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Merging of shock waves produced by a moving pulsating optical discharge

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***Abstract*. Gas-dynamic perturbations produced by a pulsating discharge are studied. The mechanism of shock-wave merging and criteria of its manifestation are confirmed.**

Keywords: *pulsating discharge, shock waves, interaction of radiation with matter*.

The merging mechanism of shock waves (MMW) produced by a pulsating optical discharge (POD) is of interest as the method for transformation of repetitively pulsed laser radiation to low-frequency pressure waves of gases or a magnetic field [2, 3]. The aim of this paper is to verify experimentally the MMW and criteria of its manifestation theoretically found in [1 – 3].

A moving POD studied in our experiments was first obtained in papers [4 – 6], where the method of its excitation, the results of preliminary studies, and the scheme of the setup were described. Therefore, we consider the experimental conditions only briefly. The POD was produced by pulses from a CO_2 laser [7] with the pulse repetition rate $f = 6 - 30$ kHz and the average power ~ 1.5 kW. The pulse duration was ~ 1 μs and the pulse energy was 50 – 80 mJ. The breakdown was developed at the leading edge of pulses for the time 100 – 150 ns. The POD absorbed 40 % – 50 % of the pulse energy q if the radiation intensity at the focus was close to the breakdown threshold, and up to 70 % – 80 % when the radiation intensity was twice – thrice that of the threshold.

The POD could be moved along the optical axis z by means of an opto-mechanical system based on the Cassegrain mirror telescope. A fixed concave spherical mirror had a diameter of 24 cm, a scattering mirror of diameter 3.5 cm could be moved with the help of a pneumatic device, the focus and the POD burning in it being moved toward the incident radiation. The POD propagation velocity was constant, the instability of the POD parameters (q, f, and the propagation velocity V_0) being approximately ± 5 %. The length of the POD path (~ 50 cm) was limited by the laser power and the size of a chamber in which the discharge was produced. The pulse energy ($\sim 100 - 300$ kW) was insufficient for the optical breakdown of air. Experiments were performed in argon or in a mixture of argon with helium at a pressure of $P_0 = 1$ atm.

We measured the parameters of laser radiation and the POD propagation velocity. Plasma and hydrodynamic perturbations produced by the discharge were recorded with a pressure gauge and shadow photographs. The gauge was placed in the POD path at a distance of 40 cm from its start point and at a distance of 2 cm from the z axis; the receiving area was oriented at an angle of 20° to the z axis. The centre of the optical field of shadow photodetection (with an exposure of 0.5 μs) was located on the z axis at a distance of ~ 25 cm from the POD start point. The diameter of the optical field was 10 cm. The perturbations produced by the POD were recorded for a time that was much shorter than the arrival time of waves reflected from chamber walls to the measurement region. The POD propagation velocity V_0 was varied in experiments from 100 m s^{-1} up to $C_0 = 320$ m s^{-1} (the sound speed in argon) and the pulse repetition rate f was varied from 6 to 30 kHz (the upper limit was limited by the optical breakdown threshold in a gas). The pulse energy and radiation intensity in the focus decreased approximately as $1/f$.

A photograph of the moving POD is shown in Fig. 1. Repetitively pulsed radiation produced successive sparks of length $L \sim 0.5$ cm. Depending on V_0 (for $f = 25$ kHz), the POD trace consisted of isolated decomposing laser sparks or represented a continuous plasma channel if the distance between sparks was small. Shock waves were produced due to the thermal expansion of the sparks.

Consider the merging mechanism of shock waves [1, 2]. In a continuous medium, periodic shock waves are produced, whose initial velocity is much greater then the sound speed C_0, while the velocity V_0 of the source of shock waves

Figure 1. Photographs of the POD moving in argon: emission of individual laser sparks for $f = 25$ kHz and $V_0 = 260$ m s^{-1} (a) and emission of a continuous plasma channel for $f = 25$ kHz and $V_0 = 75$ m s^{-1} (b). The camera shutter operated in manual exposure regime. Radiation is incident from left to right, the focus and POD move in the opposite direction.

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is smaller than C_0. If the POD parameters correspond to the merging criteria, the compression phases of shock waves are combined to produce a low-frequency quasi-stationary wave whose length depends linearly on the number of pulses and greatly exceeds the lengths of compression phases of individual shock waves.

