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Analysis of the effect of regular and stochastic phase structures on the optical quality of the active medium flow in gas-dynamic lasers

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Abstract. **The detailed structure of the active medium in a gas-dynamic laser is analysed. The parameters of regular and stochastic phase field components are reconstructed from the results of processing the schlieren patterns of the flow field simulated by cold air. The second-order characteristics are obtained in the form of the spectral density of power and correlation distribution function of stochastic inhomogeneities; the integral scale of the phase perturbation is also determined. The standard deviations in perturbations of the regular and stochastic components are compared and a correct prediction of laser radiation parameters is made for several cases of the laser beam propagation through the phase-perturbing active medium.**

Keywords: *active medium, gas-dynamic laser, regular phase perturbations, stochastic phase perturbations*

Optical inhomogeneities of the medium in which laser radiation propagates are, as a rule, the perturbations of the refractive index caused by a change in the density and (or) composition of the medium. These inhomogeneities adversely affect the parameters of the laser beam, leading to its deviation, flicker, scattering, divergence, etc., and, hence, reduce the intensity of radiation focused on a target or propagating through considerable distances.

In the present case, we can speak not only of inhomogeneities encountered by a laser beam propagating from the output aperture to the region of operation, such as atmospheric turbulence or gas screens separating the optical cavity from the outer atmosphere, but also of fluctuations in the active medium (AM) itself. Perturbations in the AMs of gas-flow lasers affect their operation most significantly. Such lasers include gas-dynamic lasers (GDL) because their active medium is extended considerably in the direction of propagation of a laser beam and the optical homogeneity of the AM is disturbed by a variety of complex processes.

The gas-dynamic parameters of the AM in GDLs are such that the regular (static) and stochastic (fluctuation) components can be separated in the structure of emerging phase perturbations. The first component corresponds to a nonuniform distribution of gas-dynamic parameters in the averaged flow and is associated with the formation of a regular shock-wave structure in the supersonic flow and inhomogeneous distributions of its parameters in the turbulent wake. It is quite reasonable to assume that the parameter averaged over the lasing time remain virtually unchanged and that such perturbations lead to the formation of a nonuniform wave front (WF) of radiation at the output aperture of the laser.

The second component, which is exclusively spatially irregular and nonstationary in the general sense, corresponds to oscillating perturbations caused by gradual turbulisation of the flow. The averaging of this component over the lasing time does not lead to any visible distortion of the WF, but this component causes the loss of spatial coherence of radiation, resulting in the deterioration of the integral quality of the laser beam.

Because the above phase perturbations of the gas-dynamic field (the refractive index field) are evidently of different physical origin, it can be expected that the extents to which each component affects the final parameters of laser beam will be different. Therefore, the models for taking into account the effect of each component will differ in principle. For the regular phase field, the application of the scalar diffraction theory [1] is the most traditional method of simulating the propagation of radiation, while the approaches developed in the theory of optical wave coherence [2] are suitable for describing the action of the stochastic component.

It should be noted that the problem of aerooptics of the AM of gas-flow lasers as such has been investigated comprehensively [3 – 8], including the AM of a GDL [4, 7, 8]), but some of its aspects remain unclear. This problem is of fundamental importance in the search of ways for improving the efficiency of gas-flow lasers. The aim of this paper is to analyse in detail the structure of phase perturbations in the AM of a GDL, to reveal their origin and the relation between the contributions from individual components of the structure, to predict reliably the extent of the influence of perturbations on the integral quality of laser radiation estimated from the radiation pattern [1]. Since we consider in the long run the parameters of laser radiation propagating through the phase-inhomogeneous AM, it is expedient to use optical probing for measuring the extent of AM inhomogeneity. In this case, the radiation WF at the output aperture carries information on the integral structure of inhomogeneities along the direction of optical probing.

To obtain detailed information on the structure of local, especially statistical perturbations, it is necessary to use a

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number of restricting hypotheses. Such an approach is quite justified because an analysis of the dynamics of statistical ensembles encounters considerable difficulties even in the case of numerical simulation, while experimental data are, as a rule, incomplete and do not reflect the evolution of the structure of the gas-dynamic field in detail.

