INVESTIGATION OF THE POSSIBILITY OF COMPENSATING THE CROSS EFFECT OF THE DRIVES OF A FLEXIBLE ADAPTIVE MIRROR

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The response functions of piezoelectric flexible mirrors were studied experimentally. It is shown that the cross effect of the drives of a flexible adaptive mirror can be compensated by control in transformed coordinates.

In compensating the nonstationary phase distortions arising when a wavefront propagates in an optically nonuniform medium flexible mirrors with a continuous deformable surface are used as the actuators of adaptive optical systems for aperture sounding and phase conjugation.[1,2] In Refs. 3, 4, and 5 it is shown that such a wavefront corrector makes it possible to obtain a better approximation of the phase profile than that achievable with a segmented corrector, since the phase distortions are usually smooth. However, in addition to their advantages, adaptive optical aperture-sounding systems with such mirrors have certain drawbacks, connected with the fact that the neighboring drives of the flexible adaptive mirror affect one another.[6] In this case, cross terms appear in the quality functional which result in a reduction of the speed of operation and diminishment of stability[6] ($2\pi n$ problem), and the adaptive optical system may not achieve a global extremum. Methods for compensating this effect were studied theoretically in Ref. 1. In Ref. 7 it is shown that compensation of the cross effect of the drives of a flexible adaptive mirror makes it possible to increase substantially the speed of operation of adaptive optical aperture-sounding systems with multichannel phase modulation.

This paper is devoted to the experimental investigation of the characteristics of a flexible adaptive mirror and confirmation of the possibility of compensating the effect of the drives of a flexible adaptive mirror on one another.

For the experiments we prepared flexible adaptive mirrors based on piezoelectric plates consisting of TsTBS-3 piezoelectric ceramic. The reflecting surface of the 50 mm in diameter mirror was shaped by silver electrodes deposited on the surface of a 1 mm thick piezoelectric-ceramic plate. We built a model with five electrodes, arranged as shown in Fig. 1.

To evaluate the frequency properties of the flexible adaptive mirrors based on piezoelectric-ceramic plates a model with one continuous electrode was studied (Fig. 1). The deflections of the flexible adaptive mirror, clamped at the center, were recorded with the help of the experimental setup in Fig. 1. A narrow collimated laser beam 1 was directed at different points of the sample 2, and the position of the reflected beam was recorded on the scale 3. A controlling voltage was applied to the electrodes of the flexible adaptive mirror, and the position of the reflected beam was once again recorded on the scale 3. Thus the local slopes φ_i of the surface of the sample S were recorded:

$$\varphi_i = \alpha \frac{dS}{dr_i},$$

where α is the coefficient of proportionality and r_i are the coordinates of the i-th point on the surface of the sample. The measurements were performed in the planes c and d (Fig. 1) with the step $h = 2$ mm. To obtain more reliable results we performed a series of experiments whose results were analyzed by the methods of mathematical statistics. The real response functions of the flexible mirror studied were reconstructed by numerical integration on a computer.

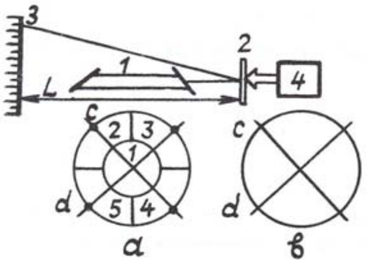

FIG. 1. Diagram of the sample: 1) laser; 2) flexible adaptive mirror studied; a) model with five controlling electrodes; b) model with one continuous electrode; 3) scale; 4) power supply; L = 4 m.

It is very difficult to describe analytically the deflections of a circular corrector with segmented controllable electrodes. We obtained a solution only for the case of one continuous electrode. For this reason the experimental data on the formation of the relief of a flexible adaptive mirror and on the possibility of compensating the cross effect of their drives are very important.

