An optical pulsating discharge (OPD) has been generated by periodic laser radiation in argon jet flowing into the air at velocity up to 400 m/s. We have measured a velocity of longitudinal expansion of laser plasma, pressure and spectrum of shock waves (SW) being generated by OPD in the stationary air. These measurements have shown that the plasma jet velocity under some definite conditions is several times as large as the velocity of an incident flow. For the first time it has been established that OPD is a generator of SW, the spectrum of which can be rearranged in the frequency range from tens of Hertz to hundreds of kilohertz. At repetition frequency of laser pulses \( f \geq 50 \text{kHz} \) in the spectrum of periodic SW dominated a line at frequency \( f \). A spectrum of SW tandems, being repeated at frequency \( F \ll f \), included both ultrasonic and low-frequency components. The tandems produced a strong acoustic effect. In the experiment at sparks volume \( \sim 0.002–0.005 \text{cm}^3 \) we have obtained the following maximum values: average power of SW \( \sim 160 \text{W} \), efficiency of transformation of laser radiation into SW \( \sim 25\% \).

In the report we have presented the results of the experiment that should be taken into account as negative factors while using OPD to control the flow over bodies. At pulse input of energy into a supersonic flow, a track with high temperature and low density of gas is being formed as well as shock waves (SW) \([1,7]\). The track plasma pulsates greatly and its velocity can exceed the incident flow velocity in a value that is equal to the sound velocity in plasma \( \sim 2 \text{km/s} \) \([8]\) (“a plasmotron” in front of a flying unit). This problem can be solved by choosing the parameters of laser radiation and medium, at which the average velocity of plasma doesn’t exceed the velocity of the incident flow (at the scale being sufficiently larger than the laser spark length). The pressure in the laser spark is much more than the pressure of undisturbed gas, that’s why a spark can be determined as a microexplosion, at which a shock wave carries away a substantial part of its energy. A power of energy supply at large velocity makes up tens kilowatts. This is due to the threshold conditions for OPD combustion in the air and compensation of turbulent cooling of plasma \([9]\). OPD may be a powerful source of gas-dynamic and acoustic influences upon the flying unit and the surrounding. The problems mentioned above can arise at any method of pulse-periodic input of energy into gas, in case a peak pressure in every pulse is much more than the pressure of the surrounding gas and the pulse duration is much less than a characteristic time of thermal expansion of the heating area. Proceeding from all those facts we have defined the main objectives of our investigations, namely: efficiency of transformation of periodic laser radiation into SW; the dependence of pressure and spectrum of periodic SW upon the power and repetition frequency of laser radiation. The given problems may be of interest in some other fields as well. For example, in papers \([10-15]\), the sound generation in liquid at large repetition frequency of laser pulses has been investigated.

Generation of Periodic Shock Waves

Description of the experiment

A simplified scheme of the experiment is presented in Fig.1. A static photograph of plasma luminescence is shown in Fig.2. During the exposition more than 10 laser sparks have been formed, i.e. we observe a superimposition of the pictures of many sparks. An optical pulsating discharge (OPD) in gas has been initiated by using a \( \text{CO}_2 \)–laser \([16]\) that generated a periodic radiation with the following parameters: an average power \( \sim 0.7–1.5 \text{kW} \), a pulse duration \( \sim 1 \mu s \), their repetition frequency \( f \sim 7–117 \text{kHz} \). An optical resonator of the laser allowed us to generate both periodic radiation and periodic tandems of laser beams. There was no any radiation outside the tandems. In the tandems there was the given number of beams \( N \sim 10–30 \) that followed at frequency \( f \). OPD was created in a lens focus at the axis of an argon jet flowing into the atmospheric air. The jet is necessary for steady OPD combustion. The energy of laser pulses was small \( \sim 0.02–0.08 \text{J} \) (depends upon \( f \) but sufficient for an optical \( \text{Ar} \) breakdown under the OPD conditions. The axes of radiation and jet were aligned. Each radiation pulse initiated a laser spark that at the
waves at the distance~3cm from OPD a SW form was close to a spherical one. Pressure in SW was measured by a microphone and sound from OPD. A longitudinal velocity of plasma was measured by superhigh-velocity photo-scanning (SPS). 1 and 2 – control over the parameters of laser radiation.

