Separate BOS-visualization of temperature and pressure distributions in a solid medium

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Abstract. Background Oriented Schlieren (BOS) is a technique widely used for visualizing disturbances in optically transparent objects. This method makes possible to visualize the variation of the refractive index, which depends on such physical parameters as temperature, pressure and concentration. Therefore, obtaining information about these parameters is also possible. In the course of the work, an experiment was conducted to visualize the optical inhomogeneity formed by changes in pressure and temperature in plane-parallel glass plate. Processing of experimental data has shown that under certain conditions it is possible to obtain information about the individual parameters of the environment which forms a complex inhomogeneity.

1. Introduction
Flows of gases and liquids are very common phenomena, both in natural and industrial conditions. Necessity to visualize gas flows in industrial aviation has provided optical methods with wide recognition in the field of experimental gas dynamics, since they allow the flow to be diagnosed without introducing additional disturbances into it [1].

Various refractometric methods (such as schlieren, shift-interferometry) are most often used in the study of optically transparent inhomogeneities. These methods are based on the use of the same phenomenon-the reaction of the light beam to refractive index alterations [2]. Refractometric methods are usually used to investigate the distribution fields of the refractive index or its gradients, which are able to be converted into quantities related to the refractive index itself.

Following the evolution of digital technology, techniques which based on the main principles of the above-mentioned methods began to develop and at the present times have reached the mark of an independent measuring technique; for example - Background Oriented Schlieren which application will be described in this work. Currently, it is widely used for qualitative and quantitative visualization of wind tunnels flows [3], in full-scale flight tests [4], and in explosive engineering [5]. The significant advantage of this method is the simplicity of its practical implementation and the modest requirements for technical base which are lower in comparison with analogues.

The main objective of this work is to study the possibility of obtaining information about each of the environment characteristics involved in the formation of complex optical inhomogeneity. In this paper, we will consider the BOS-visualization of optical inhomogeneities caused by the heating and deformation of the glass plate.
2. **Background Oriented Schlieren in quantitative diagnostics**

As already noted, the basis of BOS is the phenomenon of refraction: due to the violation of the optical homogeneity of the medium in the path of propagation of light rays, the trajectory of their movement is distorted. Violation of the optical homogeneity of the medium is expressed in the inconstancy of the refractive index $n$ over its volume. Pressure, temperature and concentration are the main parameters of the medium, affecting its refractive index. For clarity, consider the dependence of the refractive index of air on its pressure and temperature [6]:

$$n_{t,p} - 1 = (n_0 - 1) \cdot \left[ \frac{p \cdot (1 + (1.049 - 0.0157 \cdot t) \cdot 10^{-6} \cdot p)}{720.883 \cdot (1 + 0.003661 \cdot t)} \right].$$

(1)

Here $n_0$ – is the refractive index of air at initial conditions ($t_0 = 15 ^\circ C$, $p_0 = 760$ mm. Hg.), $p$ – pressure in mm. Hg., $t$ - temperature in Celsius degree. Figure 1 shows the corresponding graphs.

![Graph](image1)

(a)

![Graph](image2)

(b)

**Figure 1.** The dependence of the refractive index of air on its pressure and temperature. (a) – dependence of the refractive index of air on its temperature; (b) – dependence of the refractive index of air on its pressure.
From figure 1 it is clear that temperature has a significantly greater effect on the refractive index in comparison with pressure. Therefore, if the problem in question does not require exceptional accuracy in its solution, then small changes in pressure can be neglected. Information about the studied medium is obtained by analyzing a series of consecutive images of the background screen, distorted by small gradients of the refractive index. In addition to distorted images of the background screen, there must be at least one image in which these distortions are absent. This is necessary to perform cross-correlation processing, the result of which will be the vector field of the image displacements, which is, in fact, the visualization of optical inhomogeneity. The vector field of displacements can be recalculated into the surface distribution of the index of refraction. If the refractive index gradient was caused by a change in any one of the characteristics of the medium, then the distribution of the refractive index can be recalculated into the distribution of this characteristic itself. As an example, figure 2 shows the temperature distribution in the air flow from an industrial dryer.

![Figure 2](image)

**Figure 2.** The surface temperature distribution in the jet assembly industrial dryer.

It is worth to be noted that this result was obtained without taking into account changes in pressure (the gradient of the refractive index arising from a change in pressure was considered negligible). However, such neglect is not always permissible. Therefore, the issue of the possibility of obtaining separate information on several environmental parameters that have formed complex optical inhomogeneity is highly relevant.

3. **Experiment**

The main goal of this work was to obtain and visualize optical inhomogeneity formed by changes in pressure and temperature. Due to the fact that in laboratory conditions it is rather difficult to create a pressure gradient in the air that is perceptible for BOS, it was decided to perform an experiment using a solid. The experimental setup scheme was a standard BOS-scheme, in which a plane-parallel glass plate with internal defects caused by residual mechanical stresses acted as a test object. A schematic representation of the experimental setup is presented in figure 3.

