Laser Propelled Hypersonic Air-Vehicle

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Abstract

Laser propulsion is a concept in which energy of a thrust producing reaction mass is supplied via beamed energy from an off-board or on-board power source. A variety of laser/beamed energy concepts were theoretically and experimentally investigated since early 1970s. Laser propulsion offers the advantage of both high thrust and high specific impulse; $I_{SP}$ in excess of 1000s. Other advantages are the simplicity and reliability of the engine set-up, because of fewer moving parts, simpler propellant feed system, and high specific impulse. Another major advantage is the reduction in pollution as the major propellant used can be hydrogen, air or water vapor. In this paper we explore the futuristic concept of use of laser propulsion as a main propulsion mechanism for air-vehicles. The thrust is obtained by formation of a Laser Sustained Detonation (LSD) wave of plasma. The vertical thrust is produced by an off-board Repetitive-Pulsed (RP) laser whereas the forward thrust is produced by an On-Board Continuous Wave (CW) laser producing unit. The flight attitude is controlled by the conventional primary flight controls. The possible design of the propulsion units has also been discussed in the paper. There are 3 parabolic retractable reflectors attached on the lower surface of the air-craft- one below the nose and the other to below the main planes. This will provide a sufficient track area as well as stability during take off. The concept of parabolic reflectors has been deduced from the experimental Lightcraft concepts. On each of these retractable parabolic reflecting nozzles, a laser is fired producing high intensity radiation, which is sufficient to cause an electrical breakdown of a small propellant (air) volume creating a high temperature rapidly expanding plasma. This plasma closely resembles a supersonic blast wave and rapidly exits a supersonic nozzle which gives a high speed vertical lift-off. The speed of the lift-off thrust can be controlled by controlling the intensity and power of the laser incident on the reflectors. The method involved here, for obtaining thrust from this propulsion setup is that, the laser intensity is focused into a gas (air) near the solid surface in order to breakdown the gas (air) and induce a detonation wave transferring momentum to the surface.

Introduction

Advanced propulsion for the 21st century include the use of beamed energy such as ground based or on-board lasers to provide thrust to a air-vehicle, propelled by a laser induced blast wave. Laser propulsion offers the advantage of both high thrust and theoretically infinite specific impulse $I_{SP}$ at altitudes less than 20 km. Other advantages are simplicity and reliability of the engine because of fewer moving parts, simpler propellant feed system and high specific impulse. Major limitations of this approach are the laser power available, absorption and distortion of the pulsed laser during the vertical take-off and coupling laser power into thrust throughout the flight envelope. The mission requirements are the formation and propagation of the Laser Sustained Detonation Wave and inlet air replenishment. The concept of laser propulsion originates to at least 1972 and is accredited to Kantrowitz.

In our proposed setup there are three parabolic retractable reflectors attached on the lower surface of the air-craft- one below the nose and the other to below the main planes. This will provide a sufficient track area as well as stability during take off. The concept of parabolic reflectors has been deduced from the experimental Lightcraft concepts. On each of these retractable parabolic reflecting nozzles, a laser is fired producing high intensity radiation, which is sufficient to cause an electrical breakdown of a small propellant (air) volume creating a high temperature rapidly expanding plasma. This plasma closely resembles a supersonic blast wave and rapidly exits a supersonic nozzle which gives a high speed vertical lift-off. The speed of the lift-off thrust can be controlled by controlling the intensity and power of the laser incident on the reflectors. The method involved here, for obtaining thrust from this propulsion setup is that, the laser intensity is focused into a gas (air) near the solid surface in order to breakdown the gas (air) and induce a detonation wave transferring momentum to the surface.

For the forward thrust, in the proposed setup, a concave reflecting surface is provided with laser focusing components, preferably optical pipes. An intense laser source is provided on-board the air-vehicle, preferably a high power CO$_2$ laser. In this Continuous Wave (CW) laser thruster, CW laser is focused onto the concave reflecting
surface in a way that, the CW laser from each focusing unit gets reflected back to meet at the focus, of the concave reflector, just outside the cavity enclosed the concave reflector. At the focus the laser intensity is absorbed by the propellant gas (air). This again causes an electrical breakdown of the propellant (air) volume creating high temperature rapidly expanding plasma. The plasma resembling a high speed supersonic blast wave imparts an enormous thrust over the reflector surface; thus imparting momentum to the surface, in turn transferring momentum to the air-vehicle itself.

According to Raizer, the initial absorption wave of the laser source, in a stagnant gas produces electrical breakdown and propagation of a blast or Laser Supported Detonation (LSD) wave. According to Pirri for this propulsion setup:

$$V_{LSD} = [2(\gamma^2-1) \{T/\rho_0\}]^{1/3}$$  

Where, \( L \) is the initial length of the plasma, \( V_{LSD} \) is the detonation velocity and \( t_p \) is the laser pulse duration. In this plasma zone, the laser beam energy is absorbed into the gas and \( L \) is proportional to the electron mean free path. According to Pirri, the initial absorption wave or Laser Supported Detonation (LSD) wave velocity is given by:

$$V_{LSD} = (\rho_0 V_{LSD})^2 / (\gamma+1)$$  

The specific impulse is given by Simmons and Pirri for this propulsion set up:

$$I_{sp} \approx \left[ (u_0) \right]^{1/2} \left[ \frac{E}{(M^{1/4} (\gamma-1) D^*)} \right]$$  

Where \( u_0 \) is the gas sonic injection velocity in the thrust cavity, \( E \) is the total laser energy deposited, \( D^* \) is the nozzle throat diameter, \( t_p \) is the time between the pulses, \( M \) is the propellant (air) molecular weight and \( t_i \) is the ignition time of the blast wave.