Fig.2. A photograph of luminescence of an optical pulsating discharge burning in argon jet (diameter 6mm). The discharge was initiated by radiation of a CO2 -laser at the average power ~ 1.5kW and at the pulse repetition frequency f= 50kHz. The jet of accelerated laser plasma is propagating from the focus in the direction of argon jet flowing.

initial stage had a length L ~ 0.3–0.5cm, a radius ~ 0.03÷ 0.05cm and pressure of tens atmospheres. 75% of laser radiation was absorbed in OPD. At thermal expansion of laser sparks there formed SW leaving the jet for stationary air and carrying away ~ 10÷25% of the laser radiation power, absorbed in OPD. At the distance ~ 3cm from OPD a SW form was close to a spherical one. Pressure P(t) in shock waves at the distance R=5÷40cm from OPD was measured by a piezo-transducer and at R=140cm was used a microphone, that had, as well as the transducer, a linearity range not less than 100kHz. Either from the transducer or the microphone, the signal came to a data monitoring system where 4096 values with discreteness 10⁻⁶s were memorized in a computer (the first point had a time value t=0). The number of points mentioned above was sufficient to memorize several shock wave tandems (at F=1kHz). Spectrum P(f), obtained by a Fourier transformation, had a discreteness ~ 244Hz. To obtain a more detailed spectrum, as the experiment has shown, it is necessary to have a sample of ~ 2·10⁷ data with discreteness ~ 0.5μs. At low repetition frequency of tandems the wave spectrum was measured by a spectrometer. An average power, carried away by SW, was determined by the average measured values of SW intensity and on the assumption of a spherical symmetry of SW. A videocamera recorded sound and plasma luminescence of OPD at the distance ~ 30cm from OPD. In the experiments the following parameters have been changed: a repetition frequency of laser pulses, a diameter (3÷6mm) and velocity (V=100÷400m/s) of the jet, tandem duration (0.0001+0.03s) and their repetition frequency (0.036÷10kHz), the location of the P detector relative to OPD (R=5÷40cm). We have investigated two modes of OPD combustion, namely: a pulse-periodic one and tandem generation. In the first case OPD generated “noiseless” SW, the spectrum of which was in the frequency range F > 10kHz where the acoustic organs of a person have a low response. In the tandem mode there appeared the aural impressions of high intensity. The influence of the reflected waves and background acoustic field upon the results of measurements was small because the wave intensity in the measurement range exceeded the background by 40÷60db.

**Periodic shock waves**

In Fig.3 and 4 one can see the pressure in shock waves and their spectrum. At low repetition frequency of laser pulses, shock waves do not interact with each other as a time interval between SW (~ 1/f) is substantially larger than the duration of compression phases t₁ and low pressure t₂ in SW. At high repetition frequency the following conditions are fulfilled – 1/f < t₁ + t₂. The spectrums of the measured signals P(t) have been obtained by the Fourier transformation. A center of the first line in the spectrum agrees with the repetition frequency of both laser pulses and shock waves. At small repetition frequency f of laser sparks, as it is seen from Fig.3a, the signal spectrum has a line at the repetition frequency of laser radiation F=1/f and higher harmonics. In Fig.4 one can see a dependence S(F) of the relation of wave power, which is in the spectrum range from 0 to F, upon the total wave power. At f=7.6kHz the main part of the wave power radiated in the range of high frequencies and only ~ 3% correspond to the range
$F < 10\, \text{kHz}$, that’s why during OPD combustion a sound of weak intensity was recorded. While increasing $f$, the number of intensive harmonics in the spectrum was decreasing. In Figs.3b and 4b we presented a pressure in waves $P(t)$ and their spectrum at $f=116.3\, \text{kHz}$. At high repetition frequency of laser pulses and therefore shock waves one can observe the interaction of SW [6,7] and, as a result, a pressure profile of SW is distorted greatly as compared to a shock wave of point explosion. In the low spectral range near the first harmonic $F_0$ there is the main part of wave power $S \sim 80\%$. At further increasing $f$, the value $S$ approached 1. From the measurements made by the $P$ detector, it follows that while increasing the distance from OPD, the pressure in shock waves is decreasing and their average power, form and spectrum are practically unchanged.

**Shock wave tandems**

In Fig.5 there are SW tandems that have been created by periodic tandems of laser pulses. Figs.5 and 6 illustrate the influence of repetition frequency $f$ and the number of laser pulses $N$ in the tandem upon the form of shock waves and their spectrum. At OPD combustion the tandems $P(t)$ are repeated with good accuracy. Within the limits of a tandem, especially at large $f \sim 100\, \text{kHz}$, the difference in the SW form may be substantial, that is due to different conditions for generation of laser sparks in a gas jet. The repetition is higher at large energy values of laser radiation in the pulse and if for the pause time between the pulses, plasma of sparks is carried away downstream. During the pause between the tandems, the $P$ detector records pressure pulsations caused by the working laser and the jet having a decaying laser plasma. In Fig.6 one can see the spectrums of pressure signals obtained by the Fourier transformation. The greatest difference from the mode of generation of periodic waves lies in the following fact: in the spectrum there appears a low-frequency component at frequency $F_0$; at frequency $F \approx f$ instead of one line we can observe the formation of a group of closely arranged narrow lines; a low-frequency sound is being created at frequency $F_0<<f$ and harmonics $F_0$. The background with intensity $B\approx80\, \text{db}$ (being total round the spectrum) was weak as compared with the sound created by OPD (see Fig.7).
Fig. 5. Pressure in the shock waves generated by tandems of laser pulses at $R=5\text{cm}$. $N$ is a number of pulses in the tandem, the repetition frequency of tandems $F_0=1.2\text{kHz}$, $T_s=N/f$ is a duration of tandems, $V$ is a jet velocity. Average values of powers of both the absorbed laser radiation ($W$) and shock waves emitted by OPD ($W_a$) are equal to:

a) $W=677\text{W}, W_a=161\text{W}$;  
b) $W=363\text{W}, W_a=39.2\text{W}$;  
c) $W=536\text{W}, W_a=28.6\text{W}$.
Acoustic effects have been observed both near OPD, where SW affect either the videocamera microphone or acoustic organs of a person, and at the large distance, where the influence of reflected signals is substantial. Using the piezo-transducer we measured the pressure at the distance $R=5\pm40$cm from OPD. Decreasing of the signals’ amplitude has been observed, while their form (SW tandems) and spectrum have changed slightly. At the large distance, as follows from the microphone readings ($R=140$cm), the intervals between the tandems were filled up with waves. The structure of waves and tandems was greatly smoothed. The spectrum remained qualitatively the same, that is, the main part of the wave power was concentrated in an ultrasound at frequency $F-\omega$, in presence of the low-frequency component.

To investigate the possibilities for control over a wave spectrum in a wide range of frequencies we have performed an experiment in which the sound has been obtained at low frequency 36Hz or simultaneously at two frequencies 36Hz and 1200Hz. In Fig.7 we presented the spectrums, obtained by a spectrometer that had measured the average intensity in the ranges of frequencies $0.7 < F_j < 1.4$ GHz ($F_j$ - are shown in the figure) corresponding to the mode of octave measurements. In Fig.7a one can see a background spectrum that has been created by the working laser as well as simultaneously by the laser, the jet and a modulator...

Fig.6. Spectrum of the shock waves represented in Fig.5. $S$ is a relation of shock waves in the spectral range from 0 up to $F$ to a total power of waves. In a large scale are shown the spectrum fragments close to the repetition frequency of laser pulses in tandems.
of laser radiation (in absence of shock waves the microphone didn’t make any measurement errors). Fig.7b illustrates the spectrums of waves, generated by OPD at some values of tandems’ repetition frequencies $F_0$ and tandems’ packages make up $F_0=1.2$ and $F_0=0.036kHz$, respectively. The power of radiation put to OPD is $W=440W$. 
- “o” – $f=25kHz$, $F_0=1.2$ and $F_0=0.036kHz$, $W=285W$, $B=147db$;
- “+” – $f=25kHz$, $F_0=0.036kHz$, $W=675W$, $B=149db$.

II. Acceleration of Laser Plasma by an Optical Pulsating Discharge

OPD motion in gas can be accompanied by a generation of a plasma jet [8] (calculations). Recently weak jets have been seen only in a single laser spark [17,18]. The object of the experiment is to test an effect of the plasma jet formation.

A scheme for the plasma jet formation

A scheme for the plasma jet formation looks like the following [8]. A pulse periodic laser radiation creates optical breakdowns of gas in a focus of the laser beam. The focus moves along the beam axis at such a velocity that every following spark adjoins the preceding one $V_{0}=L/f$ ($L$ is a length of laser sparks, $f$ is their repetition frequency). Under certain conditions an
acceleration of laser plasma takes place, namely: if OPD moves, for example, in a stationary air, then a jet is being formed which moves relative to the air in the direction being opposite the OPD propagation, the maximum velocity of this jet is equal to a sound velocity in plasma $C \approx 0.5 \times 10^2 \text{km/s};$ if OPD is burning in a gas flow with OPD being stationary with respect to the laboratory system (as in the given experiment), then in this system the velocity of the plasma jet $V_j$ will be equal to the sum of the velocities (jet velocity $V_0$ + velocity $V$ obtained by the plasma due to its acceleration). An acceleration mechanism is gas-dynamic, that is, the plasma of every spark is accelerated at the pressure gradient while flowing out into a “vacuum channel” created by the preceding sparks. The plasma jet velocity depends upon the relations of many parameters of radiation and medium. In [8] we have revealed an acceleration criterion, namely: if a dimensionless number $W$ is close to zero, then the value $V/C$ fluctuates near zero and at $W$ seeking to a unit, $V/C$ fluctuations are small and the value $V/C$ also approaches 1.

