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Stationary force production: experimental and theoretical investigations

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Abstract: Basic characteristics of the laser-based engine are compared with theoretical predictions and important stages of further technology implementation are investigated under low frequency resonance. Relying on a wide cooperation of different branches of science and industry organizations, it is very possible to use the accumulated potential for launching nano-vehicles during the upcoming years.

Key words: optical pulsating discharge; laser engine; shock waves; propulsion

稳态力输出的实验与理论研究

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摘要:对低频共振情况下激光引擎的基本特性与其理论预测值做了比较,并研究了实现这些技术的重要步骤,认为基于不同学科与工业组织之间的合作,不久的将来会实现利用累计势能来驱动微型汽车。

关 键 词:光学脉冲放电;激光引擎;冲击波;推进

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1 Introduction

Up to now the possibility of using a laser engine to launch light satellites into orbit looks like a very attractive idea for world wide spectrum of researchers[1-9]. The solution of problems considered in Ref. [3] is still of current interest. This is an increase in the efficiency—the coupling coefficient J_r of using laser radiation (the ratio of the propulsion to the radiation power) by several times and the prevention of the shock damage of the apparatus, which appears when high-power repetitively pulsed laser radiation with low repetition rates is used. For example, for $J_r \sim 0.3$ kN/MW (this value is typical for an air-jet laser engine), the mass of 200 kg, and the acceleration of 10 g, the required laser power should be ~ 60 MW (the energy Q ~ 100 g in the TNT equivalent, f ~ 100 Hz), and the power of a power supply should be 0.5 - 1 GW. However, it seems unlikely that such a laser will be created in the near future. In our experiments, $J_r \sim 1$ kN/MW (obtained

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experimentally) and 3 – 5 kN/MW(estimated, special conditions), which allows us to reduce the laser power by a factor of 3 – 10. A power of 10 – 15 MW can be obtained already at present with the help of gas-dynamic lasers by using the properties of repetitively pulsed lasing with high repetition rates and methods for power scaling of lasing[10,11].

To solve these problems, it was proposed to use repetitively pulsed radiation with $f\sim 100$ kHz, the Optical Pulsating Discharge(OPD), and the effect of merging of shock waves produced by the OPD[12 – 14]. The merging criteria were confirmed in experiments[15]. The OPD is laser sparks in the focus of repetitively pulsed radiation, which can be at rest or can move at high velocities [16 – 20]. The high frequency repetitively pulsed regime is optimal for continuously-pumped Q-switchedhigh-power lasers. In this case, the pulse energy is comparatively small and the stationary propulsion is possible. The aim of our paper is to verify experimentally the possibility of using laser radiation with a high pulse repetition rate to produce the stationary propulsion in a laser engine.

2 Experiments

In the model considered in Ref. [12 – 14], the pulsed and stationary regimes are possible. Fig. 1 explains the specific features of these regimes. An OPD is produced at the focus of a lens on the axis of a gas jet flowing from a high-pressure chamber or an air intake to a cylindrical reflector. The shock waves generated by the OPD merge to form a quasi-stationary wave-high-pressure region between the OPD and reflector.