The most traditional hypotheses are listed below.

(1) The gas flow under study is two-dimensional (planar) by nature because the AM flow formed by a model block of planar nozzles and a rectangular gas-dynamic channel were considered in the experiments [8].

(2) The structure of phase perturbations in the AM has two components (regular and random). The first component is reproduced completely from experiment to experiment for identical flow parameters, while the second component is statistically repeated taking into account the assumption concerning its ergodicity.

(3) The statistical characteristics of the random WF component vary slowly and, hence, we can speak of the inhomogeneity of a random process in a broad sense within the probing aperture.

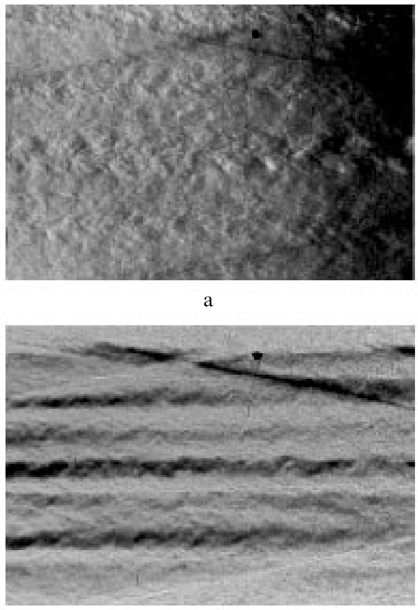
(4) A random process caused by refractive index (density) fluctuations due to turbulence is regarded as homogeneous in space and isotropic in the plane orthogonal to the flow; this allows us to go over to an analysis of radiation parameters in any direction.

(5) The lasing and gain time in a GDL is assumed to be several orders of magnitude longer than the turbulence characteristic time scale, which necessitates the application of the coherence theory for the calculation and analysis of the radiation pattern.

(6) The distorting effects of the regular and random components of phase perturbations in the AM on the initially plane WF of radiation passing through the gas flow can be analysed separately; the regular component of the signal can be analysed using the geometrical optics approximation, while the scattering caused by the stochastic component should be estimated in the approximation of the solution of Maxwell's equations using the method of small perturbations, i.e., taking into account diffraction and flicker [2].

The limitations considered above determine the requirements imposed on the method of optical visualisation of the structure of a supersonic flow with the characteristic Mach number ~ 5. The method should provide a high space – time resolution and the possibility of restoring the adequate quantitative information on the distribution of local angles of inclination of the probing radiation WF or of the quantities proportional to phase incursion. To a certain extent, these requirements are met in the schlieren method [9]. The spatial resolution of this method is determined by the optical system, discreteness, and the dynamic range of a detecting instrument, while the time resolution is determined by the duration of the probing radiation pulse.

Fig. 1 shows two schlieren patterns (kindly provided by V M Mal'kov) of a gas flow (cold air blowing under the stagnation pressure $P_0 = 2.5 \times 10^6$ Pa and the stagnation temperature $T_0 = 300$ K) behind the fragment of a nozzle vane block of a GDL, whose structural features are described in detail in Ref. [10]. The schlieren patterns differ in the orientation of the optical knife relative to the flow direction: the patterns shown in Figs 1a and 1b were observed for its horizontal and vertical orientations, respectively. The time resolution $\sim 10^{-6}$ s was provided by a spark source of white light. It is important to note that although the real AM flow was simulated with the help of cold air, all main peculiarities of the gas-dynamic structure of the flow were observed during the simulation.



a

b

Figure 1. Schlieren patterns of the AM part in a GDL simulated by cold air at a distance of 16 cm from the nozzle block exit section (flow direction from left to right) for (a) horizontal and (b) vertical orientations of the optical knife.

The investigated region of the supersonic flow formed by three nozzle vanes was separated from the nozzle exit section by ~ 15 cm, i.e., approximately by 10 diameters of the exit section of the nozzle. At such a distance from the nozzle array, the regular shock-wave structure dissipates almost completely and only the perturbations of turbulent wakes remain in the field of vision.