**Experiment**

An experimental scheme is shown in Fig.1. OPD was initiated in Ar jet of 6 mm diameter. The aim of the experimental testing is to show that at some certain conditions a plasma jet velocity $V_j$ exceeds substantially a gas flow velocity $V_0$. The velocity of longitudinal (along the channel) plasma expansion was measured by using a superhigh-velocity photo-scanning according to an angle of inclination of the plasma luminescence boundary of sparks. In the experiment the energy of laser pulses and dimensions of sparks corresponded to the parameter $\tau \sim 0.2 \times 10^3$. Consequently, an acceleration has to occur under the condition of continuity of OPD motion, that is, continuity of a thermal track - $V_0= L/f$ ($L$ – is a spark length). In the experiment we varied the argon jet velocity $V_0 \sim 100 \div 400 \text{m/s}$ and repetition frequency of laser pulses $f=12 \div 100 \text{kHz}$. We managed to observe an acceleration effect at $f = 100 \text{kHz}$ when a time interval between the pulses was less than the time of sparks luminescence that was recorded by a photographic film. In Fig.8 are shown photo-scanning of a cross-section of sparks plasma in time and along the jet axis. One can see a substantial difference in expansion dynamics of the sparks isolated from each other (Fig.8b) and the sparks forming a continuous channel (Fig.8a). In Fig.9 for different conditions of the experiment we have shown time variations in velocity of expansion of the laser spark boundary. In the given case the direction of acceleration coincides with the direction of plasma flowing out into a “vacuum” channel created by the optical pulsating discharge in the argon jet. Time $t=0$ corresponds to the generation of laser pulses. At large space and time scales we haven’t managed to measure a velocity of the plasma jet. It is due to the fact that fast cooling

![Fig.8. A photo-scanning of plasma luminescence of periodic laser sparks - in time and along the axis of a laser beam (and a jet) at velocity $V_f = 750 \text{m/s}$. An optical pulsating discharge (OPD) is burning in argon jet. At $Z=0$ and $V_f=100 \text{m/s}$ a luminescence movement is due to the plasma expansion from the region with high pressure (spark) into a “vacuum” channel that is formed as a result of OPD motion in gas. At $V_f=400 \text{m/s}$, that is, thermal expansion of sparks, the channel is not formed and plasma is not accelerated (as $L/f>V<1$). The symbols: $f$ and $W$ are pulse repetition frequency and the average power of the CO$_2$ - laser radiation absorbed in OPD, respectively, $L$ is a spark length, $V_0$ is $Ar$ velocity in the jet.](image)

![Fig.9. Time measurement of a longitudinal velocity $V$ of the laser plasma. Data have been obtained by a treatment of the photo-scannings of plasma luminescence (see Fig.8). Time $T=0$ is the beginning of formation of a laser spark. Plasma was accelerated (see curves A and o), if $L/f>V>1$. Here $L$ is a length of laser sparks ($\sim 0.3 \text{cm}$), $f$ is repetition frequency of laser pulses and sparks, $V_0$ is a velocity of an incident gas flow. 1 - $f=100 \text{kHz}$, $V_0=400 \text{m/s}$ - plasma is not accelerated as $L/f>V<1$; 2 - $f=100 \text{kHz}$, $V_0=100 \text{m/s}$ - plasma is accelerated, $V>V_0$. 3 - $f=50 \text{kHz}$, $V_0=100 \text{m/s}$ – plasma is accelerated, $V<V_0$.](image)
of plasma and, as a consequence, decreasing of radiation intensity from the plasma allowed us to record luminescence only for a short period of time (not more than ~ 20μs) at sensitivity of a color film of 800 units.

Conclusions

The pulsating optical discharge transforms periodic laser radiation into spherical shock waves or periodic waves or waves united into tandems. The spectrum of periodic waves has several intensive lines in the ultrasonic range of frequencies (“noiseless” shock waves). In the spectrum of periodic tandems of shock waves there are lines both (and their harmonics) at the repetition frequency of laser pulses and at the low repetition frequency of tandems. Here a strong low-frequency sound arises at the frequency being close to the repetition frequency of tandems. In both cases the main part of the wave power is concentrated in a spectrum, close to the repetition frequency of laser pulses. During the discharge combustion we can execute routine control over the wave spectrum in a wide range of frequencies by changing the modulation frequencies of laser radiation and (or) its power. The efficiency of laser radiation transformation into shock waves reached ~ 25% and the maximum average power of waves ~ 160W. The measurements of a velocity of laser sparks’ expansion point out to a feasibility of generation of a plasma jet during the motion of the optical pulsating discharge in free gas space. It should be also mentioned that an extended plasma jet is being formed at the values of power of energy input into gas exceeding many times the power of the laser used in the experiment.

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References