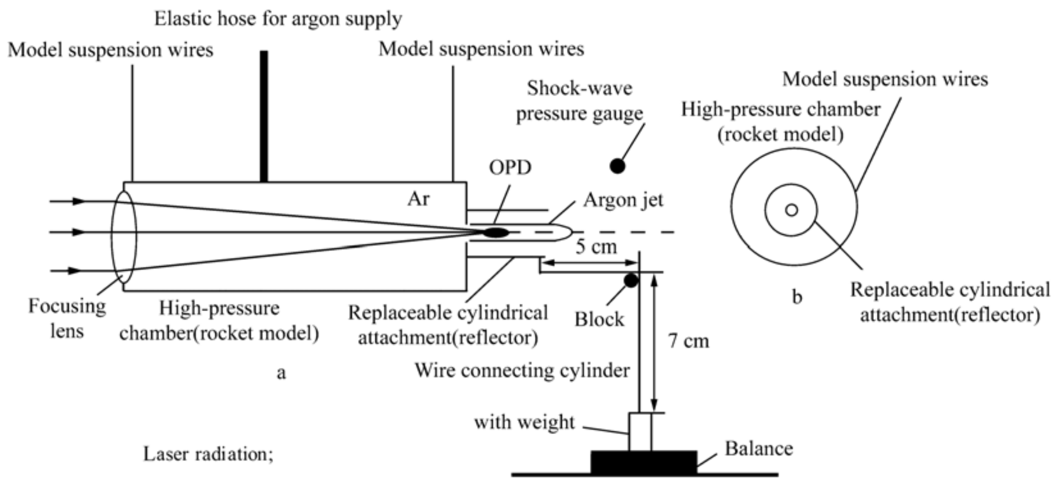

Fig. 1 Scheme of the experiment side(a) and front(b) view.

As a result, the propulsion F_r appears. In a cylindrical reflector, the coupling coefficient is maximal, $J_r = 1.1$ N/kW[13], as for a plane explosion[21]. In the pulsed regime, the OPD is produced by trains of laser pulses. A narrow jet of diameter $D_j \sim 0.3\ R_d$[13], which is smaller than the reflector diameter D_r, carries a plasma out from the OPD region, which is necessary for the efficient formation of shock waves. Here, $R_d = 2.45\ (q/p_0)^{1/3}$ is the dynamic radius of a spark, q(in J) is the laser pulse energy absorbed in a spark, and p_0(in Pa) is the gas pressure. The propulsion acts during a pulse train, whose duration is limited by the air heating time. The hot atmospheric air is replaced by the cold air during the interval pulses. In the stationary regime, gas continuously arrives to the reflector from the bottom, by forming a jet over the entire section. In the experiments of this regime, we have $D_j \sim 2R_d$

~3 mm, which is comparable with the reflector diameter D_r ~5 mm.

The scheme of the experiment is shown in Fig. 1. The OPD was produced by the radiation from a pulsed CO_2 laser. The pulse duration is ~1 μs, the duration of the front peak is 0.2 μs. The pulse repetition rate is varied from 7 to 100 kHz, the pulse energy is 0.1 – 0.025 J. The peak power is 300 – 100 kW, the average power of repetitively pulsed radiation is 600 – 1700 W, and the absorbed power is $\eta W(\eta \approx 0.7)$. Fig. 2 shows the shapes of the incident pulse and the pulse transmitted through the OPD region. Note that for a short pulse duration and high power, η ~0.95. Because the radiation intensity at the focus is lower than the optical breakdown threshold in air, the argon jet was used. The length l of sparks along the flow was ~0.5 cm.

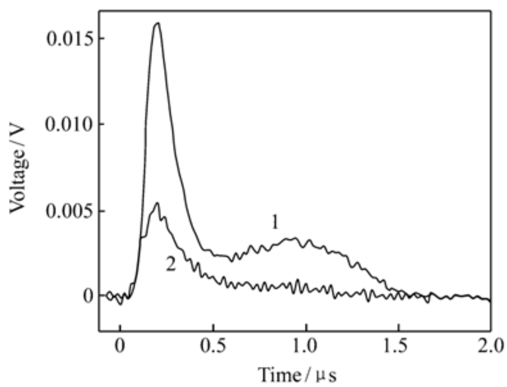

Fig. 2　Oscillograms of laser pulse (1) and radiation pulse transmitted through the OPD (2) for f = 50 kHz.

The model of a rocket with a laser engine was a duralumin cylinder of diameter ~8 cm, length ~26 cm, and weight 1.1 kg, which was suspended on four thin wires of length 1.1 m and capable of moving only in the axial direction. A reflector (replaceable cylindrical attachment) was mounted on the chamber end. Laser radiation was directed to the chamber through a lens with a focal distance of 17 cm. The argon jet was formed during flowing from a high-pressure chamber through a hole with the diameter of 3 – 4 mm. The jet velocity v was controlled by the pressure of argon, which was delivered to the chamber through a flexible hose. The force produced by the jet and shock waves was imparted with the help of a thin (diameter ~0.2 mm) molybdenum wire to a weight standing on a strain-gauge balance (accurate to 0.1 g). The wire length was 12 cm and the block diameter was 1 cm.