In the geometrical optics paraxial approximation, the schlieren method provides the detection of the intensity variation $\Delta I = I - I_0$ at each point of the observation plane at the right angle to the optical knife edge [9]. This variation is proportional to the inclination angle ε of the WF in the object plane; i.e., the following relation holds:

$$\varepsilon = -\frac{2a}{f_1}\frac{\Delta I}{I_{00}}.$$

Here, I is the intensity distribution in the observation plane in the presence of the object under study; I_0 is the intensity distribution in the absence of distortions introduced by the object (i.e., without the object); I_{00} is the intensity distribution in the observation plane in the absence of the knife and the object; $f_1 = 1.6$ m is the focal length of the principal objective and $a = 0.25$ mm is the half-width of the optical slit. In order to maintain a high spatial resolution in the entire probing region of size ~ 76 mm $\times$ 56 mm for a probing depth of 50 mm, photometric fields were recorded on a photographic film whose blackening density was then digitised with a high spatial resolution.

The schlieren patterns for different orientations of the optical knife were recorded in different experiments under identical operating conditions. This means that the regular component of phase perturbation corresponding to the averaged flow is reliably produced on the patterns (taking into account the spatial referencing). However, for the random component of the signal caused by turbulent irregularity, various realisations of a stochastic process exist, i.e., these realisations are similar only in a statistical sense.

Because the random component is superimposed on the regular component additively and the assumption concerning the reproducibility of the regular perturbation component is valid, we managed to separate correctly the regular and random components, i.e., to reconstruct the 2D regular WF component and the 1D transverse and longitudinal cross sections of the random component from the angles ε_x and ε_y of deviation of the WF of probing radiation in orthogonal directions. The separation procedure is based on a specially developed linear filtration algorithm [11], where the pulse characteristic of the filter is taken in the form of a 2D sequence of counts in the form

$$h(i,j) = \mathrm{rect}\left(\frac{i}{h_n}\right)\mathrm{rect}\left(\frac{j}{h_m}\right).$$

Here,

$$\mathrm{rect}(x) = \begin{cases} 1 \text{ for } x \in [-0.5, +0.5], \\ 0 \text{ for } x \in]-\infty, 0.5[\text{ and } x \in]0.5, +\infty[; \end{cases}$$

and indices i and j are the numbers of counts in two selected orthogonal directions (any integer values); h_n and h_m are the dimensions of this 2D sequence (of counts). In order to find the filter parameters, the signal was analysed only in the spatial region. Because the stochastic component averaged over the sequence of realisations as well as over the space is equal to zero, we can choose the maximum size of the filter window in the directions of the x and y axes for which the regular component of the signal can be still regarded as linear and the effect of the fluctuation component is reduced to zero as a result of its almost complete averaging within the same window. It is in this case that we obtain the best estimate of the regular distortion of the WF by averaging the signal for the central count in the chosen window.

The filter is invariant to the displacement and separable; consequently, the parameters h_n and h_m were sought independently. The size of the optimal window of the filter was chosen proceeding from the dependence of a certain criterion on the window size. This criterion characterised, first, the quality of the averaging of the stochastic component within a window and, second, the degree of linearity of the regular component in the same limits. Such a criterion can be the local dispersion of the signal averaged by the filter with a given window size in the direction x, which was calculated for its individual cross section parallel to the y axis (similarly, we can carry out averaging in direction y and calculate dispersion for cross sections parallel to the x axis). However, we chose for the criterion the dispersion calculated over the entire aperture of probing because the regular component changes insignificantly within the aperture, which corresponds, for example, to the structure of a developed turbulent wake.

The processing of schlieren patterns (see Fig. 1) proved that after the separation of components, the root-mean-square deviations of the slopes ε_x and ε_y of the regular WF component for the longitudinal and transverse gradients are 25 and 55 mrad, respectively, while the corresponding values for the fluctuation components in the same directions are 13 and 9 mrad. Thus, the deviation in the slopes for the regular component is obviously larger than for the stochastic component. In addition, it is also apparent that the spread of the slopes in the orthogonal directions is also anisotropic, the transverse spread for the regular component being approximately twice as large as the longitudinal spread, while for the stochastic component, on the contrary, the longitudinal spread is larger than the transverse spread almost by a factor of 1.5.

