LASER APPLICATIONS

PACS numbers: 42.55.Lt; 42.62.Cf; 43.28.Mw
DOI: 10.1070/QE2007v037n08ABEH013361

Laser air-jet engine: the action of shock waves at low laser pulse repetition rates

V.V. Apollonov, V.N. Tishchenko

***Abstract*. The impact and thermal action of laser sparks on the reflector of a laser engine in which the propulsion is produced by repetitively pulsed radiation is estimated. It is shown that for a low pulse repetition rate, the thermal contact of a plasma with the reflector and strong dynamic resonance loads are inevitable. These difficulties can be surmounted by using the method based on the merging of shock waves at a high pulse repetition rate.**

Keywords: *laser air-jet engine, repetitively pulsed laser radiation, laser sparks, shock waves.*

A laser air-jet engine (LAJE) uses repetitively pulsed laser radiation and the atmospheric air as a working substance [1 – 4]. In the tail part of a rocket a reflector focusing radiation is located. The propulsion is produced due to the action of the periodic shock waves produced by laser sparks on the reflector. The laser air-jet engine is attractive due to its simplicity and high efficiency. It was pointed out in papers [3, 4] that the LAJE can find applications for launching space crafts if $\sim$ 100-kJ repetitively pulsed lasers with pulse repetition rates of hundreds hertz are developed and the damage of the optical reflector under the action of shock waves and laser plasma is eliminated. These problems can be solved by using high pulse repletion rates ($f \sim 100$ kHz), an optical pulsed discharge, and the merging of shock waves [5, 6]. The efficiency of the use of laser radiation in the case of short pulses at high pulse repetition rates is considerably higher. It is shown in this paper that factors damaging the reflector and a triggered device cannot be eliminated at low pulse repetition rates and are of the resonance type.

Let us estimate the basic LAJE parameters: the forces acting on a rocket in the cases of pulsed and stationary acceleration, the wavelength of compression waves excited in the rocket body by shock waves, the radius R_k of the plasma region (cavern) formed upon the expansion of a laser spark. We use the expressions for shock-wave parameters obtained by us. A laser spark was treated as a spherical region of radius r_0 in which the absorption of energy for the time ~ 1 μs is accompanied by a pressure jump of the order of tens and hundreds of atmospheres. This is valid for the LAJE in which the focal distance and diameter of a beam on the reflector are comparable and the spark length is small. The reflector is a hemisphere of radius R_r. The frequency f is determined by the necessity of replacing hot air in the reflector by atmospheric air.

Let us estimate the excess of the peak value F_m of the repetitively pulsed propulsion over the stationary force F_s upon accelerating a rocket of mass M. It is obvious that $F_s = Ma$, where the acceleration $a = (10 - 20)g_0 \approx 100 - 200$ m s^{-2}. The peak value of the repetitively pulsed propulsion is achieved when the shock-wave front arrives on the reflector. The excess pressure in the shock wave (with respect to the atmospheric pressure P_0) produces the propulsion $F_i(t)$ and acceleration a of a rocket of mass M. The momentum increment produced by the shock wave is

$$\delta p_i = \int_0^{1/f} F_i(t)\mathrm{d}t \simeq F_a t_a \ [\mathrm{N \cdot s}]. \quad (1)$$

Here, F_a is the average value of the propulsion for the time t_a of the action of the compression phase of the shock wave on the reflector, and $F_m \approx 2F_a$. By equating δp_i to the momentum increment $\delta p_s = F_s/f = aM/f$ over the period under the action of the stationary propulsion F_s, we find

$$\varDelta = F_m/F_s = 2/(f t_a).$$

The value of $\varDelta$, as shown below, depends on many parameters. The momentum increment per period can be expressed in terms of the coupling coefficient J as $\delta p_i = JQ$, where Q [J] is the laser radiation energy absorbed in a spark. The condition $\delta p_i = \delta p_s$ gives the relation

$$W = aM/J \quad (2)$$

between the basic parameters of the problem ($W = Qf$ is the absorbed average power of repetitively pulsed radiation, and $J \approx 0.0001 - 0.0012$ N s J^{-1} [3, 4, 6].

The action time of the compression phase on the reflector is $t_a \sim R_c/V$, where $V \approx k_1 C_0$ is the shock-wave velocity in front of the wall ($k_1 \sim 1.2$) and $C_0 \approx 3.4 \times 10^4$ cm s^{-1} is the sound speed in air. The length R_c of the

V.V. Apollonov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: vapollo@kapella.gpi.ru;
V.N. Tishchenko Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavent'eva 13, 630090 Novosiobirsk, Russia; e-mail: tishenko@mail.nsk.ru

