DYNAMICAL ALGORITHMS FOR COMPENSATION OF NONSTATIONARY WIND REFRACTION

F.Yu. Kanev and S.S. Chesnokov

M.V. Lomonosov State University, Moscow
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The efficiency of adaptive control of a light beam under conditions of nonstationary wind refraction was analyzed numerically. The time required to optimize the parameters of the radiation was determined. Methods for reducing the optimization time are proposed.

The extensive development of atmospheric-optics systems has generated great interest in the theoretical prediction of the adaptive correction of distortions of light beams propagating in natural media. The basic principles of adaptive control of beams (aperture sounding and phase conjugation) have been investigated in detail in Refs. 1 and 2 for the example of stationary thermal self-action. In this approach the transient processes in the system "beam-medium" that strongly affect the efficiency and stability of the control algorithms are excluded from the analysis.

Compensation of nonstationary self-action was studied in Refs. 3–5; the main results are summarized in the monograph Ref. 6. It was established that phase conjugation, performed in real time, makes it possible to improve the focusing of low-intensity beams; for more powerful beams the average energy characteristics on the object increase, but a steady light field in the image plane is not formed. There are grounds for assuming that a detailed analysis of transient processes as well as a reasonable organization of a real-time iteration procedure will make it possible, on the one hand, to improve the convergence of the phase conjugation algorithm and, on the other, to reduce the focusing optimization timein the aperture sounding algorithm.

In this work adaptive focusing of intense light beams propagating under conditions of nonstationary wind refraction was studied numerically. The algorithms of aperture sounding and phase conjugation were studied from a unified point of view, the effect of the relaxation of the temperature field in the beam channel on the effectiveness of correction was analyzed, and the maximum optimization time for focusing performed both according to stationary and nonstationary parameters of the beam in the observation plane was evaluated.

MODEL OF THE ADAPTIVE SYSTEM

The theoretical analysis was performed based on the mathematical model for a typical adaptive system,[7] the controlling element of which is an elastic mirror with four servo-drives which is clamped at the center. A given phase distribution of the reflecting surface of the mirror was approximated with the help of the method of least squares. The degree of distortions of a beam propagating in a moving nonlinear medium is determined by the nonlinearity parameter R_V, which is proportional to the beam power $P_0 = \pi I_0 a_0^2$ and the radiation-medium interaction time $\tau_V = a_0/V$. Here a_0 is the initial radius of the beam, I_0 is the characteristic power density of the radiation at the inlet into the medium, and V is the velocity of the medium. The quantitative characteristic of the concentration of the light field in the observation plane $z = z_0$ is the focusing criterion

$$J_f(t) = \iint \exp(-(x^2+y^2)/a_0^2) I(x,y,z_0,t)\,dxdy, \qquad (1)$$

which is the relative fraction of the light power falling within an aperture of radius a_0.

We shall study briefly the basic beam-control algorithms.

1. In the aperture-sounding algorithm the goal function of control (this is usually the criterion $J_f(1)$) is optimized based on the procedure of "ascent on a hump":

$$\vec{F}_{n+1} = \vec{F}_n + \alpha_n \operatorname{grad} J_f(t), \qquad (2)$$

where F_n is the vector of the controlling coordinates of the mirror (forces and moments), n is the number of the iteration, and a_n is the gradient step, which in the general case depends on n. The vector of the control coordinates determines uniquely the deflection of the mirror $W(x, y, t)$ and the phase profile of the beam $U = 2kW$ (k is the wave number).

2. In the phase conjugation algorithm the correcting phase is given by the equation

$$U_{n+1}(x,y,t) = -\varphi_n(x,y,t), \qquad (3)$$

where $\varphi(x, y, t)$ is the phase measured in the plane $z = 0$, of the wave scattered by the object. In a nonlinear medium the algorithm has an iterative character and converges only if the nonlinearity of the medium is weak ($|R_V| < 10$).[3] To improve the stability of the algorithm, different modifications are employed:

$$U_{n+1} = U_n - \alpha_n (U_n + \varphi_n); \tag{4}$$

$$U_{n+1} = U_{max} - \alpha_n (U_{max} + \varphi_n), \tag{5}$$

where U_{max} is the phase profile giving the best compensation in all preceding iterations and a_n is a positive number, which decreases by a factor of two with each unsuccessful correction. As shown in Refs. 1 and 8, using Eqs. (4) and (5) substantially improves the convergence of the correction algorithms, but in the process additional information about the distribution of the field of the emitted wave in the object plane is required.

TRANSIENT PROCESSES IN THE "BEAM-MEDIUM" SYSTEM AND CONTROL STABILITY

Transient processes arise in the "beam-medium" system accompanying a change in both the amplitude and phase profiles of the beam. Numerical estimates show that the processes connected with the change in the amplitude (switching on of the pulse) and phase profiles have different durations, equal to, correspondingly, $\tau_A \simeq 5\tau_V$ and $\tau_{PH} \simeq 2\tau_V$. It should be noted that τ_A and τ_{PH} can change when parameters such as the data length, the beam power, and the amplitude of the changes in the profiles change, but in the process x^ and x remain practically constant in a wide range of values of the parameters of the problem.

