LARGE SPHERICAL ADAPTIVE MIRROR

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Received December 9, 1991

Construction of an adaptive mirror based on a thin plate lying on the elastic substrate fabricated from the highly porous metal (HPM) and deformed under the action of the forces exerted by the discrete actuators is described. Using the HPM allows one to fabricate a mirror of large diameter, which can be cooled maintaining the wide range of displacements of the working plate under the action of forces exerted by the actuators, to extend the frequency range of operation of the mirror, to enhance stability, and to improve the performance of its reflecting surface. The model for calculation of the basic characteristics of the mirror is proposed. Dimensionless parameters, characterizing the shape of the response function and the range of displacements of the working plate under the action of forces exerted by the actuator, are determined within the scope of the model.

Methods of adaptive optics are currently widely used in astronomy and laser radar technique.[1] As applied to the adaptive optics systems, which are intended to be used in the large astronomical telescopes and in the wide–aperture laser systems, the problem of constructing the large light–weight multicomponent actively–deformed mirror capable to maintain the prescribed shape of the reflecting surface to an accuracy comparable with the accuracy of the final operations of its fabricating under the action, in general, of nonstationary thermal, gravitational, and radiating loads is one of the main problems.

The large light–weight active mirror based on the thin composite plate was studied in Refs. 2–4. This mirror was intended to be used in the satellite astronomy for solving the traditional problem of the large–size optical parts, i.e., for ensuring the enhanced stability of the reflecting surface geometry under the action of the gravitational and thermal forces of the environment by means of the methods for the active control. The shape of the reflecting surface of this mirror was controlled by the point–size forces (or moments). That made it impossible to fabricate the mirror surface of high optical quality by means of polishing the extended plate of small thickness supported by the finite number of the pointed mechanical actuators.[5,6]

This paper is devoted to the study of the large light–weight active mirror based on the thin plate lying on the elastic substrate fabricated from the layer of the permeable elastic highly porous material (HPM). In such a construction the pointed action of the force exerted by the actuators is eliminated due to their embedding in the elastic layer. As a result, the shape of the reflecting surface of the mirror is controlled by the controlling elastic deformation of the reflecting plate and its elastic substrate.

The use of the interlayer fabricated from the HPM in the construction of the large static mirrors allows us to reduce the weight of the mirrors by a factor of 6–8 maintaining the high specific stiffness of the construction and to perform the thermostatic control by means of convective cooling. It provides the possibility of fabricating of the reflecting surface of different shapes (plane, spherical, and aspherical) with high optical quality.[7]

The control of the shape of the reflecting surface of such mirrors can be used to compensate for the static defects in the shape of the reflecting surface associated with inaccuracy of polishing for the dynamic distortions due to vibrations excited in the process of operation of the mirror and, in addition, to provide the correction of the phase distortions of the wave front attendant to the propagation of radiation through the optical system and the atmosphere.

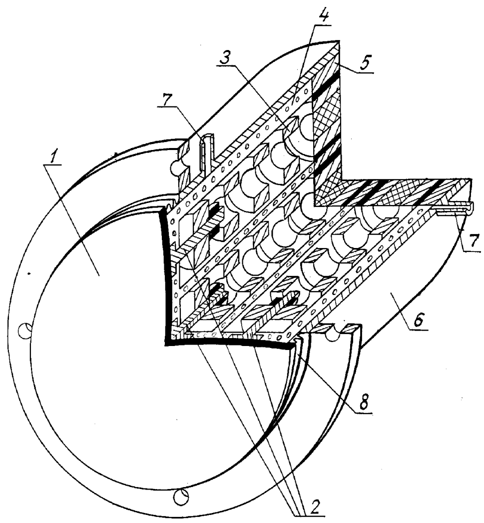

FIG. 1. The diagram of the active spherical mirror.