Received 31 July 2006
Kvantovaya Elektronika **37** (8) 798 – 800 (2007)
Translated by M.N. Sapozhnikov

shock-wave compression phase can be found from the relation

$$\frac{R_c}{R_d} = 0.26\left(\frac{h}{R_d}\right)^{0.32}. \tag{3}$$

Here, h is the distance from the spark centre to the reflector surface and $R_d \approx 2.15\,(Q/P_0)^{1/3}$ is the dynamic radius of the spark (distance at which the pressure in the shock wave becomes close to the air pressure P_0). In this expression, R_d is measured in cm and P_0 in atm. The cavern radius can be found from the relation

$$\frac{R_k}{R_d} = 0.6\left(\frac{r_0}{R_d}\right)^{0.29} = 0.22 - 0.3 \approx 0.25. \tag{4}$$

Final expression (4) corresponds to the inequality $r_0/R_d < 0.03 - 0.1$, which is typical for laser sparks (r_0 is their initial radius). Let us find the range of P_0 where the two conditions are fulfilled simultaneously: the plasma is not in contact with the reflector surface and the coupling coefficient J is close to its maximum [3, 4, 7]. This corresponds to the inequality $R_k < h < R_d$. By dividing both parts of this inequality by R_d, we obtain $R_k/R_d < h/R_d < 1$, or $0.25 < h/R_d < 1$. As the rocket gains height, the air pressure and, hence, h/R_d decrease. If we assume that at the start ($P_0 = 1$ atm) the ratio $h/R_d = 1$, where h and R_d are chosen according to (2), then the inequality $0.25 < h/R_d < 1$ is fulfilled for $P_0 = 1 - 0.015$ atm, which restricts the flight altitude of the rocket by the value 30–40 km ($h =$ const).

The optimal distance h satisfies the relation $h/R_d \approx 0.25 b_i$, where $b_i \approx 4 - 5$. By substituting h/R_d into (3), we find the length of the shock-wave compression phase and the time of its action on the reflector:

$$\frac{R_c}{R_d} \approx 0.17 b_i^{0.32}, \tag{5}$$

$$t_a = \frac{0.17 b_i^{0.32} R_d}{k_1 C_0} = \frac{s_1 Q^{1/3}}{P_0^{1/3}} = \frac{s_1}{P_0^{1/3}}\left(\frac{aM}{Jf}\right)^{1/3}, \tag{6}$$

where $s_1 = 0.37 b_i^{0.32}/(k_1 C_0) \approx 9 \times 10^{-6} b_i^{0.32}$. From this, by using the relation $\Delta = F_m/F_a = 2/(f t_a)$ we find

$$\Delta = \frac{2P_0^{1/3}}{s_1 f^{2/3} W^{1/3}} = \frac{2P_0^{1/3} Q^{2/3} J}{s_1 aM} = \frac{2}{s_1 f^{2/3}}\left(\frac{P_0 J}{aM}\right)^{1/3}. \tag{7}$$

Of the three parameters Q, W, and f, two parameters are independent. The third parameter can be determined from expression (2). The conditions $1/f \sim t_a$ and $\Delta \approx 1 - 2$ correspond to the merging of shock waves [5].

The important parameters are the ratio of t_a to the propagation time $t_z = L/C_m$ of sound over the entire rocket length L (C_m is the sound speed in a metal) and the ratio of t_z to $1/f$. For steel and aluminum, $C_m = 5.1$ and 5.2 km s^{-1}, respectively. By using (6), we obtain

$$U = \frac{t_a C_m}{L} = \frac{s_1 C_m}{L P_0^{1/3}} Q^{1/3}. \tag{8}$$

Here, L is measured in cm and C_m in cm s^{-1}. Expression (8) gives the energy

$$Q = \frac{35.4 P_0}{b_i^{0.96}}\left(U\frac{C_0}{C_m}\right)^3 L^3. \tag{9}$$

From the practical point of view, of the most interest is the case $U \gg 1$, when the uniform load is produced over the entire length L. If $U \ll 1$, the acceleration is not stationary and the wavelength of the wave excited in the rocket body is much smaller than L. If also $C_m/f \ll L$, then many compression waves fit the length L. The case $U \approx 1$ corresponds to the resonance excitation of the waves. Obviously, the case $U \leqslant 1$ is unacceptable from the point of view of the rocket strength.

By using the expressions obtained above, we estimate Δ, U, and R_k for laboratory experiments and a small-mass rocket. We assume that $b_i = 4$, $J = 5 \times 10^{-4}$ N s J^{-1}, and $s_1 = 1.4 \times 10^{-5}$. For the laboratory conditions, $M \approx 0.1$ kg, $R_r \approx 5$ cm, $L = 10$ cm, and $a = 100$ m s^{-2}. The average value of the repetitively pulsed propulsion F_{IP} is equal to the stationary propulsion, $F_{IP} = F_s = 10$ N; the average power of repetitively pulsed radiation is $W = F_{IP}/J =$ 20 kW, and the pulse energy is $Q_p = W/f$. We estimate the frequency f and, hence, $Q_p \approx Q$ for the two limiting cases.

