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Background Oriented Schlieren Method as an Optical Method to Study Shock Waves

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Abstract—Background oriented schlieren method is applied in diagnostics of shock waves in air. The method can be used for visualization of shock waves that are generated after explosion or due to motion at ultrasonic speeds. Experimental data make it possible to observe propagation of a shock wave in space, estimate the asymmetry of energy liberation in explosion, and determine parameters of shock wave.

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INTRODUCTION

Detection of shock waves (SWs) that result from explosions or motion at ultrasonic speeds is a problem of optical detection of fast processes. Relatively high time resolution is needed for the experimental study of fast processes. Optical methods, which exhibit extremely short response times, may serve as appropriate instruments in physics of pulsed, fast, and high-energy processes. An important advantage of the optical methods is related to the fact that data are simultaneously collected from a spatial region rather than a single point.

The development of digital methods for data storage and processing and digital photo- and video-recording has stimulated progress in optical methods and made them more convenient for experimental applications. The application of digital processing of results makes it possible to substantially increase quality and amount of data on various physical effects. Background oriented schlieren (BOS) method [1] is widely employed in scientific research [2], since it allows measurement of qualitative and, in several cases, quantitative fields of thermodynamic parameters using substantially simpler equipment in comparison with shadow methods [3, 4]. The method does not require application of optical elements the sizes of which are comparable with typical sizes of the flow under study. Thus, the procedure is convenient for field applications and experiments in which large-scale flows must be visualized. In this work, we employ the BOS method for visualizations of SWs that result from the motion at ultrasonic speed and explosion-induced SWs. The SW parameters can be determined using the BOS data when a spherical SW is generated by explosion.

BOS METHOD

The BOS method can be used in the study of SWs due to the dependence of the refractive index of gas on gas density and, hence, pressure at the SW front. The Gladstone–Dale relationship is satisfied for unionized gases with a relatively high accuracy:

$$n = 1 + G\rho. \tag{1}$$

Here, n is the refractive index, G is the Gladstone–Dale constant (coefficient that is constant for the given gas and wavelength), and ρ is the density.

Figure 1 shows the detection scheme based on the BOS method [5]. A plane random pattern that serves as a background screen is located in the $\xi\eta$ plane. The xy plane is the detection plane in which we place the CCD array of video camera. *OS* is the imaging optical system with focal length f, and *Ob* is the plane in the vicinity of which the object under study is located. The method is sensitive to components of the gradient of refractive index that are perpendicular to the line of sight. Deflection of beam $\Delta\theta$ due to passage through the medium with optical inhomogeneity leads to the displacement of the image of the corresponding fragment of random pattern in the plane of the CCD array by Δx and Δy. The BOS method is based on the measurement of displacements Δx and Δy. The beam prop-

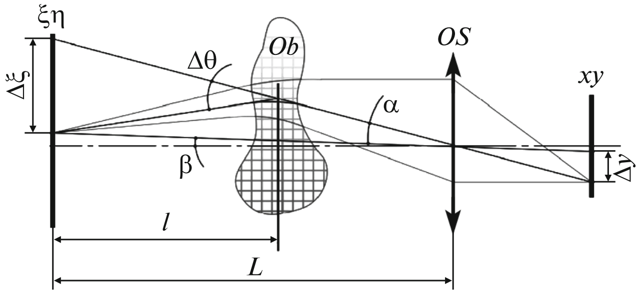

Fig. 1. Trajectory of a beam that passes through optical inhomogeneity.

agation through inhomogeneity in the $Z0Y$ plane is described using the relationships

$$\Delta\theta = \int_0^S \frac{1}{n}\frac{\partial n}{\partial y} dz, \tag{2}$$

$$\Delta y' = \int_0^S \left(\int_0^S \frac{1}{n}\frac{\partial n}{\partial y} dz \right) dS, \tag{3}$$

where $\Delta y'$ is the displacement and $\Delta\theta$ is the beam deflection at the exit from inhomogeneity. The integration is performed over the beam path inside inhomogeneity (S).

We assume that angle α is relatively small and the object is localized in the *Ob* plane. Then, displacement Δy in the given configuration can be used to calculate angle $\Delta\theta$:

$$\Delta\theta \approx \Delta y \frac{L - f}{lf} \cos^2 \beta. \tag{4}$$

Normally, angle β is small and multiplier $\cos^2\beta$ can be omitted, since it tends to unity.