Fig. 2 shows isometry of the regular component of the WF reconstructed as a result of simultaneous processing and filtration of two schlieren patterns. Apart from the transverse periodic perturbations from turbulent wakes, the component also contains longitudinal large-scale aberration. Its origin can be easily explained by the presence of intense dissipative processes accompanied by a gradual stagnation of the supersonic flow and an increase in the background

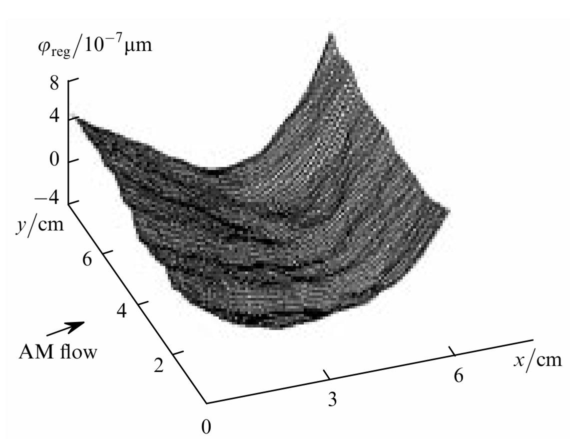


Figure 2. Regular WF component of probing radiation at $\sim$ 0.5 mm.

density (i.e., an increase in the refractive index as well).

A more detailed analysis proved that the downstream variation in the refractive index is quadratic, as in the case of a cylindrical lens with an off-central (along the flow) arrangement relative to the aperture. This allows us to separate a linear component from such an aberration, which is known to produce no effect on the radiation divergence. The remaining symmetric quadratic aberration directly affects the radiation divergence without violating, however, the self-similar structure of the radiation pattern. Moreover, the lens aberration can be compensated quite easily using the simplest optical methods.

At the same time, the residual component of regular aberration of the WF after elimination of the wedge and lens components has a noticeable wave aberration (the difference between the maximum and minimum phase incursion) $\Delta\varphi_{\mathrm{reg}} = \max\varphi_{\mathrm{reg}} - \min\varphi_{\mathrm{reg}} = 0.6$ μm and the root-mean-square deviation $\sigma(\varphi_{\mathrm{reg}}) = 0.1$ μm. If we conditionally assume that the wavelength of probing radiation is $\lambda \approx 0.5$ μm, then $\Delta\varphi_{\mathrm{reg}} = 1.2\lambda$ and $\sigma(\varphi_{\mathrm{reg}}) = \lambda/5$.

Fig. 3a shows the downstream variation of the root-mean-square deviation of the regular WF component in the transverse cross sections (i.e., along the longitudinal coordinate x). Such a nonmonotonic variation in the phase spread points to a complex type of the flow in which turbu-