We shall study the effect of transient processes on the efficiency of control algorithms. In the case of control based on the aperture-sounding algorithm (2) the direction of the gradient step is given by the vector grad J_f, whose components are the derivatives $\partial J_f / \partial F_j$ ($j = 1, \ldots, N$, where N is the number of control coordinates). To determine the derivative coordinates small trial increments δF_j are given to F_j. If the trial variations are performed until the transient processes terminate, then it is difficult to separate against the background of the change in the criterion $J_f(t)$ in time the response of the system to the increment δF_j; this causes the correction algorithm to diverge.

In reality, the change in $J_f(t)$ in a transient process can be described approximately by the expression

$$J_f(t) = A_1 + A_2 \exp(-t / \tau_x), \tag{6}$$

where A_1 and A_2 are empirically chosen coefficients and τ is the characteristic time of the transient process (τ_A or τ_{PH}). Since in calculating a gradient expressions of the form $\delta J_f = J_f(t_0 + \tau) - J_f(\tau)$, where t_0 is the time when the trial variation starts and τ is the characteristic time of the adaptive system, are employed we shall have$\delta J_f = A_2(\exp(-t_0 + \tau)/\tau_x - - \exp(-t_0/\tau_x) + B_1 + B_2(\exp(-\tau/\tau_x)$. Here B_1 and B_2 are analogous to A_1 and A_2, except that $B_j \ll A_j$ ($j = 1,2$). The gradient of the goal function can be determined reliably if the amplitude of the change in J_f in the transient process is less than the change in J_f caused by variation of the phase, i.e., when

$$|A_2 \exp(-t_0 \tau_x) \exp(-\tau/\tau_x - 1)| < |B_1 + B_2 \exp(-\tau/\tau_x)| \tag{7}$$

In the case of control based on an aperture-sounding algorithm the system has the following characteristic times: τ_1 is the time between the switching on of the pulse and the start of the trial variations; τ_2 is the time between the trial variations; and, τ_3 is the time between the start of the displacement of the mirror on the gradient step and the start of trial variations at the next gradient step. The condition (7) will be satisfied for the following ratios of the characteristics times:

1) $\tau_1 > \tau_A$; τ_2, $\tau_3 > \tau_{PH}$ – control based on the established field;

2) $\tau_1 \simeq \tau_A$; τ_2, $\tau_3 \simeq \tau_{PH}$ – the relation (7) is realized by selecting the coefficients A_2, B_1, and B_2, i.e., by choosing the amplitude of the displacement of the mirror; control in this case is realized under conditions close to steady-state conditions; and,

3) $\tau_1 < \tau_A$; $\tau_2 < \tau_{PH}$; $\tau_3 \ll \tau_A$, τ_{PH} – control based on nonstationary field.

It should be noted that in the case of control based on a nonsteady field there arises the problem of choosing the optimal length of the gradient step a, which does not change in the control process. For fixed conditions of propagation the optimal valueof a can be determined numerically.

As we have indicated above, when phase conjugation is used in highly nonlinear media ($|R_V| > 20$) the characteristics of the field in the observation plane indergo significant undamped oscillations, which can be suppressed with the help of the algorithms (4) and (5). In particular, the algorithm (5) has the following characteristic times: the time τ_1 between the start of the pulse and the start of the first iteration and the time τ_2 between iterations. The quantity U_{max} and the change in a can be determined only after the transient processes terminate (for $\tau_1 > \tau_a$, $\tau_2 > \tau_{PH}$). Otherwise it is impossible to determine U_{max} and a reliably. This limits the speed of the algorithm (5).

The time between iterations can be reduced by using the algorithm (4) with constant a, control based on which is realized for any ratio of the characteristic times of the system and the duration of the transient processes.

THE SPEED OF APERTURE SOUNDING

Control based on the aperture-sounding algorithm using stationary parameters of the light field is illustrated in Fig. 1a. The characteristic times of the adaptive system were chosen as follows: $\tau_1 = 5\ \tau_V$, and τ_2, $\tau_3 = 2\ \tau_V$. Figure 1 shows the change in the criterion $J_f(t)$ in the iteration process; the transient processes on the trial variations and the initial relaxation of the field are omitted. Based on the data presented we can conclude that over the optimization time $t_{opt} \simeq 100\ \tau_V$ the concentration of the field on the object increases by 90% and the efficiency of the control algorithm is close to that of aperture sounding, employed under conditions of stationary wind refraction.[1]