The sequence of operations in each experiment was as follows. A weight fixed on a wire was placed on a balance. The model was slightly deviated from the equilibrium position (in the block direction), which is necessary for producing the initial tension of the wire (~1 g). The reading F_m of the balance was fixed, then the jet was switched, and the reading of the balance decreased to F_1. This is explained by the fact that the rapid jet produces a reduced pressure (ejection effect) in the reflector. After the OPD switching, the reading of the balance became F_2. The propulsion F_r produced by the OPD is equal to $F_1 - F_2$. The pressure of shock waves was measured with a pressure gauge whose output signal was stored in a PC with a step of ~1 μs. The linearity band of the pressure gauge was ~100 kHz. The gauge was located at a distance of ~5 cm from the jet axis (see Fig. 1) and was switched on after the OPD ignition ($t = 0$). The pressure was detected for 100 ms.

Let us estimate the possibility of shock-wave merging in the experiment and the expected values of F_r and J_r. The merging efficiency depends on the parameters $\omega = fR_d/c_0$ and $M_0 = v/c_0$ ($M_0 < 1$), where c_0 is the sound speed in gas. If the distance from the OPD region to the walls is much larger than R_d and sparks are spherical or their length l is smaller than R_d, then the frequencies characterizing the interaction of the OPD with gas are:

$$\omega_0 \approx 2.5M_0, \quad (1)$$

$$\omega_1 \approx 0.8(1 - M_0), \quad (2)$$

$$\omega_2 \approx 5.9(1 - M_0)^{1.5}. \quad (3)$$

For $\omega < \omega_1$, the shock waves do not interact with each other. In the range $\omega < \omega_1 < \omega_2$, the compression phases of the adjacent waves begin to merge, this effect being enhanced as the value of ω approaches ω_2. In the region $\omega < \omega_2$, the shock waves form a quasi-stationary wave with the length greatly exceeding the length of the compression phase of the shock waves. For $\omega < \omega_0$, the OPD efficiently (up to ~30%) transforms repetitively pulsed radiation to shock waves.

In the pulsed regime, the value of M_0 in formula (1) corresponds to the jet velocity. Because shock waves merge in an immobile gas, $M_0 \approx 0$ in formulas (2) and (3). The frequencies $f = 7 - 100$ kHz correspond to $R_d = 0.88 - 0.55$ cm and $\omega = 0.2 \sim 1.7$. Therefore, shock waves do not merge in this case. In trains, where the energy of the first pulses is greater by a factor of 1.5 − 2 than that of the next pulses ($\omega \approx 2$), the first shock wave can merge. The propulsion produced by pulse trains is $F_r = J_r \eta W =$ 0.3 N, where $J_r = 1.1$ N/kW, $\eta = 0.6$, and $W \approx$ 0.5 kW.

In the stationary regime for $M_0 \sim 0.7$, the shock wave merge because $\omega > \omega_2$ ($\omega = 1.8$, $\omega_2 \approx 1.3$). A quasi-stationary wave is formed between the OPD and the cylinder bottom. The excess pressure on the bottom is $\delta p = p - p_0 \approx 25 - 50$ kPa, and the propulsion is $F_r \approx \pi(D_r2 - D_j2)\delta p/4 = 0.03 - 0.06$ kg.

3 Measurement results

3.1 Control measurements

The jet propulsions F_j and F_r and the excess pulsation pressure $\delta p = p - p_0$ were measured for the model without the reflector. We considered the cases of the jet without and with the OPD. The jet velocity

