

LETTERS

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Simulation of shock waves at high repetition rate of laser sparks

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***Abstract*. It is shown that a train of periodic laser sparks with high repetition rate can produce an extended shock wave in air. This wave is either identical to the wave appearing upon instant absorption of the train energy in a spark, or simultaneously contains both ultrasonic and low-frequency components.**

Keywords: *laser spark, simulation, shock waves.*

Single or periodic (with low repetition rate) laser sparks produce shock waves that are described by the point explosion theory [1]. In Ref. [2], an optical pulsed discharge (OPD) with the spark repetition rate F as high as ~ 100 kHz was obtained. In this paper, we simulated, within the framework of the problem on the transformation of a laser beam to a plasma beam in a free gas space [3], the production of a shock wave whose profile depends on F and the spark energy Q and differs from that known so far.

1. Theory

Gas dynamics equations were solved numerically, taking into account the properties of air at high temperature. We assumed that a pulse packet of N pulses with the repetition rate F heated a coaxially symmetrical region whose length L was much greater than its radius (a cylinder). The heating time was $t_0 \approx 1$ μs, pressure was $p_0 = 1$ atm, the first spark radius was $R = 0.5$ cm, and the energy input was close to that used in experiment [4]. The ratio $E = Q/Q_0$ of the energy absorbed in a spark to the energy of a cold gas in the spark volume is used as the energy parameter.

Shock waves were studied at fixed total spark energy within a packet $Q_s = \sum_1^N Q_i$ (i is the spark number). If the sparks in the packet have the same energy Q, the parameter $E_s \equiv Q_s/Q_0 \approx EN$ describes the shock wave created by a single powerful spark with energy Q_s. In this work, we assume for definiteness that $E_s = 1000$. Fig. 1 shows shock waves produced by 10 sparks at different repetition rates ($N = 10$, $E = 100$). Pressure and distance along the radius are normalised to p_0 and R_0, respectively.

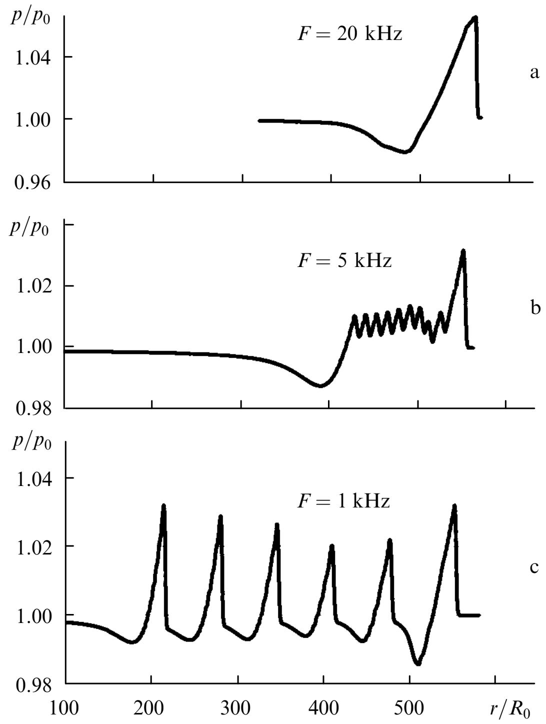

Figure 1. Radial distribution of pressure in shock waves produced by a train of spark scalculated for different spark repetition rates (at the instant of time $t = 8$ ms).

If the time between sparks $T_s \approx F^{-1}$ is less than the time T_r of high pressure relaxation in the heated area (dependent on E and R_0), the packet of sparks produces a shock wave, which slightly differes from the shock wave created by a single spark with energy $Q_s = Q_0 E_s$ (Fig. 1a). Shock waves created at lower F have a more extended compression phase $R_+ \sim c_0 N/F$ (Fig. 1b; c_0 is the sound speed in air). The low pressure phase in this case has approximately the same extension as in the case of $E = E_s$.

The high-frequency component behind the front corresponds to distortions caused by every shock wave (ultrasound at low E or R_0). Shock waves do not interact with each other if during the time T_s every wave moves away from the plasma channel by the distance greater than the

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extension of a shock wave created by a single spark (Fig. 1c). It follows from the calculations that at the same value of energy E_s we can create shock waves of a larger extension by reducing E and increasing N. The condition required for the effect described above is $-t_0 \ll T_r$.

2. Experiment

Argon was delivered at high pressure into a mixing chamber, from which it arrived into a tube of length 4 cm and diameter 7 mm (the argon speed ~ 20 m s^{-1}) to be released to the atmosphere. The OPD was created on the tube axis by focusing radiation from a repetitively pulsed CO_2-laser [5] (the pulse duration was ~ 1 μs, and the power absorbed in the OPD was ~ 650 W). The OPD created a heat 'plug', resulting in its disruption and periodic generation of laser spark trains. We studied the influence of laser spark repetition rate ($F \approx 8 - 64$ kHz) on the spectrum of sound generated by the OPD.

Fig. 2 shows the OPD sound spectra for different F (the background signal was subtracted). The total sound intensity was ~ 125 dB, and the background intensity was 85 dB. For $F = 8$ kHz and 20 kHz, ultrasound dominated, while at a higher repetition rates, the OPD generated both ultrasound and low-frequency sound. Our calculations showed that the sound component with frequency $f \gg F$ was produced by shock wave pulsation within the tube, the radiation being emitted by the plasma jet at the tube output. The radiation emitted from the tube side surface was strongly absorbed. The sound component with frequency $f \ll F$ was produced by sparks with $F > 25$ kHz, in agreement with the calculation performed for our experiment.

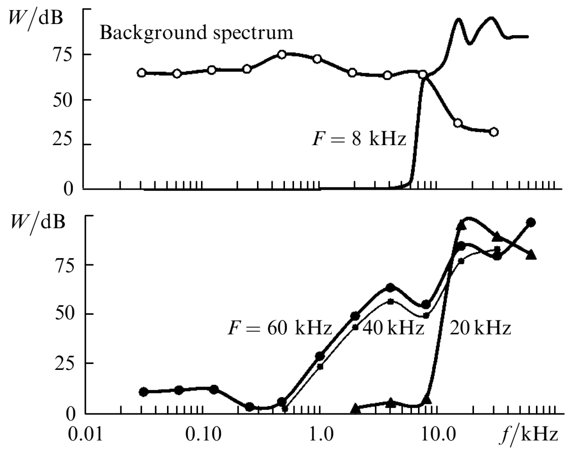

Figure 2. Experimental spectra of sound produced by an optical pulsed discharge at different laser pulse repetition rates F, and the background spectrum. The measurements were taken within the fundamental frequency range $f \pm f/2$ (octave measurements).

Thus, the input of energy into a gas with a high repetition rate can produce periodic shock waves, either low frequency or both low frequency and high frequency ones. This effect is energetically 'strong': the shock waves carry away $\sim 25 - 50\,\%$ of the power absorbed.

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