Coming to the horizontal thrust producing unit, the moment-coupling co-efficient is given by:

$$C_m = F/ P_{laser}$$  

Where \( F \) is the thrust generated and \( P_{laser} \) is the laser accumulated at focus of the concave reflector.

Now specific impulse given by Yabe and Uchida is:

$$I_{sp} = (\int F dt) / (g_0 \int m^* dt) = v_p / g_0$$  

Where \( m^* \) and \( g_0 \) are the propellant mass flow rate and gravity constant respectively, and \( v_p \) is
the velocity of propulsion. Combining the expressions for moment-coupling co-efficient and the specific impulse, we get:

\[ I_{SP}C_m = \frac{(v_pF)}{(g_0E_{LASER})} \]  

(9)

Now, \( F = m.v_p \), Therefore, \( I_{SP}C_m = \left[ 2\left(\frac{1}{2}m.v_p^2\right) / (g_0E_{LASER}) \right] \)

\[ => I_{SP} = \frac{1}{C_m} \frac{2(E_{PROP}/E_{LASER})}{2} \]

(10)

where \( E_{PROP} \) and \( E_{LASER} \) is the kinetic energy of the exhausted propellant (air) and kinetic energy of the laser, respectively. According to calculations from P.K. Wu’s work, we get that the total heat transferred to the reflector wall in a depth \( L \) of the reflector cavity, is given by:

\[ Q = 3.5 Hu\mu mL \]  

(11)

Where \( H, u \) and \( \mu \) are the stream total enthalpy, velocity and viscosity respectively; \( m \) is the mass flow in the space enclosed in the reflector cavity; and \( L \) is the depth of the cavity. The co-efficient 3.5 comes from Wu’s limited boundary layer calculations.

**Suggested Design for the Vertical Thrust Producing Components**

Retractable Parabolic Reflector below the Wing Assembly

Retractable Parabolic Reflector below the Nose

The suggested structure of this component basically consists of a retractable parabolic reflector. The reflector used of is high strength and coated with a solid propellant for initial ignition by inverse bremsstrahlung effect. The solid propellants, with low ionization potential, that can be used are lead or vanadium.

The equation for this relation in units of inches is obtained from Douglas Feikema’s:

\[ z(y) = 1.9504y - 0.4564y^2 \]  

(12)

The following figure shows optical system perfectly focused with traced rays in three dimensional perspectives:

The graph below shows the relation between specific impulse and energy conversion efficiency (defined as the ratio of the exhaust kinetic energy per pulse to the laser energy per pulse) obtained with self-focusing parabolic nozzle, with argon and hydrogen propellants, and a back ground environment of \( 10^{-4} \) atm.
Suggested Design for the Horizontal Thrust Producing Components

The suggested design for this unit consists mainly of three units:
- The On-Board Laser Producing Unit
- The Reflecting Concave Surface
- The Projection Unit for the Laser

1. On-Board Laser Producing Unit:
   This unit comprises any modern Laser Production Mechanism. The required power is almost 100 MW of continuous wave laser. This unit can be placed in the fuselage of the design.

2. The Concave Reflecting Surface:
   This unit is basically a highly reflecting surface. This surface is also made very strong so as to absorb the thrust of the plasma explosion and to transfer the momentum to the craft, without failing throughout the flight envelope. The approximate surface area of this surface can be made to be around 250m$^2$.

3. The Projection Unit for the Laser:
   This unit comprises of either optical fibers or optical pipes. They are arranged in a way that they focus the laser on the concave surface parallel to the principle axis. As a result the laser intensity is made to converge at the focus.

The thruster performance map; relating mass flow rate $m$, thrust $F$, specific impulse $I_{sp}$, and exhaust gas power $P_G$ is provided below:
3-View Schematic

FRONT VIEW

SIDE VIEW

TOP VIEW
Conclusion

The concept of Laser-Propulsion is the future of the aviation industry. With the fast degeneration of fossil fuels from our planet, this propulsion mechanism promises a much reduced and more efficient usage of the fuel. It can also fulfill man’s dream to cross cosmic limits at lesser risks and cost. Till date Laser-Propulsion has only been considered for space transportation; but in this paper the application of this propulsion mechanism in for flight within the earth’s atmosphere has been enlightened. This is mainly owing to the fact that Laser-Propulsion can use atmospheric air as its propellant till an altitude of approximately 60,000 feet.

The complete unit with suggested working mechanisms has been discussed. There are a number of areas where further research is needed before this design along with its propulsion mechanism can be materialized.

References

[1] Kantrowitz, A., “Propulsion to Orbit by Ground Based Lasers”

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