Adaptive correction of beams from several lasers

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An adaptive system for correction of radiation from several mutually incoherent lasers is analyzed. Different adaptive correction algorithms are studied. It is shown that the character of an algorithm and its parameters significantly affect the system behavior. The speed of the adaptive correction system can be considerably increased due to proper selection of the algorithm.

Introduction

Application of adaptive optic systems (AOS) to focusing radiation from multibeam lasers seems to be promising in devices forming laser radiation with the given distribution of the field amplitude or intensity in some spatial region. Examples of the multibeam lasers are multichannel lasers[1,2] which make an assembly of several parallel waveguide tubes; the Yupiter laser[3] having a coaxial design of the discharge chamber and generating radiation in the form of beams of multipass modes (M-modes), as well as arrays of semiconductor lasers.[4] Multibeam lasers find use in optical astronomy, in systems for long-range transmission of radiation energy, as well as in open laser communication channels. Application of such systems for atmospheric optical communication lines is illustrated by “laser bridges” of MicroMax Computer Intelligence Inc.[5] These systems with a radiation source in the form of a set of semiconductor lasers are used in big settlements with continuously growing needs for new telecommunication services and no possibility of using fiber optics lines.

At the same time, practical use of the multibeam laser radiation in communication systems is limited due to atmospheric turbulence, which manifests itself in amplitude-phase distortions, decrease of radiation coherence, and random angular fluctuations of laser beams. Under these conditions, tuning beams toward the receiver and confining them within the receiver’s aperture is a very urgent task, in which the use of adaptive optical systems, being, in essence, systems for angular correction of radiation, becomes a necessity.

Characteristics of one of such systems designed for correction of wave fronts of the Yupiter laser were considered in Refs. 6 and 7, which present the results of numerical simulation of the laser, as well as demonstrate how the optical parameters of the measuring-control channel and radiation polarization affect the AOS operation. Investigations in these papers were conducted with allowance for coherent properties of M-modes of the Yupiter laser.

The search of ways to improve characteristics of real devices due to the AOS usage in the “laser bridge” systems revealed the need in additional investigations. Their urgency is caused by the fact that laser beams in these systems are not mutually coherent. Therefore, the results obtained for coherent systems cannot be directly extrapolated to the multibeam “laser bridges.”

In this paper, we study functioning of an adaptive optical system designed for correction of angular positions of beams from several mutually incoherent lasers.

Mathematical model

In the accepted model of an adaptive system, the correction quality is estimated in the standard way, that is, from the value of the focusing functional $J_{\rm d}$ for radiation having passed through the diaphragm of the measuring-control channel.[8]

As is known, in this case the focusing functional is determined by the equation

$$J_{\rm d} = P/P_0, \quad (1)$$

where P is the power of radiation having passed through the measuring diaphragm, P_0 is the power of radiation having passed through the same diaphragm in the case of ideal correction, that is, when all beams are brought together to the diaphragm’s center.

Note that the receiver’s aperture should be taken as a diaphragm in the considered laser bridges. However, the simulation can be restricted to the case of a diaphragm placed at the focus of an ideal lens located near the radiation source, since the character of the field distribution at the focus and in the far zone is the same. Certainly, this is valid for beams in the atmosphere affecting only their angular parameters. It is also assumed that the effect of atmospheric turbulence on the beam amplitude parameters is negligible. These assumptions correspond to the case of the weakly perturbed atmosphere and, thus, weak fluctuations of parameters of the received signal, when the beam profile is characterized by a rather high degree of homogeneity.[9]

It is usually believed that radiation is well corrected at $J_{\rm d} \geq 0.8$ (Ref. 8). In the process of an

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adaptive system operation, the focusing functional is estimated at each adaptation step, and the wave front is corrected so that J_d satisfies this condition.

In the mode under analysis, it is assumed that the amplitude distribution A_j in the cross section of each beam in the diaphragm plane is Gaussian and the same for all beams:

$$A_j = \exp[-(r_j/W)^2], \quad (2)$$

where W is the cross section radius of each beam; r_j is the current radial coordinate of a beam in the system related to its center; j is the beam number (j = 1, 2, 3).

The energy parameters of the beam in the diaphragm plane will be analyzed in the coordinate system with the origin at the diaphragm center. The number of lasers entering into the system is taken equal to three, since just this number is characteristic for the existing "laser bridges," in particular, those made by MicroMax.

Perturbations lead to random arrangement of beams. Denote the distance from the center of each beam to the diaphragm center as R_j. Its position in the accepted coordinate system is characterized by angle Ψ_j. In this case, the equation for the radiation power of beams of three mutually incoherent lasers within a diaphragm can be written as

$$P \approx \int_0^a \int_0^{2\pi} \sum_{j=1}^{3} \left| A_j(R_j, \Psi_j, r, \psi) \right|^2 r \mathrm{d}r \mathrm{d}\psi , \quad (3)$$

where a is the diaphragm radius; r and ψ are current radial and angular coordinates. The value of P_0 is determined by the same equation at $R_j = 0$.