In this case, there are no restrictions on the type of a medium, the energy and nature of a pulsation source producing shock waves. The universal nature of the MMW and its criteria was proved by calculations for gases [2] and plasmas with a magnetic field [3], where a quasi-stationary wave of the magnetic and vortex electric fields is formed.

Consider a spherical source of shock waves. The criteria for their merging for a fixed POD are fulfilled in all directions, so that a quasi-stationary wave is spherically symmetric. When the POD moves at the velocity $0 < V_0 < C_0$, shock waves merge by transforming in front of the POD to quasi-stationary waves. The perturbation region represents a sphere in which quasi-stationary waves occupy a segment. If the POD is produced by repetitively pulsed radiation, the leading edge of quasi-stationary waves goes out to infinity, while the trailing edge is located near the POD. The repeated trains (packets) of laser pulses produce periodic quasi-stationary waves. The pulses in trains should correspond to the merging criteria.

The interaction of shock waves depends on the parameters q, f, V_0, P_0, C_0, and L. Laser pulses should be short, i.e., the condition $t_r < (q/P_0)^{1/3}$ should be fulfilled, where t_r is measured in μs, q in joules, and P_0 in atmospheres (for $q \sim 1-5$ J and $P_0 = 1$ atm, we have $t_r < 0.9-1.5$ μs) [2]. In this case, a gas is immobile during the time t_r. A pressure jump in a spark and a fraction of energy carried away by shock waves are maximal. The length of sparks can be neglected if $L < R_d = 2.19(q/P_0)^{1/3}$ (R_d is the dynamic radius, the distance at which pressure in the shock wave becomes close to P_0). In our experiment, $R_d \approx L \approx 0.6$ cm, and the merging criterion for a spherical source of shock waves can be used [1, 2].

The solution of the problem is described [1, 2] by the dimensionless pulse repetition rate $\omega = fR_d/C_0$ and the POD propagation velocity $M_0 = V_0/C_0$. This means that a set of values of dimensional parameters corresponds to each point in the plane (M_0,ω). There exist three main frequencies found from calculations: $\omega_0 \approx 2.5M_0$, $\omega_1 \approx 0.65(1-M_0)$, and $\omega_2 \approx 5.8(1-M_0)^{1.5}$.

For ω/ω_0, the POD produces a continuous channel; for $1/\omega = 1/\omega_1$, the distance between sparks is equal to the shock wave length; and for $\omega = \omega_2$, the shock wave catches up with the trailing edge of a quasi-stationary wave for the time between pulses. The main frequencies allow one to distinguish four regions in the plane (M_0,ω) in which the POD action on the gas is qualitatively different.

Region I: $\omega_0 > \omega \leqslant \omega_2$, the POD produces a quasi-stationary wave.

Region II: $\omega_1 < \omega < \omega_2$ and $\omega < \omega_0$, the transient region for the MMW. The quasi-stationary wave is modulated in amplitude, the modulation depth increasing with ω approaching ω_1.

Region III: $\omega_0 > \omega < \omega_1$, shock waves do not interact and the MMW does not work.

Region IV: $\omega > \omega_0$, the POD produces a continuous plasma channel. Breakdowns occur in the plasma of preceding sparks if the mechanism or the method of plasma removal from the focal region is absent. The efficiency of radiation transformation to the shock wave is low.

The frequencies ω_0, ω_1, ω_2 and regions I–IV are shown in Fig. 2. In the experiment aimed to confirm the correctness of determining these frequencies and regions, we used the following procedure. The POD parameters were varied, each set of them corresponding to a point in the plane (M_0,ω). Some of these points are presented in Fig. 2. The results of experiments in which pressure signals and shadow photographs correspond to the merging of waves are denoted by black points; in the opposite case, the experimental results are denoted by light points. The experiments were performed in the following way. PODs with different velocities V_0 were excited at a fixed pulse repetition rate. Points in curves (*1*) and (*2*) in Fig. 2 correspond to the variation of V_0 for $f \sim 12-15$ and $25-30$ kHz. The average power W_r of repetitively pulsed radiation absorbed in the POD changed from 200 to 750 W. The data are presented for $f = 6$ kHz and the POD in the argon–helium mixture where the sound speed is high. Dependence (*4*) is related to the experiment with the POD burning in a narrow argon jet flowing out to air [8]. The jet carried the plasma out of the burning region. A weak merging of waves was observed because $\omega = 2$ ($f = 120$ kHz) is small compared to ω_2.