At the start, $P_0 \approx 1$ atm and the cavern radius R_k is considerably smaller than R_r. Here, as in the unbounded space, the laser plasma is cooled due to turbulent thermal mass transfer. For $Q_p < 20$ J, the characteristic time of this process is 2–5 ms [8, 9], which corresponds to $f = 500 - 200$ Hz. If $R_k \sim R_r$ ($P_0 < 0.1$ atm), the hot gas at temperature of a few thousands of degrees occupies the greater part of the reflector volume. The frequency f is determined by the necessity of replacing gas over the entire volume and is $\sim 0.5 C_0/R_r \sim 850$ Hz [3, 4]. Let us assume for further estimates that $f = 200$ Hz, which gives $Q_p = 100$ J. We find from (7) and (8) that $\Delta = 74$ and $U = 3.5$. This means that the maximum dynamic propulsion exceeds by many times the propulsion corresponding to the stationary acceleration. The action time of the shock wave is longer by a factor of 3.5 than the propagation time of the shock wave over the model length. For $P_0 = 1$ and 0.01 atm, the cavern radius is $R_k = 2.5$ and 11.6 cm, respectively.

Let us make the estimate for a rocket by assuming that $M \approx 20$ kg, $R_r \approx 20$ cm, $L = 200$ cm, and $a = 100$ m s^{-2}. The average repetitively pulsed propulsion is $F_{IP} = F_s =$ 2000 N, the average radiation power is $W = 4$ MW, for $f = 200$ Hz the pulse energy is $Q_p = 20$ kJ, $\Delta = 12.6$, $U = 1$, $R_k = 14.7$ and 68 cm ($P_0 = 1$ and 0.01 atm), and $F_m = 25.6$ kN $= 2560$ kg. One can see that the repetitively pulsed acceleration regime produces the dynamic loads on the rocket body which are an order of magnitude greater than F_s. They have the resonance nature because the condition $U \sim 1$ means that the compression wavelengths are comparable with the rocket length. In addition, as the rocket length is increased up to 4 m and the pulse repetition rate is increased up to 1 kHz, the oscillation eigenfrequency C_m/L of the rocket body is close to f (resonance).

Thus, our estimates have shown that at a low pulse repetition rate the thermal contact of the plasma with the reflector and strong dynamic loads are inevitable. The situation is aggravated by the excitation of resonance oscillations in the rocket body. These difficulties can be eliminated by using the method based on the merging of shock waves [4, 5]. Calculations and experiments [10] have confirmed the possibility of producing the stationary propulsion by using laser radiation with high pulse repetition rates. The method of scaling the output radiation power is presented in [11].

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 06-08-01192).

References

1. Kantrowitz A.R. *Astronautics and Aeronautics*, **10** (5), 74 (1972).
2. Pirry A.N., Monsler M., Nebolsain R. *Raket. Tekh. Kosmonavt.*, **12,** 112 (1974).
3. Ageev V.P., Barchukov A.I., Bunkin F.V., Konov V.I., Prokhorov A.M., Silenok A.S., Chapliev N.I. *Kvantovaya Elektron.*, **4**, 2501 (1977) [*Sov. J. Quantum Electron.*, **7**, 1430 (1977)].
4. Bunkin F.V., Prokhorov A.M. *Usp. Fiz. Nauk*, **119**, 425 (1976).
5. Tishchenko V.N., Apollonov V.V., Grachev G.N., Gulidov A.I., Zapryagaev V.I., Men'shikov Ya.G., Smirnov A.L., Sobolev A.V. *Kvantovaya Elektron.*, **34**, 941 (2004) [*Quantum Electron.*, **34**, 941 (2004)].
6. Apollonov V.V., Tishchenko V.N. *Kvantovaya Elektron.*, **34**, 1143 (2004) [*Quantum Electron.*, **34**, 1143 (2004)].
7. Korobeinikov V.P. *Zadachi teorii tochechnogo vzryva* (Problems of the Theory of Point Explosions) (Moscow: Nauka, 1985).
8. Kabanov S.N., Maslova L.I., Tarkhova T.I., Trukhin V.A., Yurov V.T. *Zh. Tekh. Fiz.*, **60**, 37 (1990).
9. Tishchenko V.N., Antonov V.M., Melekhov A.V., Nikitin S.A., Posukh V.G., Tret'yakov P.K., Shaikhislamov I.F. *Pis'ma Zh. Eksp. Teor. Fiz.*, **22**, 30 (1996).
10. Grachev G.N., Tishchenko V.N., Apollonov V.V., Gulidov A.I., Smirnov A.L., Sobolev A.V., Zimin M.I. *Kvantovaya Elektron.*, **37**, 669 (2007) [*Quantum Electron.*, **37**, 669 (2007)].
11. Apollonov V.V., Egorov A.B., Kiiko V.V., Kislov V.I., Suzdal'tsev A.G. *Kvantovaya Elektron.*, **33**, 753 (2003) [*Quantum Electron.*, **33**, 753 (2003)].