The detection scheme and formulas (1)–(4) show that the sensitivity of the BOS scheme at fixed parameters of the optical inhomogeneity (SW with certain ΔP) depends on the parameters of the detection scheme (L, l, and f). When the cross-correlation processing is employed, the minimum detectable displacement Δy is determined by the parameters of screen and physical size of a pixel.

The SW visualization with the aid of the BOS method is implemented using the detection of two and more images of the background screen with a relatively high optical contrast and structure. One image of the background screen is measured in the absence of the SW in the space of observation, and the remaining images are measured in the presence of the SW. The further computer analysis of the images makes it possible to visualize the SW. Artificial (generated) and natural backgrounds may serve as the background screen [6].

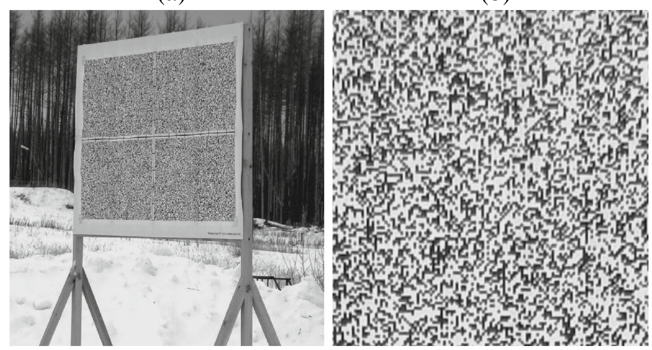

Fig. 2. (a) General view and (b) magnified fragment of the background screen (the size of the working region is 2 × 1 m).

SW VISUALIZATION USING THE BOS METHOD

The applications of the BOS method in the visualization of optical inhomogeneities (in particular, SWs) can conditionally be divided into two groups. For the first group, the optical detection using specifically generated background screens with predetermined optimal parameters (grain size and spread) is employed to reach positive results on the visualization of the optical inhomogeneity under study. Figure 2 shows such a screen. For the second group, natural backgrounds (forest, clouds, grass, sand, etc.) serve as the background screens. Below, we present SW visualization using specific screens (Figs. 3–6) and natural backgrounds (Figs. 7 and 8).

Figure 3 presents a fragment of the high-speed video detection of the motion of the rifle-fired bullet (Dragunov sniper rifle SVD with 7.62 × 54*R* PS cartridge) and the result of visualization of the SW caused by the ultrasonic motion of the bullet. The video recording is performed at a distance of about 15 m from the rifle. The bullet speed in the region of video detection is 775 m/s.

Figures 4 and 5 show fragments of the visualization of shots for the KPVT heavy machine gun and the PBU-14.5 powder launcher (caliber 14.5). We observe the front of the muzzle wave and the front of the head-on pressure jump. The speeds of the launched objects (LOs) in the detection region are 998 and 1695 m/s for KPVT and PBU-14.5, respectively.

(Semi)spherical shapes of explosive charges are rare (except for specific experiments). Most charges represent cylinders with length L and diameter D, such that $L/D > 1$ (elongated cylinders). In general, the SW wave front is not spherical at relatively large distances from the explosion of a cylindrical charge. Figures 6 and 7 show fragments of video recording of the SW propagation for cylindrical explosive charges. Figure 6 presents the SW visualization for the explosion of a charge that is placed in a thin-wall plastic shell with a charge elongation of 1.8. The charge consists of VS-2