The construction of the mirror is shown in Fig. 1. The mirror comprises the substrate with the reflecting coating *1* and push rods of the actuators *2* clamped to it, the actuators *3*, the filler fabricated from the HPM *4*, the bearing plate *5*, and the body *6* with the pipes intended to feed and to remove the coolant *7*. To make the edge of the plate free in order to ensure higher accuracy of controlling the shape of the reflecting surface, it was joint with the body of the elastic bellows *8*. In this design of the mirror we propose to use (Fig. 1) the actuators in the form of the multipass cylindrical springs fabricated from the magnetostrictive material and harnessing the Wiedemann effect.[8]

Determining the reflecting surface, we will consider the mirror as the thin plate lying on the elastic substrate fabricated from the HPM and will start from the assumption that the rate of response of the elastic substrate is proportional to the deflections $W(\mathbf{r})$ of the substrate of the mirror. In this case, equation for determining the deflection of the substrate being driven by the transverse load $p(\mathbf{r})$ has the form[9]

0235-6880/92/03 167-03 $02.00

$$\Delta\Delta w(\mathbf{r}) = (p(\mathbf{r}) - kw(\mathbf{r}))/D \ , \qquad (1)$$

where k is the proportionality factor called modulus of elasticity of the substrate and D is the cylindrical stiffness of the working plate.

In the case of the substrate which is axially loaded by the force $\mathbf{P}$ the intensity $p(\mathbf{r})$ becomes zero within the substrate except for the center, and Eq. (1) takes the form

$$(\mathrm{d}^2/\mathrm{d}r^2 + r^{-1}\mathrm{d}/\mathrm{d}r)(\mathrm{d}^2w/\mathrm{d}r^2 + r^{-1}\mathrm{d}w/\mathrm{d}r) + k/Dw = 0 \ . \quad (2)$$

Denoting $k/D = l^{-4}$ and introducing the dimensionless variables $z = w/l$ and $x = r/l$, we obtain

$$\Delta\Delta z + z = 0 \ , \qquad (3)$$

where the symbol Δ denotes $\mathrm{d}^2/\mathrm{d}x^2 + x^{-1}\mathrm{dd}/\mathrm{d}x$.

The general solution of Eq. (3) to an accuracy of x^{18} inclusively has the form[13]

$$w = P/(8\pi kl^2)(a_1(1 - 1.56{\cdot}10^{-2}x^4 + 6.78{\cdot}10^{-6}x^8 - 4.71{\cdot}10^{-10}x^{12} + 9.39{\cdot}10^{-15}x^{16}) + (a_2 + \ln x)(x^2 - 1.74{\cdot}10^{-3}x^6 + 2.71{\cdot}10^{-7}x^{10} - 9.61{\cdot}10^{-12}x^{14} + 1.16{\cdot}10^{-16}x^{18}) + 1.45{\cdot}10^{-3}x^6 - 2.38{\cdot}10^{-7}x^{10} + 9.19{\cdot}10^{-12}x^{14} - 1.18{\cdot}10^{-16}x^{18}) \ , \qquad (4)$$

where a_1 and a_2 are constants being determined from the conditions of embedding of the edge of the mirror. For the mirror with the free edge these conditions are:

$$\left(\mathrm{d}^2w/\mathrm{d}r^2 + \mu r^{-1}\mathrm{d}w/\mathrm{d}r\right)_{r=R} = 0 \ ;$$
$$\mathrm{d}/\mathrm{d}r\left(\mathrm{d}^2w/\mathrm{d}r^2 + r^{-1}\mathrm{d}w/\mathrm{d}r\right)_{r=R} = 0 \ , \qquad (5)$$

where μ is Poisson's ratio and R is the radius of the substrate. For the preset size of the substrate and elastic moduli of substrate and filler relations (5) can be reduced to two equations linear in a_1 and a_2. It follows from Eq. (4) that the shape of the response functions is determined by the values a_1 and a_2 which, in turn, depend on the dimensionless parameter $L = R/l$ and Poisson's ratio of the substrate material μ.

The above–considered case corresponds to the mirror with single actuator arranged in the centre; however, if we neglect the elastic crosstalk between the actuators through the substrate, we can apply the same description to the multiactuator mirror. In this case the substrate radius in relations (5) must be equal to half the distance between the actuators, i.e., $R = a/2$. This implies that the actuators are uniformly distributed over the substrate. Such an arrangement allows one to use the entire reflecting surface of the mirror for controlling and to form the reflecting surfaces of complicated shape.