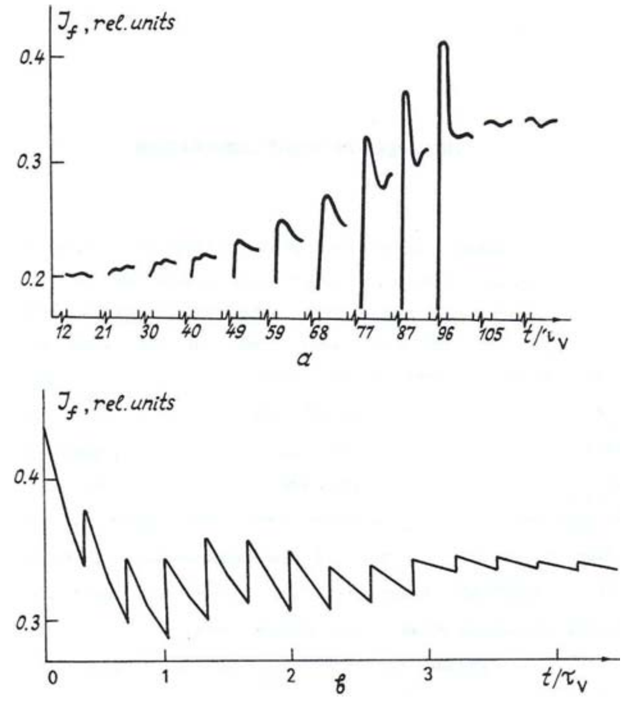

FIG. 1. The change in the criterion $J_f(t)$ in the iteration process for stationary (a) and nonstationary (b) parameters of the light field with $R_V = -20$ and $z_0 = 0.5\ z_d$.

The optimization can be reduced significantly without reducing the efficiency of the algorithm by transferring to control based on the nonstationary parameters (Fig. 1b). The characteristic times of the adaptive system in this case are $\tau_1 = 0.3\ \tau_V$; $\tau_2 = 0.3\ \tau_V$; $\tau_3 \ll \tau_{PH}$. . Initially the concentration of the field oscillates significantly, the oscillations decay over a time $t_{opt} \simeq 5\ \tau_V$, and the resulting value of the criterion J_f is not lower than in the case of control based on the stationary field. In the example studied $a = 0.5$ and does not change in the control process. When a is increased the algorithm diverges and when a is decreased t_{opt} increases.

THE SPEED OF PHASE CONJUGATION

Control based on the algorithm (5) using a stationary field is illustrated in Fig. 2a. As one can see from the Figure, the efficiency of the algorithm is not lower than in the case of aperture sounding.

The characteristic times of the system for the curves 1 and 2 are equal to $\tau_1 = 5\ \tau_V$, and $\tau_2 = 2.3\ \tau_V$. The duration of the transient process after a gradient step increased; this is connected with the increase in the amplitude of the displacement of the mirror. The total optimization time $t_{opt} \simeq 20\ \tau_V$, i.e., it is approximately five times shorter than in the case of aperture sounding using stationary parameters.

The optimization time t_{opt} can be reduced by transferring the algorithm (4), control based on which is illustrated in Fig. 2b. The concentration of the field on the object increases monotonically, and here t_{opt} is equal to 8 τ_V. The algorithm (4) has the drawback that its efficiency depends on a, which does not change in the process of control. Thus for a poor choice of a the field on the object does not reach a stationary state and the criterion J_f undergoes significant oscillations (curve 2, Fig. 2a)

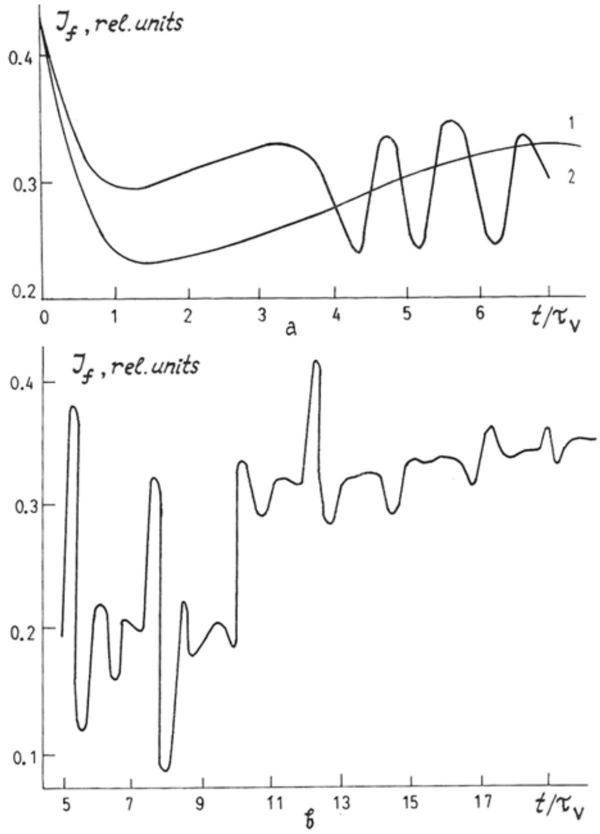

FIG. 2. Phase conjugation based on stationary (a) and nonstationary (b) parameters of the light field with $R_V = -20$ and $z_0 = 0.5\ z_d$.

BASIC RESULTS

The investigations performed show that fast dynamic control of the phase of light beams based on the nonstationary field along the path makes it possible to reduce the focusing optimization time in adaptive system for aperture sounding and phase conjugation. In addition, the efficiency of the control algorithms is very sensitive to the length of the gradient step, which for regular conditions of propagation can be determined, for example, numerically. Under conditions when the parametersfluctuate the applicability of control based on the nonstationary field requires additional justification.

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