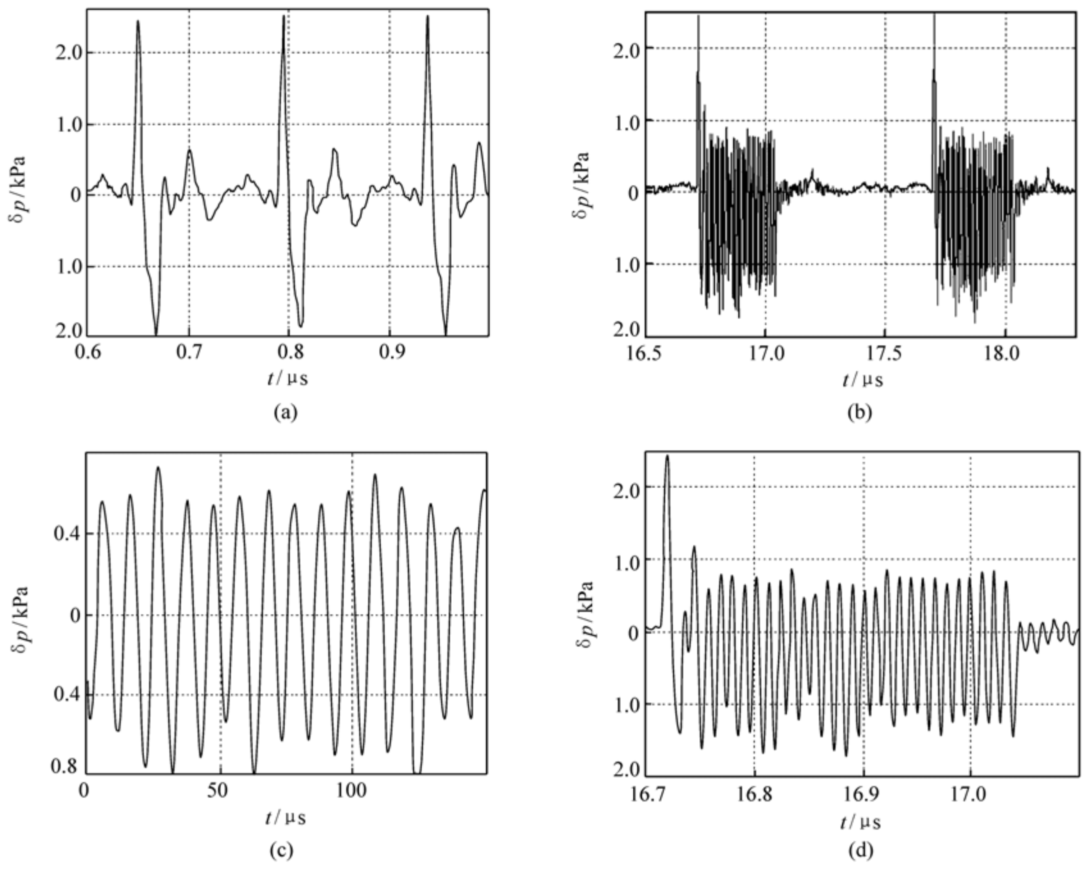

Fig. 3 Pressure pulsations produced by the OPD for $v = 300$ m/s (without reflector), $f = 7$ kHz, $W = 690$ W (a); $f = 100$ kHz, $W = 1700$ W (b), and $f = 100$ kHz, the train repetition rate $\varphi = 1$ kHz, $W = 1\,000$ W, the number of pulses in the train $N = 30$ (c); the train of shock waves at a large scale, parameters are as in Fig. 3(c)(d).

v and radiation parameters were varied. For $v = 50$, 100, and 300 m/s, the propulsion produced by the jet was $F_j = 6$, 28, and 200 g, respectively, and the amplitude of pulsations was $\delta p = 5 \times 10^{-4}$, 2×10^{-3} and 3×10^{-2} kPa. The OPD burning in the jet did not change the reading of the balance. This is explained by the fact that the OPD is located at a distance of r from the bottom of a high-pressure chamber, which satisfies the inequality $r/R_d > 2$, when the momentum produced by shock waves is small[3,22]. As follows from Fig. 3, pulsations $\delta p(t)$ produced by the OPD greatly exceed pressure fluctuations in the jet.

3.2 Stationary regime

The OPD was burning in a flow which was formed during the gas outflow from the chamber through a hole ($D_j = 0.3$ cm) to the reflector ($D_r = 0.5$ cm) (see Fig. 4). Because the excess pressure on the reflector bottom (the angle of inclination to the axis is ~30°) was ~50 kPa (see above), to avoid the jet closing, the pressure used in the chamber was set to be equal to ~200 kPa. The jet velocity without the OPD was $v = 300$ and 400 m/s, $F_j = 80$ and 140 g. The OPD was produced by repetitively pulsed radiation with $f = 50$ and 100 kHz and the average power $W \approx 1200$ W (the absorbed power was $W_a \approx 650$ W). Within several seconds after the OPD switching, the reflector was heated up to the temperature more than 100 ℃.

