ALGORITHMS FOR QUANTITATIVE DIAGNOSIS
OF OPTICAL HETEROGENEITIES BY MEANS
OF LASER REFRACTOGRAPHY

V. T. Nguyen, I. L. Raskovskaya, and B. S. Rinkevichius

The basic principles of a new measurement technology, that of laser refractography, intended for visualization and quantitative diagnostics of transparent optically heterogeneous media are described. Algorithms for processing experimental refractographic patterns and for establishing the profile of an heterogeneity are presented. Results of measurements of the temperature distribution in a spherical boundary layer on a heated sphere in water are presented. An estimator of the measurement error is presented.

Key words: laser beam, refraction, laser refractographic pattern, heterogeneous medium, structured laser radiation, boundary layer.

Laser refractography. Laser refractography is a new method of laser diagnostics of transparent optical heterogeneities and flows [1] based on the phenomenon of refraction of structured laser radiation in optically heterogeneous media, digital recording of the refraction pattern, and computer processing of this pattern. The method is used for display and quantitative investigation of transparent stationary and nonstationary heterogeneous media [2, 3].

Structured laser radiation. This type of radiation constitutes radiation that is spatially modulated with respect to amplitude, and is produced by means of classical and diffracted optical elements or a structured screen [4].

The method used to create structured laser radiation preserves the high degree of coherence of the radiation and ensures low divergence of the beams. This makes it possible to use the assumptions of geometric optics to describe the radiation. Within the framework of geometric optics, a model of structured laser radiation may be represented by a family of beams forming surfaces in the form of a discrete set of planes, embedded cylinders, cones, etc. The principal elements of the radiation sources are classified in terms of the form of the geometric spatial figures formed by the beams from the source; these may be linearly, planarly, or conically structured laser radiation.

Structured laser radiation that has passed through a heterogeneity is projected onto a screen in the observation plane, thus forming what is known as a two-dimensional refraction pattern. Note that because of the high intensity of structured laser radiation, it is also possible to conduct observations in scattered radiation using three-dimensional refraction patterns, i.e., by means of surfaces formed by refracted geometric optical beams [2].

The experimental two-dimensional refraction pattern that may be observed on the screen constitutes a two-dimensional image of a spatially structured radiation source create by an optical system, the medium being studied serving as the optical system. With the use of digital methods of recording and processing the refraction patterns as well as specialized software for the solution of the inverse problem of reconstructing the profile of a heterogeneity, it becomes possible to perform quantitative diagnostics of the heterogeneity simultaneous with visual observation of the latter.
The discrete and regular nature of the refraction patterns serves as optimal assurance of their suitability for digital recording and computer processing. Unlike direct-shadow methods, which are based on optical processing of images, computer processing enables us to achieve high precision in quantitative diagnostics of the profile of a heterogeneity. Quantitative diagnostics may be understood as referring to the solution of an inverse problem and consists in the determination of the parameters of the heterogeneity (specified by means of a parametric model) or the reconstruction of its profile in the form of a finite set of numbers [2, 3].

**Principles of Quantitative Diagnostics of the Profile of a Heterogeneity.** Quantitative diagnostics of the profile of heterogeneous media essentially represents a problem of tomography, the solution of which generally utilizes an integral Radon transformation. In the case of axisymmetric heterogeneities, this reduces to an Abel transformation possessing an analytic transformation. The problems that arise with the use of Abel’s integral equation are related to the fact that the transformation problem is ill-posed, since it is necessary to differentiate noise-contaminated experimental measurements as well as overcome a singularity in the integrand [5, 6].

An alternative approach would involve a solution of the direct problem of refraction of a family of beams forming structured laser radiation and the calculation of the corresponding diffraction patterns for the purpose of comparing them with experimental patterns. The profile of an index of refraction that assures the best coincidence of the resulting experimental refraction pattern with the calculated pattern is considered the result of a measurement. The measurement error is determined by many factors and may be significantly reduced with the use of methods for special processing of refraction patterns [7–10].

Let us consider the successive stages of such quantitative diagnostics [2] using as an example refraction patterns for a thermal boundary layer:

1) recording of a two-dimensional refraction pattern by means of a CCD photographic camera;
2) performance of special computer processing to minimize the diffraction effects;
3) comparison of the digitized experimental refraction pattern with a set of reference refraction patterns calculated for a given plant and typical profiles of a thermal layer;
4) selection of the calculated reference diffraction pattern that coincides best with the experimental pattern on the basis of the criterion of minimization of the standard deviation; and
5) selection of the profile that corresponds to the selected calculated diffraction pattern as the experimentally obtained temperature profile.

The proposed approach to the solution of the inverse problem of reconstruction of the field of the index of refraction in transparent heterogeneities makes it possible to avoid problems associated with the transformation of Abel’s equation for noise-contaminated experimental data. The use of the method of refractography also makes it possible to perform an adaptation of the field of the index of refraction not only of three-dimensional heterogeneities, but also of fine transparent layers,