For effective correction of the phase distortion of the wave front the response function must satisfy two conditions. First, their shape must differ from the plane, moreover, the value of the surface deformation on the edges must be greater than 10% of the central deformation. Second, it is desirable that the response function has monotonic behavior because that will simplify the control of the mirror.

These conditions define uniquely the range of variation of the parameter L. The typical response functions calculated for copper ($\mu = 0.34$) for different values of the parameter L are shown in Fig. 2. For $L < 1$ the response function practically does not differ from a plane (case $L = 0.1$ in Fig. 2), therefore, this range of variation of L is not interesting for the construction of the mirrors with the controllable shape of the reflecting surface. It can be seen from Table I that condition $\dfrac{W_{\max} - W_{\min}}{W_{\max}} = 0.1$ is satisfied for $L = 1.1$ which is the minimum parameter L. Violation of the monotony of the response function takes place for $L > 3.2$ (case $L = 4$ in Fig. 2). Thus, the value $L = 3.2$ is the maximum parameter L, i.e., the range of admissible variation of this parameter is $1.1 \le L \le 3.2$.

For the preset parameter L the stiffness of the actuator must fit the elastic moduli of the substrate and filler for effective operation of the actuator. We will characterize the operating efficiency of the actuator by the ratio of the elongation W of the actuator as a part of the mirror to the elongation W_0 of the actuator in the free state. Elongation of the actuator coincides with the displacement of the substrate in place of arrangement of this actuator

$$W = w(x = 0) = a_1P/(8\pi kl^2) = -PK_a^{-1} + W_0 \ , \qquad (6)$$

from which

$$W/W_0 = 1 - 1/(1 + a_1G/(8\pi)) \ , \qquad (7)$$

where $G = K_a(kD)^{-1/2}$ and K_a is the stiffness of the actuator. The dependencies $W/W_0(G)$ are shown in Fig. 3 for different values of L. For cases $L > 1$, which are important in practice, the relative elongation of the actuator W/W_0 decreases rapidly with the parameter G; therefore, to provide the effective operation of the actuator, the moduli of filler, substrate, and actuators must be fitted. As a rule, the operation of the actuator can be considered to be effective if the relative elongation $W/W_0 \ge 0.5$ is realized.

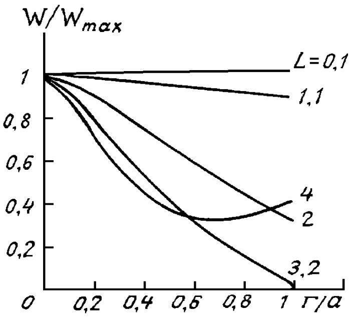

FIG. 2. The typical response functions of the active mirror against the parameter L.

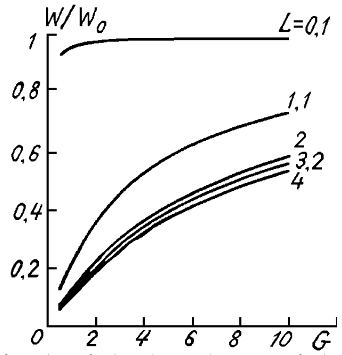

FIG. 3. The family of the dependencies of the displacement $W/W_0(G)$ of the actuator transferred through the layered substrate of the active mirror on the relative stiffness of the actuator G for different values of L.

In order that this condition was valid for any L from the preset range ($1.1 \le L \le 3.2$), the parameter G must exceed 7.5 (Table II).

TABLE I.