Figure 3 shows signals of the pressure gauge and shadow photographs of the POD whose parameters correspond to regions I and III. The shock waves doe not interact in region III – the neighbouring shock waves are separated in time and space (see Figs 3a, b). An increase in pressure corresponds to the approach of the POD to the gauge. The Doppler effect is manifested in the difference in the frequencies of the arrival of shock waves for the approaching and moving away POD. One can see from Fig. 3b that the POD with parameters corresponding to a point in the plane (M_0,ω) located closely to ω_0 produces a continuous channel. During the time between pulses, the focus has no time to come out from the plasma of preceding sparks.

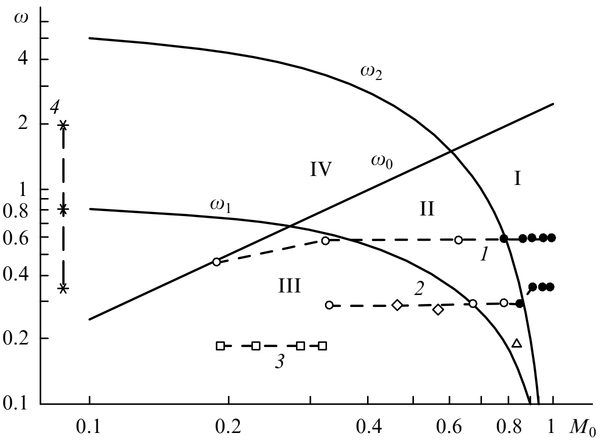

Figure 2. Boundary frequencies ω of the POD appearance as functions of the velocity M_0 (I–IV are the characteristic regions of the POD–gas interaction). Points in curves (*1*)–(*3*) and the point (△) correspond to the experiment with the POD moving in argon ($P_0 = 1$ atm); black points correspond to the case when the POD produces a quasi-stationary wave; light points correspond to the absence of this wave. The dependences presented in the figure are obtained for $f = 25-30$ kHz, $W_r \approx 750$ W (*1*), $f = 12-15$ kHz, $W_r \approx 580-670$ W (*2*), $f = 12$ kHz, $W_r \approx 200$ W (*3*); (*4*): POD in the argon jet [8] flowing out to air ($M_0 = 0$), (△) $f = 6.5$ kHz, $W_r \approx 550$ W, (◇) POD in the 70 % He + 30 % Ar mixture, $P_0 = 1$ atm, $C_0 \approx 550$ m s^{-1}, $V_0 = 315$ m s^{-1}, $f = 25$ kHz.