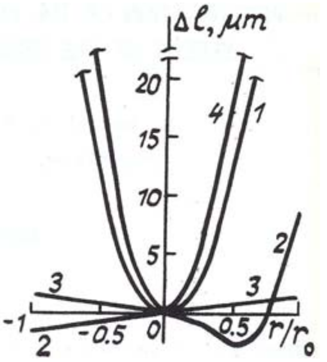

FIG. 2. Profiles of the response of the flexible adaptive mirrors studied.

Figure 2 shows the profiles of the response of model *a* and *b* when a voltage $U = 1500$ V is applied to the controlling electrodes of the mirror.

Curve 1 corresponds to the application of the voltage to the electrode 1. In this case the profile of the response on the surface of the electrode 1 is nearly quadratic. The residual deflections at the edges of the model on the surface of the electrodes 2, 3, 4, and 5 are practically linear. The curves 2 and 3 correspond to application of voltage to the second electrode. The response profile in this case was measured in the section *c* (curve 2) and in the section *d* (curve 3). The maximum deflections for the model *a* (Fig. 1) when a voltage was applied to the first controlling electrode were equal to 37 μm. Curve 4 in Fig. 2 shows the profile of the response of model *b* (Fig. 1) with one continuous electrode. The controlling voltage U was equal to 1500 V. The relief of the reflecting surface for such a flexible adaptive mirror has the form of a paraboloid of revolution. In this case the maximum deflection achieved at the edge of the plate is equal to 50 μm, which corresponds to the focal length $F = 6$ m. This was confirmed by additional experiments on the focusing of a 'wide coherent beam.

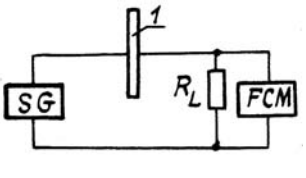

FIG. 3. Diagram of the experimental setup used to study the characteristic frequencies of the oscillations of a flexible adaptive mirror: SG — sweep generator; FCM — frequency-characteristic meter; R_L —active resistance; 1 — sample.

To estimate the possible speed of operation of adaptive optical systems with flexible mirrors based on piezoelectric-ceramic plates we studied the characteristic frequencies of the oscillations of a flexible adaptive mirror (model *b*). We used the scheme shown in Fig. 3. Figure 4 shows the frequency characteristic obtained as a result of the experiment.

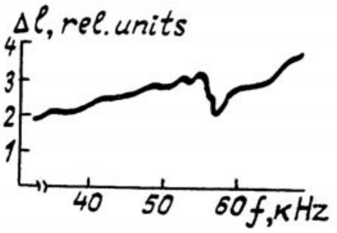

FIG. 4. The frequency characteristic of a flexible adaptive mirror.

When flexible mirrors are used as active elements in adaptive optical systems designers strive to choose the response functions so as to minimize the effect of one drive on others.[6] The speed of operation of the adaptive optical system is maximized owing to the fact that the cross couplings in the control channels of the system are decreased. The construction of flexible mirrors currently employed in adaptive optics does not always make it possible to make the effect of one drive on its neighbors small.[2,5]

The effect of one drive of a flexible adaptive mirror on the other can be compensated by employing control in transformed coordinates:[1]

$$A = F_N^{-1} \cdot B; \tag{1}$$

where $\vec{A}$ is the vector of transformed coordinates of the control; $\vec{F}_N^{-1}$ is the inverse compliance matrix of the flexible mirror; N is the number of drives of the flexible mirror; and, $\vec{B}$ is the vector of initial controls.

Suppose we are required to obtain the response of a mirror corresponding to the control vector $\vec{B}$. With the help of the compliance matrix the response of the mirror can be written in the form

$$B' = F_N \cdot B. \tag{2}$$

In the transformed coordinates the response of the mirror will be determined, with the help of the expression (1), as