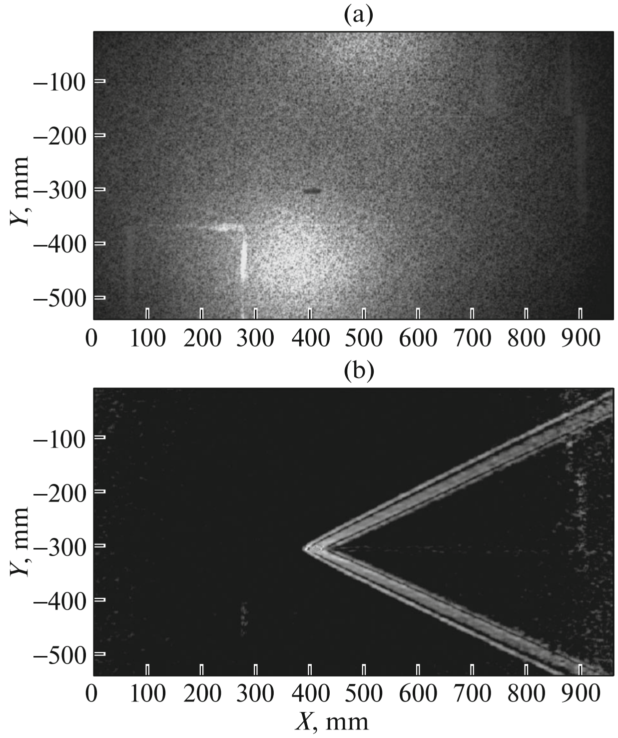

Fig. 3. (a) Original image and (b) result of the SW visualization.

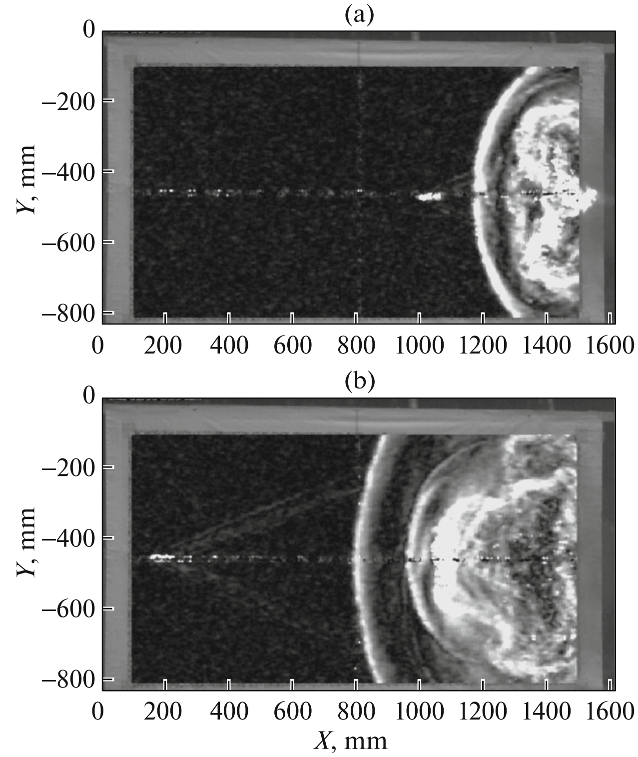

Fig. 4. SW visualization for KPVT.

[7] and penthrite (5 g). Figure 7 shows the SW visualization for the explosion of a cylindrical charge (PVV-7 with a mass of 200 g) with an elongation of $L/D = 4.3$. The charge is placed at the center of the video-detection region with the cylindrical surface on a wooden support and the axis perpendicular to the video-detection axis. The visualization shows nonuniform distribution of the SW at the initial stage of motion and gradual transformation of the SW shape into spherical shape.

The experiments with rocket-launching setup include acceleration of the tested objects (TOs) along rails using rocket trains. Such acceleration is accompanied by several effects that need to be visualized with a relatively high quality for the further analysis of the test results. Figure 8 shows visualization of the SW that is generated due to the motion of TO along rails of the rocket track at a speed of 352 m/s [8].

MEASUREMENT OF THE SW PARAMETERS

A method to determine SW parameters involves the analysis of the propagation speed of primary SW using the following dependence obtained with the aid of the Rankine–Hugoniot relations [9]:

$$\Delta P = \frac{2\rho_0}{k+1}(D^2 - c_0^2). \qquad (5)$$

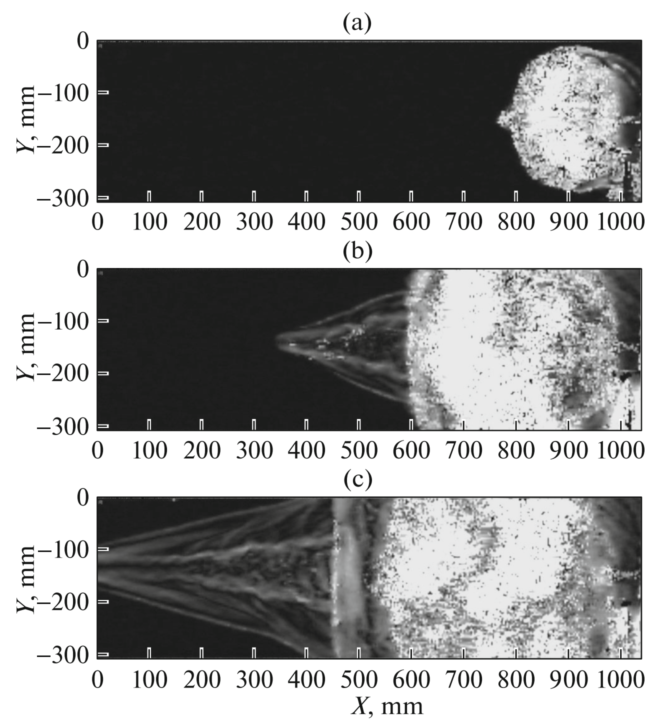

Fig. 5. SW visualization for PBU-14.5 with delays of 0.25, 0.5, and 0.75 ms relative to charge initiation.

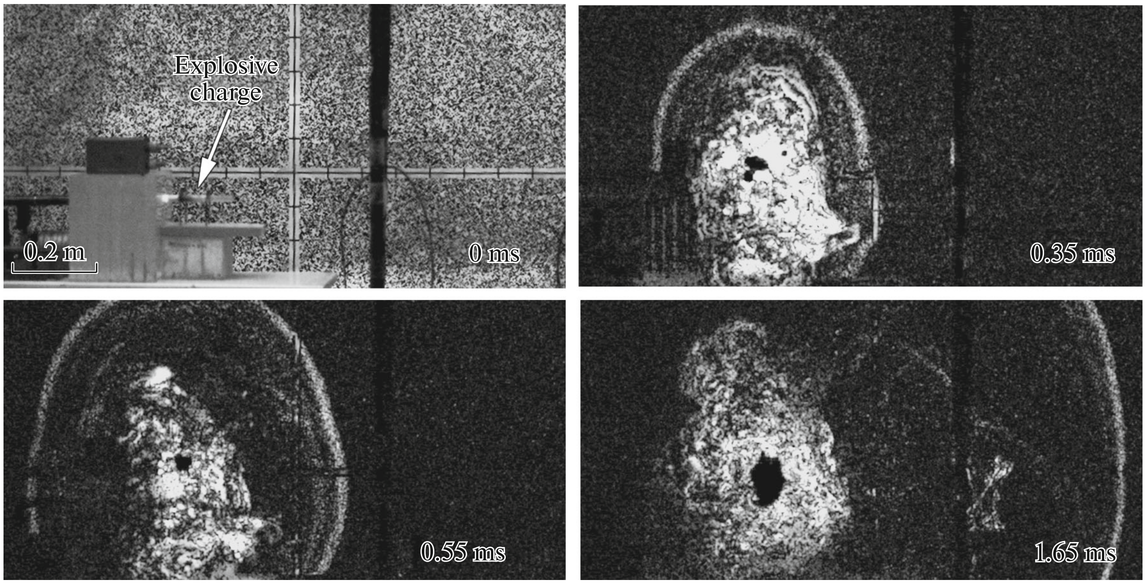

Fig. 6. Explosion of a cylindrical charge with an elongation of 1.8 measured with delays of 0, 0.35, 0.55, and 1.65 ms relative to initiation.