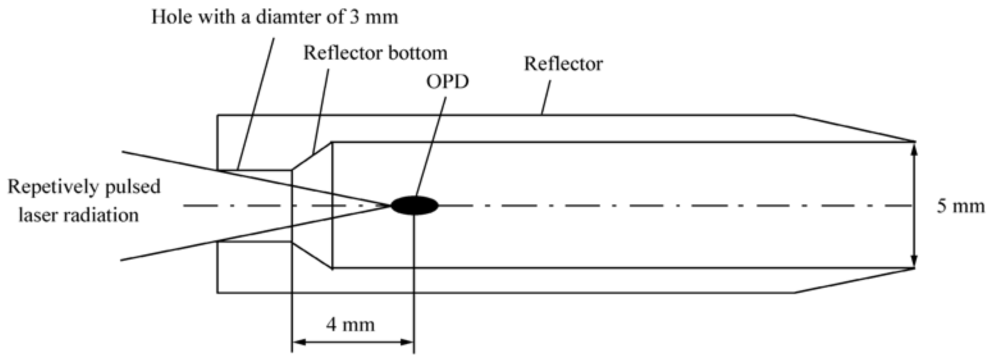

Fig. 4 Reflector of a stationary laser engine

Fig. 5 illustrates the time window for visualization of shock waves with the Schlieren system in the presence of plasma. Before 7 μs, the plasma is too bright relative to the LED source, and all information about the shock wave is lost. At 7 μs, the shock wave image could be discerned under very close examination. By 10 μs, the shock wave is clearly visible in the image. However, the shock wave has nearly left the field of view at this time. A technique was needed to resolve the shock waves at short timescales, when plasma was present.

For $f = 50$ kHz and $v = 300$ m/s, the propulsion is $F_r = 40$ g, and for $v = 400$ m/s, the propulsion is 69 g; the coupling coefficient J_r is about 1.06 N/kW. The propulsion F_r is stationary because the criteria for shock-wave merging in front of the OPD region are fulfilled. Downstream, the shock waves do not merge. One can see this from Fig. 5 demonstrating pressure pulsations $\delta p(t)$ measured outside the reflector. They characterize the absorption of repetitively pulsed radiation in the OPD and the propulsion. For $f = 50$ kHz, the instability is weak (±5%) and for $f = 100$ kHz, the modulation $\delta p(t)$ is close to 100%. The characteristic frequency of the amplitude modulation $f_a \approx 4$ kHz is close to $c_0/(2H)$, where H is the reflector length. The possible explanation is that at the high frequency f, the plasma has no time to be removed from the OPD burning region, which reduces the generation efficiency of shock waves. The jet closing can also lead