$$B'' = F_N \cdot A = F_N \cdot F_N^{-1} \cdot B = EB, \tag{3}$$

where $\vec{E}$ is the unit matrix, i.e., with the use of the transformation (1) the cross effect of the drives of the flexible adaptive mirror should be mutually compensated. In this case, the response of the mirror will be close to that of a segmented corrector, whose compliance matrix is the unit matrix. The inverse compliance matrix of a flexible mirror can be calculated starting from the mathematical model adopted for the response of the mirror or it can be determined experimentally. For mirrors with drives in the form of a system of discrete piezoelectric or magnetostriction actuators the compliance matrix can be calculated at the locations of the drives using the well-known response functions of a membrane $S(r)$:[2]

$$f_{ij} = S_i(r_j); \quad i = \overline{1,N}; \quad j = \overline{1,N}, \tag{4}$$

where f_{ij} are the elements of the matrix $\vec{F}_N$, $S_i(r)$ is the response function of the i-th actuator, and r_j are the coordinates of the j-th actuator.

To calculate the compliance matrix of a flexible mirror the coordinates of the points of the maximum of the corresponding experimentally measured response functions were chosen for the coordinates r_j. The central drive was ignored. The normalized compliance matrix constructed in this manner has the form

$$F_4 \begin{vmatrix} 1 & 0.134 & -0.149 & 0.134 \\ 0.134 & 1 & 0.134 & -0.149 \\ -0.149 & 0.134 & 1 & 0.134 \\ 0.134 & -0.149 & 0.134 & 1 \end{vmatrix} \tag{5}$$

The normalized inverse of this matrix has the form

$$F_4^{-1} \begin{vmatrix} 1 & -0.206 & 0.218 & -0.206 \\ -0.206 & 1 & -0.206 & 0.218 \\ 0.218 & -0.206 & 1 & -0.206 \\ -0.206 & 0.218 & -0.206 & 1 \end{vmatrix} \tag{6}$$

Figure 5 shows the corresponding sections of the model a with control of the form {1, 0, 0, 0,} at the coordinates $\vec{B}$ (curve 1). This control corresponds to application of a controlling voltage on the second electrode. The same action, using Eqs. (1) and (6), at the coordinates $\vec{A}$ has the form {1, –0.206, 0.218, –0.206}. The curves 2 correspond to the response profiles for this case.

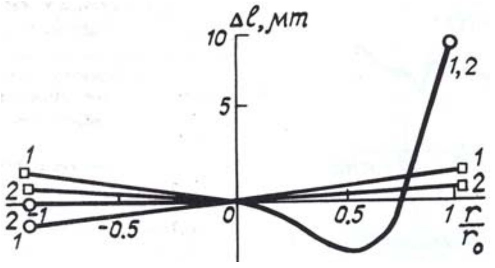

FIG. 5. The response profiles of the flexible adaptive mirror Cmodel) studied when the cross effect of the controlling electrodes is compensated.

CONCLUSIONS

The experimental data presented show that by using flexible adaptive mirrors based on piezoelectric ceramics quite large absolute deflections can be obtained. These deflections can be efficiently used in systems for correcting a phase front distorted by a turbulent atmosphere in the long-wavelength part of the optical range. Mirrors with one continuous electrode can be used in prospective optical system with variable focal length. The switching time in this case can be several microseconds. Control of a flexible adaptive mirror in transformed coordinates makes it possible to compensate the harmful effect of the neighboring drives on one another. In our experiment we were able to compensate virtually completely the cross effect on the electrode 4 and we were able to reduce the cross effect on the electrodes 3 and 5 by 50%. The residual effect of the electrode 2 on the electrodes 3 and 5 was equal to 0.7 μm in absolute units or less than 6% of the maximum deflection at the electrode 2. The incomplete compensation of the cross effect can apparently be explained by the fact that the direction of the compensating deflections does not completely coincide with the direction of deflection that must be compensated. The effect of the drives on one another can evidently be reduced further by reducing the thickness of the piezoelectric ceramic plate and increasing the number of sectors – controlling electrodes. Control of flexible adaptive mirrors ii transformed coordinates makes it possible to reduce substantially the cross effect of the control channels in adaptive optical systems. This can increase the speed of operation and the stability of adaptive optical systems operating on real paths.[7]

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