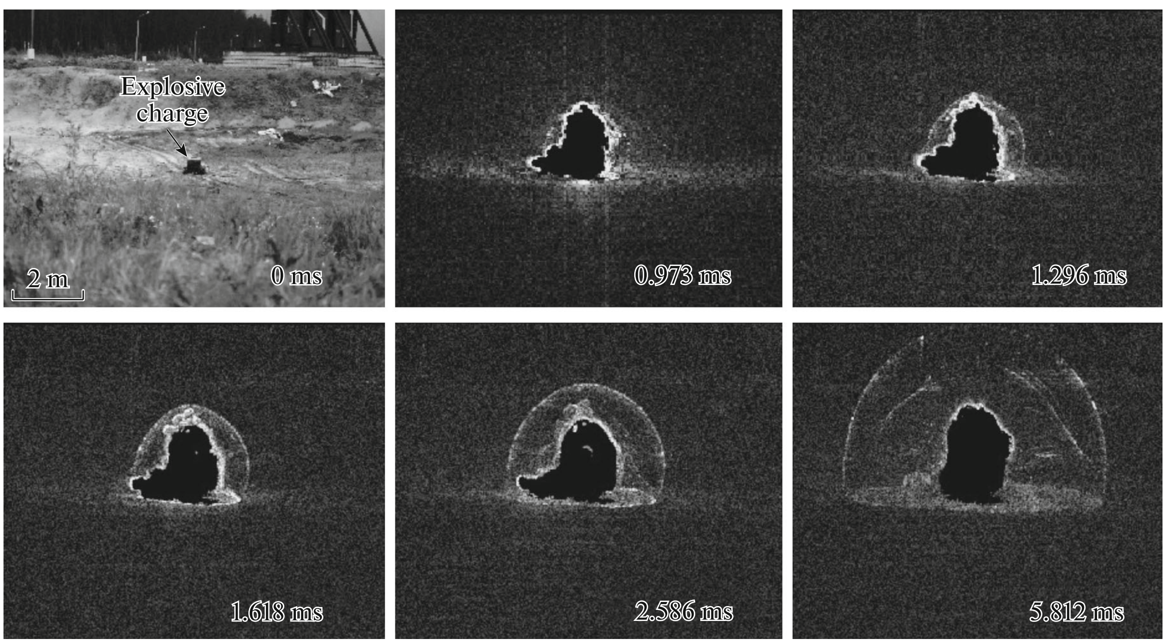

Fig. 7. Explosion of a cylindrical charge with an elongation of 4.3 measured with delays of 0, 0.973, 1.296, 1.618, 2.586, and 5.812 ms relative to initiation.

Here, ΔP is the excess pressure at the SW front (Pa), ρ_0 is the density of air in unperturbed atmosphere (kg/m^3), $k = 1.4$ is the coefficient of the Poisson adiabat for air, D is the speed of the SW front (m/s), and c_0 is the speed of sound in unperturbed region (m/s).

Several procedures can be used to determine the SW arrival time at points located at known distances from the center of charge. The most significant data array on the SW motion can be obtained using high-speed video recording (data array $R(t)$). To use such data in the calculation of the SW parameters, we must determine the SW speed. For a continuous set of discrete data $R(t)$, the SW speed at any position of the detection region can be calculated using the differentiation of the curve that is constructed with the aid of the least-squares procedure to approximate original data on the SW motion. From the moment at which

(a) (b)

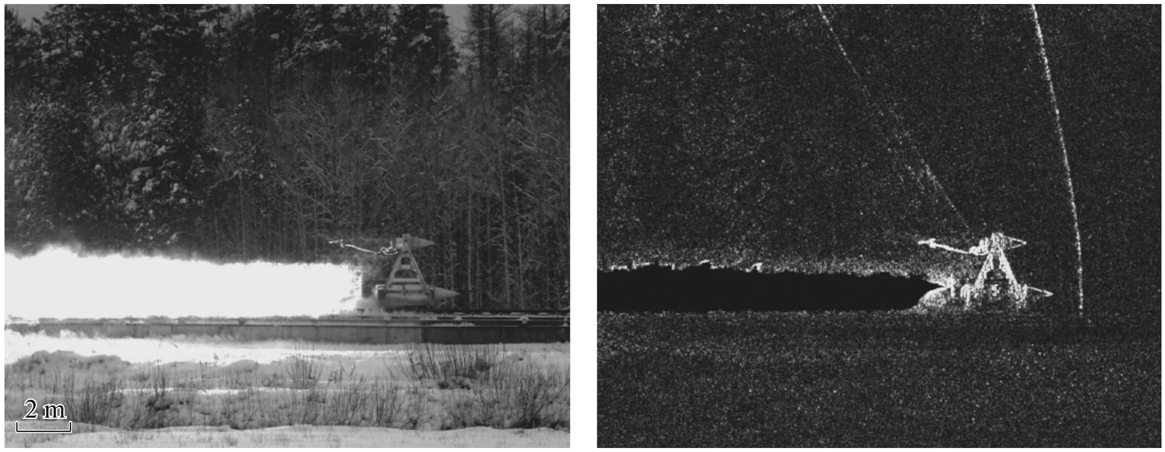

Fig. 8. (a) Original image and (b) results of the SW visualization.

the SW is separated from the detonation products (at a Mach number of about 3), the SW speed monotonically decreases with an increase in the radius and tends to the speed of sound [10]. This circumstance imposes limitations on the equation of the approximating curve, since the polynomial equation cannot be used to solve such problems. The approximating equation of [11] is written as

$$R(t) = A + Bc_0t = C\ln(1 + c_0t) + D\sqrt{\ln(1 + c_0t)}, \quad (6)$$

where A, B, C, and D are the approximation coefficients and c_0 is the speed of sound in unperturbed medium.