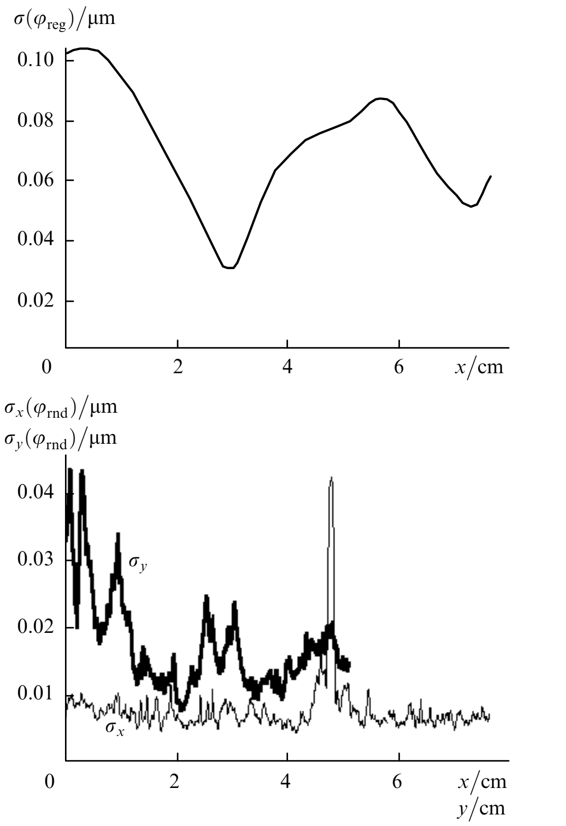


Figure 3. Root-mean-square deviations of (a) regular and (b) random components of the WF phase of probing radiation at the vertical sections as functions of the longitudinal coordinate x and in the horizontal sections as functions of the transverse coordinate y.

lent wakes interact with each other and the regular component of the gas-dynamic field can exhibit some nonstationarity.

It was mentioned above that the information on the stochastic WF component can be obtained only for individual series of 1D cross sections parallel or orthogonal to the flow. At the same time, statistical estimates in each series allow us to predict the behaviour of a 2D random process. Fig. 3b shows the dependences of the root-mean-square deviation of the pulsating component of wave aberration for cross sections in the longitudinal and transverse directions.

One can see from Fig. 3b that the spread in the phase incursion for the stochastic component in transverse series decreases slowly downstream, thus indicating a gradual decay of gas-dynamic perturbations. The dependence of the spread in the longitudinal cross sections (on the transverse coordinate y) contains a distinct multimode structure in which the periodic increase in perturbations (true, no more than by 30 % – 40 %) takes place on the longitudinal axes of each of the three turbulent wakes. The estimates of the mean spreads of the stochastic component of the WF phase incursion give the following values: $\sigma_x(\varphi_{rnd}) = 0.018$ μm for the cross sections longitudinal relative to the flow direction and $\sigma_y(\varphi_{rnd}) = 0.009$ μm for the cross sections transverse to the flow.

As in the case of spreads in the WF slopes, the twofold difference in the phase incursions for the chosen orthogonal directions can be attributed precisely to the turbulence anisotropy. Because a considerable difference in the velocity gradients of the gas flow in the transverse and longitudinal directions, the conditions for the transformation of a microvortex structure are different in these directions, which leads to the anisotropy of statistical characteristics of the phase field.

A direct comparison of the effects of the regular and stochastic WF components shows that the root-mean-square spread in the transverse sections for the regular component of the WF exceeds the spread for the stochastic component by a factor greater than 11, while the difference for the longitudinal sections is more than fivefold! In other words, along with the considerable difference in regular and stochastic distortions, a considerable anisotropy of perturbations from each component is also observed in the orthogonal directions.

It would be interesting to consider in greater detail the features of a steady-state random process associated with turbulent perturbations and to find its second-order statistical characteristics such as the spectral power density and the correlation function. Because the formal calculation of 1D spectral power densities of WF fluctuations for the x and y directions leads to statistically nonrealistic estimates, we should perform pseudoaveraging over the ensemble using, for example, a method similar to that proposed by Bartlett [12].

Taking into account the assumption concerning the quasi-uniformity of the random process under study, we can carry out pseudoaveraging over the ensemble by averaging selected spectra in several sections in the vicinity of the chosen section. It is quite reasonable to choose the size of the averaging window equal to the size of the filter window used for separating the regular and fluctuating components of the WF slopes. To obtain a statistically reliable estimate of the spectral power density, the sections should be statistically independent within the averaging window. In our case, this condition holds well mainly because of the absence of information on the second gradient in each specific realisation of the random process.

It was proved in Ref. [13] that even considerable inhomogeneities of the parameters of the random WF component over the aperture area do not affect significantly the radiation parameters in the far-field zone as compared to homogeneous distortions with the same dispersion. Thus, extending the averaging window over the entire aperture, we can estimate the space-averaged spectral power densities of WF fluctuations in the x and y directions. Fig. 4 shows the aperture-averaged spectral power density for the random component of the signal for directions perpendicular and parallel to the flow.