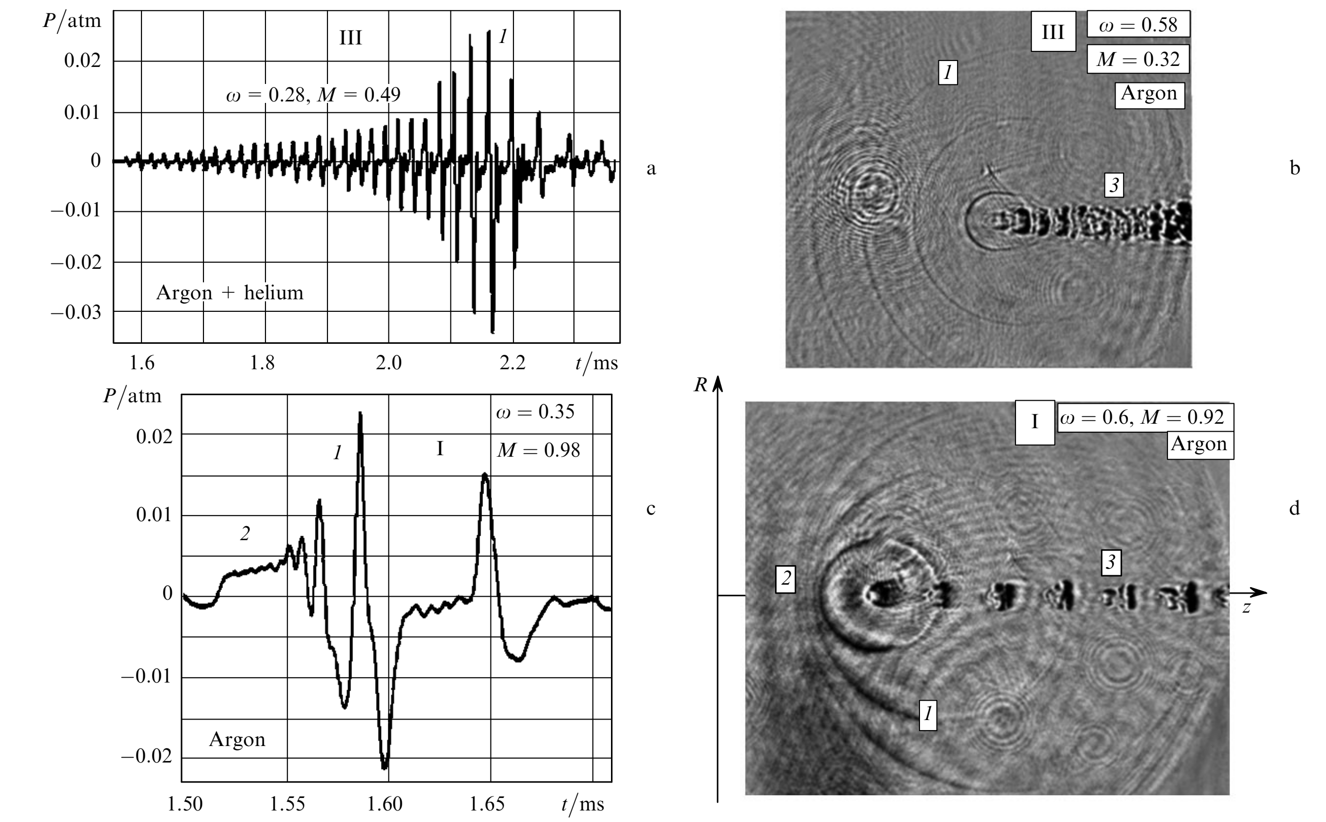

Figure 3. Time dependences of the pressure of shock waves produced by the moving POD (a, c) and shadow photographs (b, d) (the POD moves from right to left along the optical axis z toward laser radiation; pressure is maximal when the POD bypasses the pressure gauge); (*1*) shock waves, (*2*) quai-stationary waves, (*3*) decomposing laser sparks. Experiments were performed at the following parameters: the 70 % He + 30 % Ar mixture, $P_0 =$ 1 atm, $V_0 \sim 260$ m s^{-1}, $f = 25$ kHz, $q = 31$ mJ (a), $V_0 = 103$ m s^{-1}, $f = 30$ kHz, $q = 24$ mJ (b), $V_0 = 314$ m s^{-1}, $f = 14.5$ kHz, $q = 45$ mJ (c), and $V_0 = 294$ m s^{-1}, $f = 30$ kHz, $q = 26$ mJ (d).

Figures 3c, d illustrate the merging of shock waves in front of a moving POD with parameters M_0 and ω corresponding to region I. The compression phases of shock waves merge to produce a quasi-stationary wave whose width increases during the POD movement. One can see how the next shock wave catches up with the trailing edge of the quasi-stationary wave. If M_0 and ω correspond to region II, the modulation of the pressure of the quasi-stationary wave is observed. The measurements were performed in argon for $f = 6$ kHz and in the argon – helium mixture for $f = 25$ kHz. Some points in the plane (M_0,ω) are shown in Fig. 2 ($\triangle$ and $\diamond$). The POD velocity in the gas mixture did not exceed ~ 320 m s^{-1}; however, shock waves did not merge because the sound speed is ~ 550 m s^{-1} and M_0 and ω corresponded to region III.

Thus, by using a repetitively pulsed CO_2 laser, we have produced a pulsating optical discharge propagating in a gas with velocity ~ 320 m s^{-1}. The mechanism of shock-wave merging and its criteria have been confirmed by two methods (pressure measurements and shadow photographs). The outlook for various POD applications, for example, in a laser engine [9] is related to the use of short laser pulses with the average power exceeding 5 kW and a pulse repetition rate of tens or hundreds of kilohertz. Such parameters can be obtained in cw pumped Q-switched lasers [7, 10, 11].

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