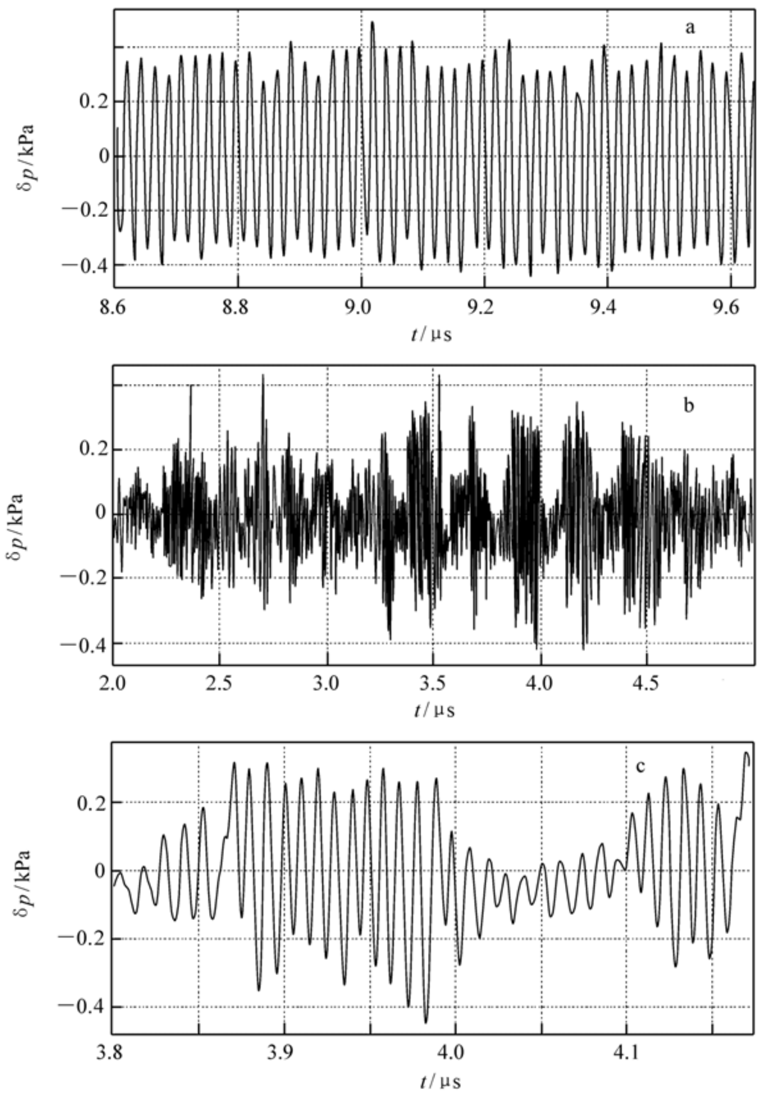

Fig. 5 Pressure pulsations δp produced upon OPD burning in the reflector with D_r = 0. 5 cm, H = 4/6 cm, v = 400 m/s, D_j = 0/3 cm for f = 50 kHz, W = 1 300 W(a) and f = 100 kHz, W = 1 200 W(b),(c).

to the same result if the pressure in the quasi-stationary wave is comparable with that in the chamber. Thus, repetitively pulsed radiation can be used to produce the stationary propulsion in a laser engine.

3.3 Pulsed regime

To find the optimal parameters of the laser engine, we performed approximately 100 OPD starts. Some data are presented in Tab. 1. We varied the diameter and length of the reflector, radiation parameters, and the jet velocity (from 50 to 300 m/s). For v = 50 m/s, the ejection effect is small, for v = 300 m/s $\approx c_0$, this effect is strong, while for $v \approx$ 100 m/s, the transition regime takes place. In some cases, the cylinder was perforated along its circumference to reduce ejection. The OPD was produced by radiation pulse trains, and in some cases-by repetitively pulsed radiation. The structure and repetition rate of pulse trains were selected to provide the replacement of the heated OPD gas by the atmospheric air. The train duration was ~1/3 of its period, the number of pulses was 15 or 30 depending on the frequency f. The heating mechanism was the action of the thermal radiation of a plasma I[23], the turbulent thermal diffusivity with the characteristic time of ~300 μs[24] and shock waves.

The propulsion F_r was observed with decreasing the reflector diameter and increasing its length. The OPD burned at a distance of ~1 cm from the reflector bottom. One can see from Fig. 6 that the shock waves produced by the first high power pulses in trains merge. For $f = 100$ kHz, the pulse energy is low, which is manifested in the instability of pressure pulsations in trains. As the pulse energy was approximately doubled at the frequency of 50 kHz, pulsations $\delta p(t)$ were stabilized. The OPD burning in the reflector of a large diameter ($D_r/R_d \approx 4$) at a distance from its bottom satisfying the relation $r/R_d \approx 3$ did not produce the propulsion.

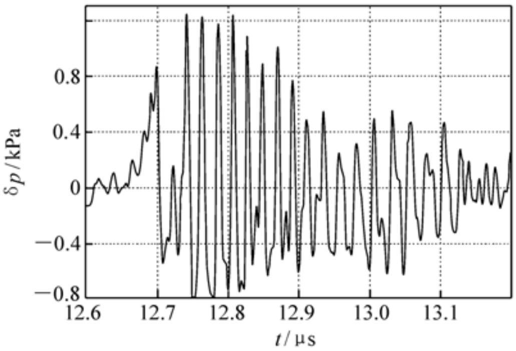

Fig. 6　Pressure pulsations δp in the OPD produced by pulse trains with $\varphi = 1.1$ kHz, $f = 50$ kHz, $W = 720$ W, $N = 15$, $v = 300$ m/s, $D_r = 1.5$ cm, $H = 5$ cm, $D_j = 4$ mm, and $F = 4.5$ g.