One can clearly see that averaged power spectra are nonmonotonic; a number of individual modes are distinctly observed against the background of the continuous spectrum. Their presence cannot be attributed to the possible error in the estimate because spikes are much higher than the specially calculated error in the reconstruction of the spectrum. The presence of the modes cannot be explained by the limited spectral resolution of the signal either because the width of individual modes is much larger than the minimum size of the spatial resolution cell. At the same time, the mode nature of the turbulence spectrum is indeed predicted by the classical theory [14].

Fig. 5 shows the dependences of space-averaged autocorrelation functions on the distance $C(\rho)/C(0)$ along and across the flow taking into account the fact that the spectral power density and the correlation function are related by the

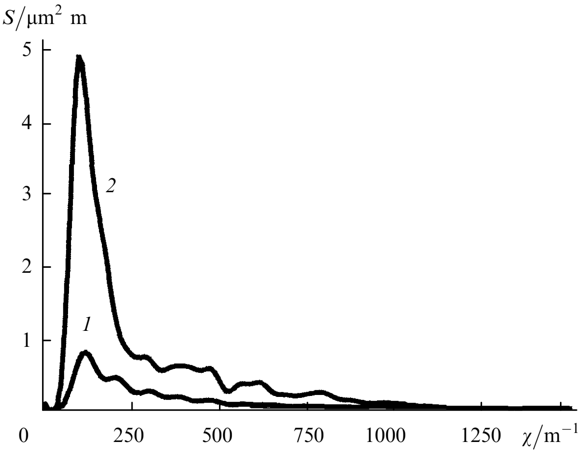


Figure 4. Aperture-averaged spectral power density of the random WF component in the longitudinal (*1*) and transverse (*2*) directions as a function of the wave number of spatial phase distortion $\chi = 2\pi\nu$.

Fourier transform in accordance with the Wiener – Khinchin theorem [11]. Knowing these data, we can easily estimate the integral scale of WF fluctuations, which is undoubtedly correlated with the integral scale of turbulent pulsations. The integral scale can be regarded as a parameter characterising the correlation radius of the stochastic WF component [3]:

$$\Lambda = \frac{1}{C(0)}\int_0^\infty C(\rho)\mathrm{d}\rho.$$

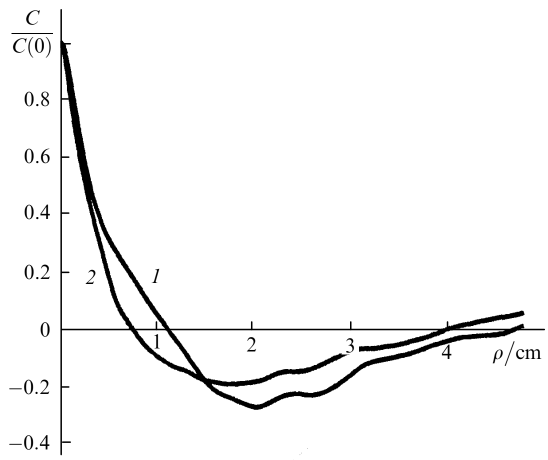


Figure 5. Dependences of the normalised correlation function on the length of the radius vector ρ of the random WF component in the longitudinal (*1*) and transverse (*2*) directions.

Thus, the absolute integral scale along the flow is $\Lambda_x = 9.5$ mm and the integral scale across the flow is $\Lambda_y = 7.1$ mm. It is interesting to note that the relative (i.e., referred to the corresponding aperture size in an appropriate direction) integral scales in both directions are 0.13. Because the integral scale along the flow turned out to be 1.3 times larger than the corresponding scale across the flow, turbulent vortices should be extended on the average along the flow (see above).

The possibility of predicting the quality of laser radiation (or the optical quality of the AM) remains the most complicated and at the same time the most important problem in estimating the efficiency of a GDL even in the case of a single-pass laser amplifier in a direction perpendicular to the direction of optical probing, i.e., at a right angle to the edges of the nozzle block vanes. The possibility of extending the obtained results adequately to an AM of a larger size in the direction of beam propagation and of restoring the information for the emission wavelength of a GDL are also important.

