cases the air-breathing to rocket mode conversion takes place at an altitude of about 41 km, however, the reduction of down-range resulted in the decrease of orbiter weight. For 3,000 km down-range the orbiter weight is 1,000 kg while it is reduced to 880 kg for 1,500 km down-range. The vehicle encounters the maximum dynamic pressure of 800 kPa and the maximum aerodynamic heating temperature of 1,800 K. These values are allowable to the existing vehicles except for the unrealistic assumption of 100 % thermal efficiency of laser propulsion (cf. 50 % thrust efficiency). Although these calculation are not yet fully optimized for the minimum propellant consumption, they suggest a compromise between the optimal flight-path and the possible laser range. A multi-laser-station placed along the flight down-range may improve the shortage of laser range to some extent.
Figure 9 Standard atmosphere model for density and temperature.

Figure 10 Calculated flight-path for long down-range 3,000 km with multi-laser-station (upper) and short range 1,500 km with single-laser-station (lower).

LASER LIGHT SOURCE

As a multi-megawatt laser light source, we can expect a CO₂ laser, a free-electron laser, and a solar pumped laser. For CO₂ laser, AVCO corporation in the US once proposed a cost estimation of $150M per 10MW laser station construction (Ref. 1). However, the far-infrared wavelength of 10.6 μm and the upper limitation of theoretical efficiency 40 % are remained as the problem. A 10 MW free-electron laser in Los Alamos National Laboratory (Ref. 10) is working now and promising, because this is a tunable laser and higher efficiency is expected in the near future by recovering the
dumped electron beam. A solar pumped laser has the possibility of high conversion efficiency, however, it inherently depends upon the concurrent weather namely the daylight, and hence this type of laser would rather be suitable to the power station in space.

Here we propose another look of the semiconductor laser for future application. This type of laser possesses excellent efficiency higher than 50% and covers almost all the wavelength from visible to near-infrared region. Figure 10 depicts a prospective application of such semiconductor laser array to the 235 MW laser power station in space. This concept was presented from NASA Langley Research Center in 1989 (Ref. 11). In this power satellite, one million semiconductor laser are integrated through three-staged amplification in series. The technical problem of smiconductor laser is its small power output of about 1 W per one chip. This value is determined by the cooling capability of the substrate which is often made of artificial diamond. Recent Japanese technology developed so-called a surface emitting semiconductor laser which is a large-scale integrated diode laser array. If we select the wavelength of laser propulsion as near-infrared, which is possible as shown in Fig. 6, we may expect mass production for a ground based laser station and technological spin-off from the optical communication market.

![Diagram of NASA Langley Research Center](image)

**Figure 11** Large-scale integrated 235 MW semiconductor laser power satellite (Ref. 11).

**CONCLUDING REMARKS**

The concept of laser direct launch by ground based power station is a peaceful and ecological proposal. In this study we have clarified the major technological problems and simultaneously pointed out that they are within the range of our capability. A sample calculation suggested that 200 MW laser will inject a 1 ton air-breathing orbiter into 500 km LEO (Low Earth Orbit). A lot of interesting tasks are remained unresolved in this feasibility study. The flight-path calculation must involve the stability of laser sustained combustion wave. It must be examined that the exhaust of laser plasma does not generate NOx or harmful chemical products. The
laser ranging of 3,000 km and series amplification of semiconductor laser are to be verified. However, it is most important that a small scale laser-driven vehicle is demonstrated as soon as possible.

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REFERENCE