Tab. 1 presents some results of the measurements. One can see that the coupling coefficient J_r strongly depends on many parameters, achieving 1 N/kW in the stationary regime and 0.53 N/kW in the pulsed regime.

Tab. 1　Experimental conditions and results

f/kHz	φ/kHz	D_r/mm(H/mm)	N	v/(m·s^{-1})	W/W	F_j/g	F_r/g	J_r/(N·kW^{-1})	Reflector material
RP	5,[46]	–	300	1 300	80	40	0.61	duralumin	
RP	5,[46]	–	400	1 300	141	69	1.06	duralumin	
RP	5,[46]	–	400	1 200	155	54	1.08	duralumin	
1	15,[50]	30	300	720	49	4	0.085	duralumin	
1	15,[50]	15	50	720	0.9	2.1	0.042	duralumin	
1	15,[50]	15	300	720	49.1	4.5	0.09	duralumin	
1	15,[50]	15	50	720	1.2	1.4	0.028	duralumin*	
1	15,[50]	15	200	720	6.3	5.6	0.11	duralumin*	
1	15,[50]	15	300	720	62.7	4	0.08	duralumin*	
45	1	15,[50]	5	170	500	17.7	3.5	0.1	duralumin*
45	2	15,[50]	5	100	600	6.3	4.8	0.11	duralumin*
45	2	15,[50]	5	164	600	18.5	7.5	0.18	duralumin*
45	3	15,[50]	5	300	600	70	−4	0.095	duralumin*
12.5	RP	25,[35]	–	60	430	2.4	4	0.13	quartz
12.5	RP	25,[35]	–	100	430	5	7	0.23	quartz
12.5	RP	25,[35]	–	150	430	11	11	0.37	quartz
12.5	RP	25,[35]	–	300	430	51	16	0.53	quartz
12.5	RP	25,[35]	–	50	430	6	1	0.033	duralumin**
12.5	RP	25,[35]	–	100	430	12	7	0.23	duralumin**
12.5	RP	25,[35]	–	300	430	195	−97	−3.2	duralumin**

Note: Laser radiation was focused at a distance of 1 cm from the reflector bottom; * six holes with diameter of 5 mm over the reflector perimeter at a distance of 7 mm from its exhaust; ** six holes with diameter of 5 mm over the reflector perimeter at a distance of 15 mm from its exhaust.

At present, the methods of power scaling of laser systems and laser engines, which are also used in laboratories, are extensively developed[10,25]. Let us demonstrate their applications by examples. We observed the effect when the OPD produced the 'negative' propulsion F_t is 97 g(see Tab. 1), which corresponds to the deceleration of a rocket. The value of J_r can be increased by approximately a factor of 1.5 by increasing the pulse energy and decreasing their duration down to ~0.2 μs. An important factor characterizing the operation of a laser engine at the high-altitude flying is the efficiency I_m of the used working gas. The value $I_m = 0.005$ kg/(N·s) can be considerably reduced in experiments by using a higher-power radiation. The power of repetitively pulsed radiation should be no less than 10 kW. In this case, F_r will considerably exceed all the other forces. The gas-dynamic effects that influence the value of F_r, for example, the bottom resistance at the flight velocity ~1 km/s should be taken into account.

Thus, our experiments have confirmed that repetitively pulsed laser radiation produces the stationary propulsion with the high coupling coefficient. The development of the scaling methods for laser systems, the increase in the output radiation power and optimization of the interaction of shock waves will result in a considerable increase in the laser-engine efficiency.

4 Impact of thermal action

A Laser Air-jet Engine (LAJE) uses repetitively pulsed laser radiation and the atmospheric air as a working substance[1-3]. 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[26] that the LAJE can find applications for launching space crafts if ~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 ~100 kHz), an optical pulsed discharge, and the merging of shock waves[12,13]. 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 $a = 10-20\ g_0 \approx 100-200\ \mathrm{m \cdot s^2}$. 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 $F_j(t)$ and acceleration a of a rocket of mass M. The momentum increment produced by the shock wave is:

$$\delta_{P_i} = \int_0^{1/f} F_i(t)\,\mathrm{d}t \approx F_a t_a [N \cdot s]. \quad (4)$$