The application of the approaches developed in Ref. [15] allows us to obtain the following relation for estimating the effect of a 3D random field of the refractive index on the spectral power density $S_1(\chi_x, \chi_r, l_1)$ of WF perturbations for any length l_1 over which radiation propagates and for the emission wavelength of radiation with the wave number k_1:

$$S_1(\chi, l_1) = \frac{k_1^2 l_1}{2k^2 l}\left[1 + \frac{k_1}{\chi^2 l_1}\sin\left(\frac{\chi^2 l_1}{k_1}\right)\right]S(\chi, l),$$

$$S_1(\chi_x, \chi_r, l_1) = \frac{k_1^2 l_1}{2k^2 l}\left[1 + \frac{k_1}{\chi_t^2 l_1}\sin\left(\frac{\chi_t^2 l_1}{k_1}\right)\right]S(\chi_x, \chi_r, l_1),$$

where $\chi = (\chi_x^2 + \chi_y^2)^{1/2} = \left[(2\pi\nu_x)^2 + (2\pi\nu_y)^2\right]^{1/2}$; $\chi_t = (\chi_x^2 + \chi_r^2)^{1/2}\left[(2\pi\nu_x)^2 + (2\pi\nu_r)^2\right]^{1/2}$ is the wave number of stochastic WF perturbations in the aperture plane (subscript x corresponds to the direction of the flow and subscript r to the direction orthogonal to the plane formed by the direction of the flow and the direction of probing); l is the probing length in the medium; k is the wave number of radiation at which optical probing was carried out; k_1 is the wave number of radiation for which the spectral power density of the WF is estimated. The 2D power density $S(\chi_x, \chi_r, l)$ of the random WF component can be estimated from optical measurements assuming the separation of variables for the probing length l:

$$S_k(\chi_x, \chi_y, l) = \frac{S_x(\chi_x)S_y(\chi_y)}{(\sigma_x^2\sigma_y^2)^{1/2}},$$

$$S(\chi_x, \chi_r, l) = \frac{S_x(\chi_x)S_r(\chi_r)}{(\sigma_x^2\sigma_r^2)^{1/2}},$$

where

$$\sigma^2 = \int_\infty S(\chi)\mathrm{d}\chi$$

is the estimate of the dispersion of the WF random component (which was obtained earlier for the x and y directions); in the case of the probing direction, the subscripts r and y are equivalent.

We can now estimate the degree of transformation of the radiation pattern for a plane monochromatic wave propagating in the medium containing the regular and random perturbation components with known parameters and structure. Using the Shell theorem [1] for a quasi-monochromatic narrow-band source, we can obtain the light intensity distribution in the far-field zone:

$$I(x, y) = \iint_\infty P(\Delta\varsigma, \Delta\eta)\mu_{12}(\Delta\varsigma, \Delta\eta) \times \exp\left[-j\frac{2\pi}{\lambda z}(x\Delta\varsigma + y\Delta\eta)\right]\mathrm{d}\Delta\varsigma\mathrm{d}\Delta\eta,$$

where

$$\varsigma = \frac{x_1 + x_2}{2}; \quad \eta = \frac{y_1 + y_2}{2};$$

$$\Delta\varsigma = x_2 - x_1; \quad \Delta\eta = y_2 - y_1;$$

$$P(\Delta\varsigma, \Delta\eta) = \iint_{\infty} p\left(\varsigma - \frac{\Delta\varsigma}{2}, \eta - \frac{\Delta\eta}{2}\right) p^*\left(\varsigma + \frac{\Delta\varsigma}{2}, \eta + \frac{\Delta\eta}{2}\right) \mathrm{d}\varsigma \mathrm{d}\eta$$

is the autocorrelation function of the pupil; $p(\varsigma,\eta) = \exp[-j\varphi(\zeta,\eta)]$ is the pupil function in the case of unit radiation intensity in the pupil; $\varphi(\varsigma,\eta)$ is the phase distribution for the regular component of the radiation WF. The complex coherence $\mu_{12}(\Delta\varsigma, \Delta\eta)$ for the Gaussian probability density distribution is determined from the relation [1]

$$\mu_{12}(\rho_1, \rho_2) = \exp[-\sigma^2 + C(\rho_1, \rho_2)],$$

where, as before, σ^2 is the dispersion of phase fluctuations and $C(\rho_1, \rho_2)$ is the autocorrelation function of phase fluctuations.