For strong SWs with a Mach number of greater than 3.5, which corresponds to an excess pressure at the SW front of greater than 13 atm, dependence (5) is not satisfied and we must use the equation for real gas [10].

For the development of the BOS method in the measurements of the SW parameters, we perform experiments with high-speed video detection and detection using pressure sensors (PSs).

Figures 9–12 present the results of such an experiment. Figure 9 shows the position of the detection device. In the experiment, we use explosion of pressed TNT charge *3* with a mass of 260 g that is placed on a wooden support. The SW generated by the explosion is detected using PS *2* and high-speed camera *4*. The video detection is performed with the aid of contrast screen *1* with a width of 2 m and a height of 1 m. The PSs are placed in the horizontal plane of the discharge to measure excess pressure at the front of propagating SW. The SW parameters are measured with the aid of an XCQ-080-25PSI PS using a verified procedure with a measurement error of ±5%.

Figure 10 presents a video frame and the result of the SW visualization. We visualize both primary *1* and secondary *2*' SWs. Using the visualized discrete posi-

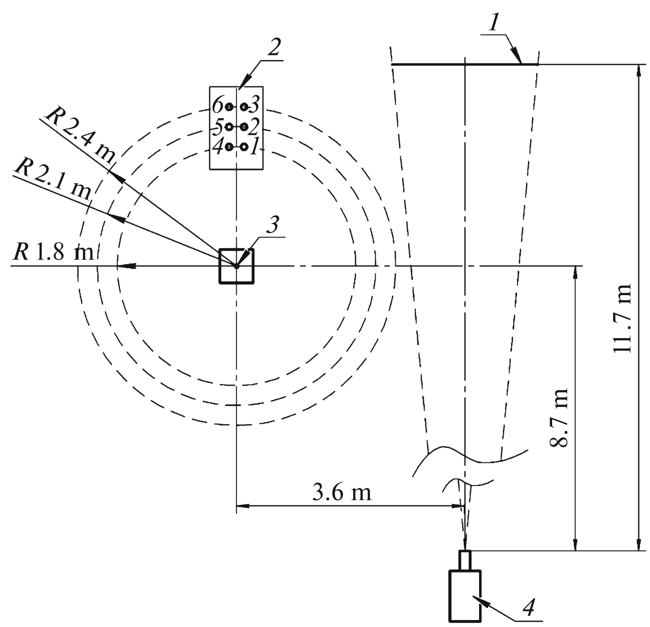

Fig. 9. Scheme for the detection of SW.

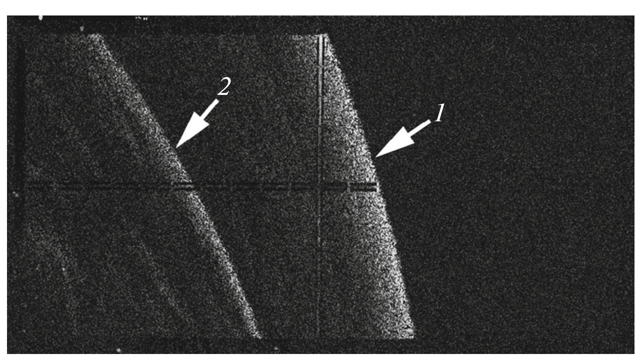

Fig. 10. SW visualization at a delay of 7.6 ms relative to the explosion.