To select the efficient correction algorithm, we should determine the behavior of the focusing functional at different variants of the control. In multibeam systems, two variants are possible: sequential and parallel.[6] In the first case, each next beam is centered at the diaphragm only after the control over the previous beam provides for the highest (current) value of J_d. In the case of the parallel variant, the control action for each beam is calculated only for one step, and then the system passes on to controlling the next beam. It is assumed that the correction takes rather short time, during which atmospheric perturbations do not change beam positions. In the process of operation, the position of only one beam is corrected at every instant, while the other beams are beyond the control.

To assess the properties of the focusing functional, a program was developed for determination of J_d at forced change of R_j. Calculations were conducted at the following system parameters: beam radius in the diaphragm plane W = 0.3 mm, laser radiation wavelength λ = 10.6 μm, and diaphragm radius a = 0.2 mm.

The calculated results are shown in Fig. 1. The plot is drawn for the case of sequential control, when the beams were initially located randomly along one of coordinates in the diaphragm plane. To simplify analysis, R_j was changed also along this coordinate with the step identical for all beams. In that case, it was convenient to analyze the behavior of J_d depending on the step number k, as shown in Fig. 1.

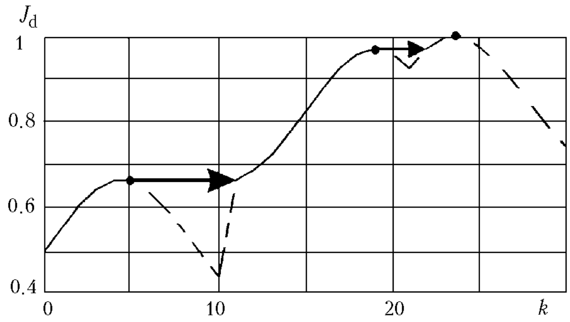

Fig. 1. Focusing functional J_d as a function of the step number k.

Note that variation of R_{j+1} for every subsequent (j + 1) beam began once the previous beam was set in the position corresponding to the local maximum of J_d. In this connection, the bold lines in Fig. 1 are for the moments of transition to the control of the next beam, and the dashed lines are for the J_d behavior after each beam has gone over its maximum.

It follows from Fig. 1 that dependence of J_d on the position of each beam is rather smooth function having one global maximum. This dependence of the focusing functional allows us to use not only the frequently used gradient method, but also the Newton method for angular correction, since, as known,[10] the latter is one of the fastest methods, but it gives good results only for smooth functions.

Results of numerical simulation of an adaptive system

To assess the efficiency of the sequential and parallel control algorithms, the operation of the adaptive correction system was analyzed using the both methods for each algorithm.

In the gradient method, the maximum of the focusing functional is determined through sequential comparison of values of $J_d(u_k)$ and $J_d(u_{k+1})$ at control actions u_k and u_{k+1} determined during the iteration procedure[10]:

$$u_{k+1} = u_k - \alpha J_d', \quad (4)$$

where α = const is the parameter of the gradient method; k is the iteration number (k = 0, 1, 2, ...).

The correction process was simulated with the system and beam parameters given in the previous section. Numerical experiments show that the best results in this case are achieved at α = 0.1. The accuracy of the gradient method, on reaching which the adaptation process was completed, was set as ε = 0.01.

Figure 2 shows the dependence of the focusing functional on k in the process of adaptation by the sequential and parallel algorithms. Both algorithms are based on the gradient method. In the first case, to complete adaptation at $J_d = 0.958$, 36 iterations were used. In the second case, after 58 iterations J_d increased only up to 0.874.

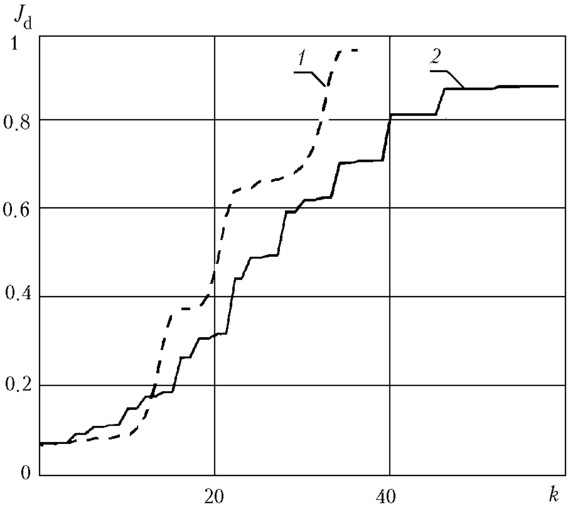

Fig. 2. Variation of the focusing functional in the process of adaptation by the gradient method: sequential (*1*) and parallel (*2*) control algorithms.