Fig. 6 shows two orthogonal one-dimensional sections of the radiation pattern obtained for radiation at $\lambda \sim 0.5$ μm. The WF distortions correspond to the AM length 56 mm in a direction orthogonal to the optical probing direction (the traditional direction of radiation formation is perpendicular to the vane edges). The existence of two phase components in the AM not only transforms the angular energy distribution in the beam, but also leads to the emergence of a characteristic incoherent halo in the radiation pattern. In addition, WF distortions reduce the maximum brightness of radiation, which is known to be the well-known criterion for the optical quality in the normalised form (Strehl number).

The results of processing of the schlieren patterns using the method described above were extended to several cases of passage of radiation through the AM, including the direction orthogonal to the vane edges, with an increase in length to 1 m. The most important predicted results are compiled in Table 1.

One can see from Table 1 that the effect of regular phase perturbations on the optical quality of the AM prevails in all cases. The fraction of the random component in the total Strehl number was found to be insignificant even for the traditional direction of the extraction of radiation orthogonally to the vane edges. This result is rather unexpected since it contradicts to a certain extent the generally accepted opinion that regular perturbations are subjected to complete integral averaging in the direction of radiation extraction.

It should be noted that the estimate presented in the last line of Table 1 is purely approximate. Even if the stagnation temperature increases to ~ 2000 K, we should not expect a fundamental difference in the structure of regular perturbations; i.e., wakes will be present in the flow all the same, as well as perturbations from shock waves in the regions close to the nozzle block. The difference can be only observed in the perturbation amplitude. On the other hand, the stochastic component may exhibit considerable changes which will be manifested in the transformation of the spectral density and the correlation function. This is due to a change in the most important parameters of the flow (such as the Reynolds number, the thickness of momentum loss at the nozzle exit section, and the dynamic viscosity of the gas), which determine the overall dynamics of the turbulent flow structure with increasing the stagnation temperature.

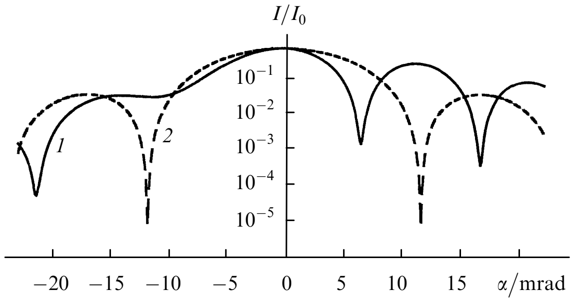


Figure 6. Orthogonal cross sections of the radiation pattern in the longitudinal (*1*) and transverse (*2*) directions.

Thus, the method developed by us for analysing schlieren patterns containing information on the regular and stochastic structures of phase perturbations in a flow simulated by cold air has made it possible to estimate the influence of each structure on the integral optical quality of the flow. It turned out that the effect of stochastic structures in the flow associated with its turbulence is not very strong. This is especially important since regular perturbations continue to play a decisive role even in the region of developed downstream turbulent wakes, in which the shock-wave structure formed behind the nozzle exit section disintegrated almost completely. Such a tendency is also preserved in a real flow in an AM in which the stagnation temperature is several times higher.

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Table 1. Prediction of the optical quality of the AM in a GDL

Blowing	Probing direction	λ/μm	l_1/cm	Strehl number		
				Total	Regular component	Random component
Cold	Optical probing direction (parallel to the vane edges)	0.5	5.6	0.39	0.4	0.98
Cold	In the traditional gain direction (perpendicular to edges)	0.5	5.6	0.51	0.52	0.98
Cold	In the traditional gain direction	10.6	100	0.77	0.79	0.99
Hot (density decrease by an order of magnitude)	In the traditional gain direction	10.6	100	0.99	0.99	1.00

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