The experiment was concluded to the registration of several series of images of the background screen. Each subsequent series differed from the previous one by introducing additional optical inhomogeneity. The plane-parallel plate was installed normally to the optical axis of the camera lens on the metal surface, with which it was fixed using a metal clamp. With the help of these clutches inside the plate, the occurrence of mechanical stresses was provoked, due to which an optical inhomogeneity was formed due to the pressure gradient. After that, without unclamping the plate under study, its lower interface was heated with a candle flame. Thus, an optical inhomogeneity
caused by a temperature gradient arose inside the plate. The heating temperature of the metal surface on which the plate was located was measured using a chromel-copel type thermocouple connected to a digital multimeter. Images were recorded at temperatures of 75 °C, 100 °C, and 125 °C on a JAI RMC-2030GE camera with a high-aperture lens. The frame-rate was 16 fps at a resolution of 1600 × 1200 pixels. The distance from the edge of the lens to the background screen was 0.515 m, the plate itself, 5 mm thick, was located at a distance of 0.2 m from the background screen.

**Figure 3.** Schematic of the experimental setup: 1 – background, 2 – test-object (plane-parallel glass plate), 3 – digital multimeter, 4 – camera, 5 – computer.

4. **Experimental results**

The processing of the obtained images was performed in the PivView 2C v.3.8.0 (demo version) with the same settings for all image sequences.

| Table 1. PIV Evaluation setup. |
|--------------------------------|
| Window size | 64×64 px             |
| Step size   | 16×16 px             |
| Correlation mode | Standart (FFT) correlation |
| Interrogation mode | Multiple-pass interrogation; 2 passes |
| Sub-pixel peak fit | 3-point Gauss fit |

At the first stage of processing, the background image without plane-parallel plate between the camera and the screen on which camera was focused was used as a reference frame. An example of the processing results is shown in figure 4.
From these results, it can be concluded that the mechanical stresses inside the plate cause significantly greater distortion of the image in comparison with the distortions caused by changes in pressure and temperature. However, analyzing the processed images for each series, it was noted that during the passage from frame to frame, the displacement fields differ slightly from each other. These minor differences are precisely due to the inhomogeneities formed due to compression and heating of the plate. For this reason, processing was performed for each sequence using background image with a plane-parallel plate between the camera and the screen as a reference. The corresponding results are shown in figure 5.

It can be seen from this figure that the image displacement values for this experimental scheme are rather small and lie in the range from 0.5 to 1.5 pixels. Nevertheless, visualizing the inhomogeneities caused by changes in pressure and temperature is possible.

Since, during the experiment the plate was first deformed and then heated up, it becomes possible to separate the effects of pressure and temperature during visualization. To do this, for processing a series of frames with heating of the plate, the image on which the plate is deformed but not yet heated should be used as a reference frame. As a result, the image displacement field will be obtained, due only to a change in temperature. An example of such processing is shown in figure 6.
5. Conclusion

One of the most commonly used refractometric methods for visualizing optical inhomogeneities is BOS. This method has a certain potential as a measuring technique for obtaining the distributions of various environment characteristics related to its refractive index. However, to obtain sufficiently accurate data, it is necessary to obtain information on each of the factors that formed inhomogeneity separately.

In the course of the work, an experiment was carried out to investigate the optical inhomogeneity formed in a glass plate by the influence of temperature and mechanical stresses. Processing of experimental images showed that it is possible to visualize the distribution field of each parameter in
the presence of another if their changes do not occur at the same time or the distribution of one of them is known.

References
[1] Belozerov A F 2014 Modern technologies for creating systems of optical and physical measurements of gas-dynamic fields with sizes up to 1000 mm *Optoelectronics, Instrumentation and Data Processing* 5 50 429–41
[2] Inshakov S I 2007 Visualization of gas flows structures by mean of schlieren and interferometry methods *Vestnik Samarskogo Gosudarstvennoy Aerocosmicheskogo Universiteta im. S.P. Koroleva* 2 13 108–13
[3] Ota M, Leopold F, Noda R and Maeno K 2015 Improvement in spatial resolution of background-oriented schlieren technique by introducing a telecentric optical system and its application to supersonic flow *Experiments in fluids* 56 48 1–10
[4] Bauknecht A, Ewers B, Wolf C, Leopold F, Yin J and Raffel M 2015 Three-dimensional reconstruction of helicopter blade-tip vortices using a multi-camera BOS system *Experiments in fluids* 56 1866 1–13
[5] Venkatakrishnan L, Suriyanarayanan P and Jagadeesh G 2013 Density field visualization of a micro-explosion using background oriented schlieren *Journal of Visualization* 16 177–80
[6] Cox A N 2000 *Allen's Astrophysical Quantities* (New York: Springer)