L	0.1	1.1	2.0	3.2	4.0
$\frac{W_{max} - W_{min}}{W_{max}}$	$7\cdot10^{-6}$	0.1	0.6	0.9	0.7

TABLE II. W/W_0

	L		
G	1.1	2.0	3.2
0.6	0.63	0.47	0.45
7.5	0.68	0.52	0.50
10.0	0.74	0.59	0.57

The results of modeling of the active mirror with use of the above–described analytic model provided the basis for the construction of the active mirror whose outline is shown in Fig. 1. In addition, this mirror can be fabricated (in example of copper) in the following way:

1. A three–layer workpiece of the mirror is assembled in which the elastic metallic interlayer is substituted by the layer fabricated from polyurethane foam with preset porosity and structure. To join these layers together, the three–layer pack is impregnated in the solution of the chemical coppering, after which it is metallized. As a result, copper is settled on the structural elements of the polyurethane foam workpiece and on the metallic parts of the construction which results in the formation of the rigid joint between these parts.

2. Thermo–oxidizing annealing of the construction at 500°C in air results in removal of the polyurethane foam from the filler.

3. The construction is reduced and agglomerated at 950°C in hydrogen. As a result of metallization and agglomeration, the rigid joint of the structural elements (tie–plates) of filler with substrate, bearing plate, and pushers is formed. Furthermore, the actuators are mounted in the fitting holes from the side of the bearing plate. The assembled construction is mounted in the body with clamped pipes intended to feed and to remove the coolant, after which the optical shaping of the substrate of the mirror is made.

The above–described technology of obtaining the rigid joint between the elements of the mirror was checked on the experimental model made in the form of two copper plates with the interlayer fabricated from the polyurethane foam filler. The copper roads were clamped with their ends by the plates. The obtained structure is shown in Fig. 4.

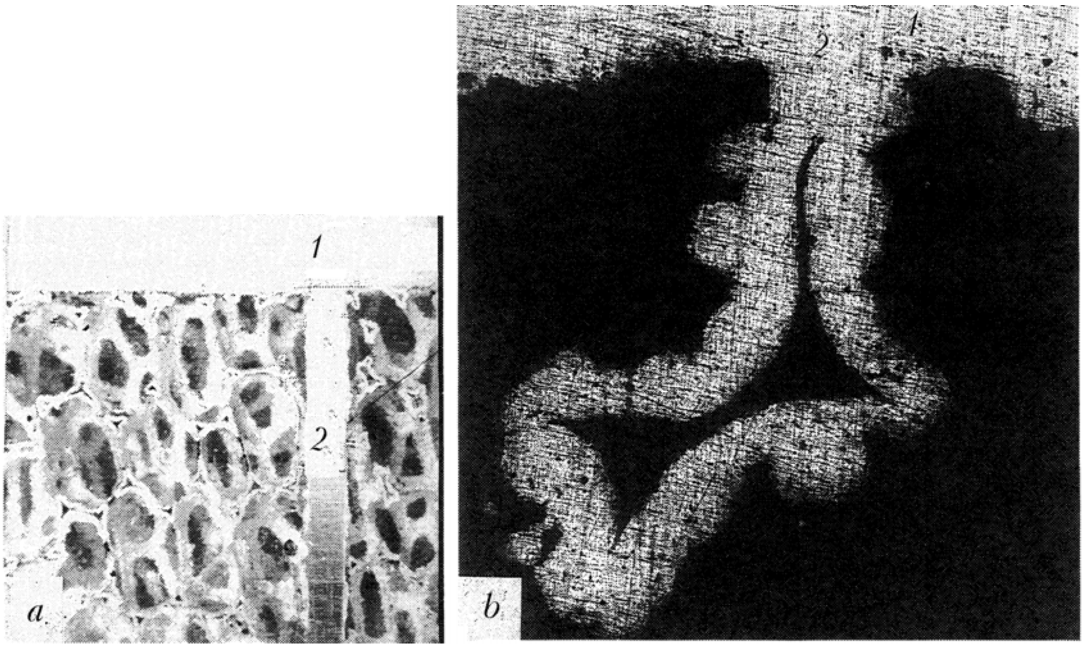

FIG. 4. Photomicrograph of the experimentally realized structure of the composite copper substrate of the active mirror: a) compact layer (substrate of the mirror) (1) and model of the actuator case (2) and b) joint of the compact substrate of the specular surface and the elastic permeable sublayer fabricated from the HPM.

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