In the Newton method, the extreme point of $J_d(u_k)$ is determined by the algorithm[10]:

$$u_{k+1} = u_k - \beta\,(J'_d / J''_d), \tag{5}$$

where $\beta = \text{const}$ is the parameter of the Newton method.

The AOS operation was simulated at the same system and beam parameters as in the gradient method. We took $\beta = -0.4$ for the parameter of the Newton method. Calculations show that this value provides for the best adaptation characteristics. The results of numerical analysis are shown in Fig. 3.

In the sequential control algorithm, the adaptation is completed for 19 iterations with $J_d = 0.882$. In the case of the parallel algorithm, the focusing functional achieves $J_d = 0.851$ for 41 iterations, that is, in this case the sequential algorithm is again faster and provides the higher correction quality. Thus, the sequential algorithm with the use of the both (gradient and Newton) methods is preferable as compared to the parallel one.

The result obtained can be explained by the following peculiarity of the AOS operation: radial motion of each beam, characteristic of the sequential algorithm, provides, on the average, a steeper dependence of J_d on the control action than in the case of the parallel algorithm, in which the beams are contracted to the diaphragm center, on the average, by a spiral. In its turn, the higher steepness of J_d variation allows the position of the maximum of the focusing functional to be determined more correctly in the correction process.

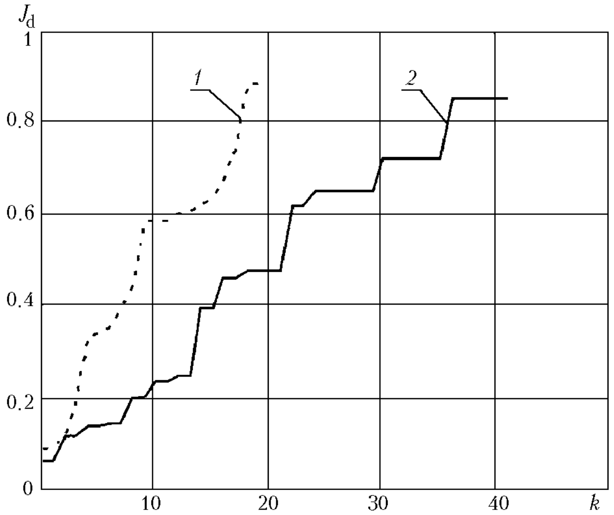

Fig. 3. Variation of the focusing functional in the process of adaptation by the Newton method: sequential (*1*) and parallel (*2*) control algorithms.

Since the most efficient method is needed in real AOSs, it is interesting to compare the algorithms' speeds based on the gradient and Newton methods. Figure 4 depicts variations of the focusing functional in the process of adaptation by two above methods in the sequential control algorithm.

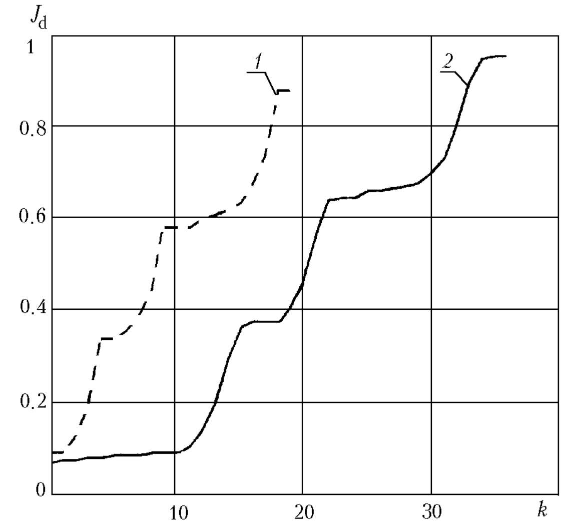

Fig. 4. Comparative characteristics of the methods in the process of adaptation by the sequential algorithm: Newton method (*1*) and gradient method (*2*).

The results depicted in Fig. 4 clearly indicate that with these AOS parameters the use of the sequential control algorithm based on the Newton method allows the speed of the adaptive correction to be almost doubled as compared to the algorithm based on the gradient method.

Conclusion

The results of investigation suggest the following conclusions:

1. For the conditions of an adaptive system functioning considered in this paper, the sequential control algorithm is more efficient than the parallel one and provides a higher speed at a higher quality of the angular correction of laser beams.

2. The dependence of the focusing functional on the control variables for several mutually incoherent lasers is a rather smooth function, which allows the use both of the gradient and Newton methods for the angular correction of beams.

3. The algorithm based on the Newton method allows the system speed to be almost doubled as compared to the algorithm using the gradient method.

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