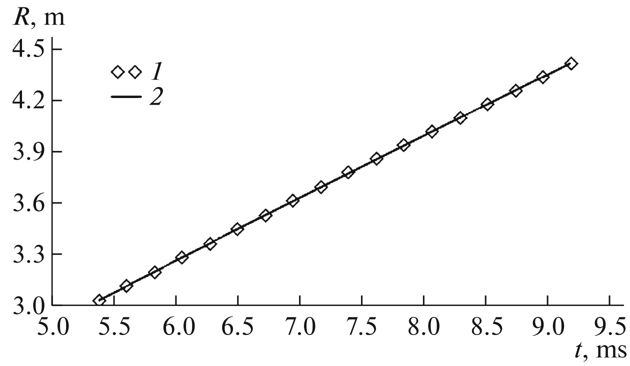

Fig. 11. $R(t)$ diagram of the propagation of primary SW.

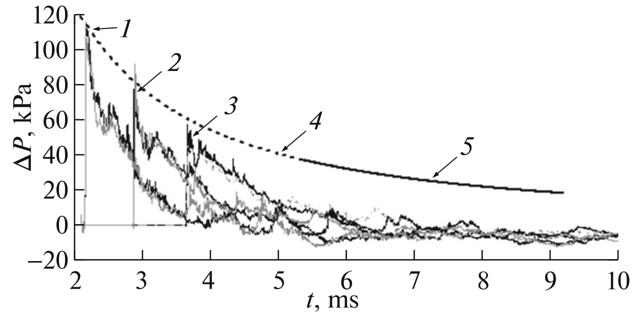

Fig. 12. (*1–3*) Pressure profiles and (*4*) and (*5*) curves resulting from recalculation of the $R(t)$ diagram.

tions of the SW and the positions of the optical detection scheme, we determine diagram of the motion of the primary SW $R(t)$. Figure 11 demonstrates the $R(t)$ diagram (dots (*1*) and solid line (*2*) show experimental radii of the SW front at discrete moments and approximating curve, respectively). Function (6) with the coefficients $A = 0.005$, $B = 1.008$, $C = -0.426$, and $D = 1.661$ serves as the approximating function. The differentiation of approximating curve $R(t)$ yields the SW propagation speed, and formula (5) is used to estimate excess pressure at the front of the primary SW.

Figure 12 shows curves that are obtained with the aid of the PS measurements (curve *1* shows the results of PS1 and PS4, curve *2* shows the results of PS2 and PS5, and curve *3* shows the results of PS3 and PS6). We also present the results of optical detection (curves *4* and *5*). The experimental scheme (Fig. 9) shows that PSs and video camera detect SWs in different regions. Curve *4* is a prognosis curve, since it is constructed using approximating dependence $R(t)$ but the results are in good agreement with the PS results.

CONCLUSIONS

The results prove that the BOS method can be used for the detection of SWs. The BOS method can be employed in practical field tests. Both qualitative and quantitative data can be obtained. The method can be used to measure the SW parameters and the reliability of the corresponding results is proven by the PS data. Comprehensive measurements of the primary, secondary, and reflected SWs in the region under study provide the desired experimental results.

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REFERENCES

1. G. Meier, Exp. Fluids **33**, 181 (2002).
2. M. Raffel, Exp. Fluids **56**, 60 (2015).
3. S. I. Gerasimov and Yu. I. Faikov, *Shadow Photography in Divergent Light* (RFYaTs-VNIIEF, Sarov, 2010).
4. V. M. Boiko, A. M. Orishich, A. A. Pavlov, and A. A. Pikalov, *Methods of Optical Diagnostics in Aerophysical Experiments* (Novosib. Gos. Univ., Novosibirsk, 2009).
5. T. V. Mironova, Candidate's Dissertation in Mathematics and Physics (Lebedev Phys. Inst., Russ. Acad. Sci., Moscow, 2012).
6. M. J. Hargather and G. C. Settles, Exp. Fluids **48**, 59 (2010).
7. S. I. Gerasimov, M. A. Ilyushin, and V. A. Kuz'min, Tech. Phys. Lett. **41**, 338 (2015).
8. S. I. Gerasimov and S. V. Butova, Nauchn. Vizualizatsiya **7** (2), 12 (2015).
9. *Explosion Physics*, 3rd ed., Ed. by L. P. Orlenko (Fizmatlit, Moscow, 2004), Vol. 1.
10. J. M. Dewey, in *Experimental Methods of Shock Wave Research*, Ed. by O. Igra and F. Seiler (Springer, 2016), p. 53.
11. J. M. Dewey, Proc. R. Soc. London A **324**, 275 (1971).

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