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 δ_{P_i} to the momentum increment $\delta_{P_s} = F/f = aM/f$ over the period under the action of the stationary propulsion F_s, we find:

$$\Delta = \frac{F_m}{F_s} = \frac{2}{ft_a}. \quad (5)$$

The value of Δ, 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:

$$W = \frac{aM}{J}. \quad (6)$$

between the basic parameters of the problem: $W = Qf$ is the absorbed average power of repetitively pulsed radiation, and $J \approx 0.0001 - 0.0012$ Ns/J[3,13,26]. 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 is the sound speed in air. The length R_c of the shock wave compression phase can be found from the relation:

$$\frac{R_c}{R_d} = 0.26\left(\frac{h}{R_d}\right)^{0.32}. \quad (7)$$

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 kPa. The cavern radius can be found from the relation:

$$\frac{R_k}{R_d} = 0.6\left(\frac{R_0}{R_d}\right)^{0.29} \approx 0.25. \quad (8)$$

The final expression (8) 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[3,22,26]. 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 ($p_0 = 100$ kPa) 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 $p_0 = 100 - 1.5$ kPa, which restricts the flight altitude of the rocket by the value 30 – 40 km ($h = \mathrm{const}$).

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 (7), we find the length of the shock-wave compression phase and the time of its action on the reflector:

$$\frac{R_c}{R_d} \approx 0.17 b_i^{0.32}, \quad (9)$$

$$t_a = \frac{0.17 b_i^{0.32} R_d}{k_1 c_0} = \frac{s_1 Q^{1/3}}{p_0^{1/3}} = \frac{s_1}{p_0^{1/3}}\left(\frac{aM}{Jf}\right)^{1/3}. \quad (10)$$

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 $\Delta = F_m/F_a = 2/(Ft_a)$, we find:

$$\Delta = \frac{wp_0^{1/3}}{s_1 f^{2/3} W^{1/3}} = \frac{2p_0^{1/3} Q^{2/3} J}{s_1 aM} = \frac{2}{s_1 f^{2/3}}\left(\frac{p_0 J}{aM}\right). \quad (11)$$

Of the three parameters Q, W, and f, two parameters are independent. The third parameter can be determined from expression (6). The conditions $l/f \sim t_a$ and $\Delta \approx 1 - 2$ correspond to the merging of shock waves[12].

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, respectively. By using (10), we obtain:

$$U = \frac{t_a c_m}{L} = \frac{s_0 c_m}{L p_0^{1/3}} Q^{1/3}, \qquad (12)$$

Here, L is measured in cm and c_m in cm/s. Expression (12) gives the energy:

$$Q = \frac{35.4 p_0}{b_i^{0.96}} (U \frac{c_0}{c_m})^3 L^3, \qquad (13)$$

From the practical point of view, the most interest is the case $U > 1$, when the uniform load is produced over the entire length L. If $U < 1$, the acceleration is not stationary and the wavelength of the wave excited in the rocket body is much smaller than L. If also $c_m/f < L$, 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, 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, hence, $Q_p \approx Q$ for the two limiting cases.

At the start, $p_0 \approx 100$ kPa 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 $Q_p < 0$ J, the characteristic time of this process is 2 – 5 ms[8,9], which corresponds to $f = 500 - 200$ Hz. If $R_k \sim R_r$ ($p_0 < 10$ kPa), 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 $\sim 0.5 c_0/R_r - 850$ Hz. 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 $p_0 = 100$ and 1 kPa, the cavern radius R_k is 2.5 and 11.6 cm, respectively.

5 Dynamic resonance loads

Let us make the estimation 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 $F_{IP} = F_s = 2\,000$ 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($p_0 = 100$ and 1 kPa), and $F_m = 25.6$ kN. 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 estimations 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. Calculations and experiments[28] have confirmed the possibility of producing the stationary propulsion by using laser radiation with high pulse repetition rates. The method of scaling up for the output radiation power is presented in the Ref. [10].

6 Conclusion

Thus, our experiments have confirmed that repetitively pulsed laser radiation produces the stationary propulsion with the high coupling coefficient. The development of the scaling methods for laser systems, the increase in the output radiation power and optimization of the interaction of shock waves will result in a considerable increase in the laser-engine efficiency.

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