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Thermal stability test and analysis of a 20-actuator bimorph deformable mirror*

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One of the important characteristic of adaptive mirrors is the thermal stability of surface flatness. In this paper, the thermal stability from 13°C to 25°C of a 20-actuator bimorph deformable mirror is tested by a Shack–Hartmann wavefront sensor. Experimental results show that, the surface P–V of bimorph increases nearly linearly with ambient temperature. The ratio is 0.11 μm/°C and the major component of surface displacement is defocused, compared with which, astigmatism, coma and spherical aberration contribute very small. Besides, a finite element model is built up to analyse the influence of thickness, thermal expansion coefficient and Young's modulus of materials on thermal stability. Calculated results show that bimorph has the best thermal stability when the materials have the same thermal expansion coefficient. And when the thickness ratio of glass to PZT is 3 and Young's modulus ratio is approximately 0.4, the surface instability behaviour of the bimorph manifests itself most severely.

Keywords: adaptive optics, bimorph deformable mirror, thermal stability
PACC: 4280

Adaptive Optics (AO) is concerned with correcting aberrated wavefronts by introducing a counter aberration into an element of the optical system, which is called wavefront corrector. In a typical AO system, the corrector is one of the most important elements and it should meet a variety of requirements:

- wide range of surface deformation;
- an appropriate number of controlling actuators;
- efficiency of response to control signal;
- thermal stability of surface flatness;
- simplicity of producing and application;
- low system cost.

Deformable mirrors (DMs) meet most of these requirements. Among the DMs considered,[1] bimorph (which is used in this paper to indicate bimorph DM) has the following advantages: larger stroke, higher damage threshold of laser power, and better correction of low-order aberrations with a given number of actuators. In addition, fabrication and application of bimorphs are relatively simple. Some institutions[2−4] have fabricated bimorphs independently, and encouragingly, most of them have obtained satisfying results in experiments.

One of the important characteristics of bimorph is thermal stability of the surface flatness. The surface instability is basically caused by difference between the thermal expansion coefficients for mirror substrate material and piezoceramic material (PZT).[5,6] But it is also influenced by the choice of thickness and Young's modulus of materials. The present paper is dedicated to test and analyse the thermal stability of a 20-actuator bimorph, concerning all these three influencing factors. Besides, this analysis is based on experimental test and a finite element model. Compared with the numerical method adopted in other papers, here we introduce less approximate conditions to ensure a more practical result.

The 20-actuator bimorph is made of three thin layers that are bonded together (Fig.1). One is made of optically polished glass, and the other two are made of PZT. We assume that the bonding is ideal. Thin conducting films deposited between each two layers act as electrodes and the voltage is distributed via them to PZT layers. Electrodes 1–19 are arranged

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on one PZT layer, and defocusing electrode 20, which covers the whole range of discrete electrodes, is on the other PZT layer. The mirror is fixed to an annular supporting mount at the edge of glass.

For the centrosymmetric structure of the bimorph, instability behaviour manifests itself in additional defocusing deformation of the mirror surface at the change of ambient temperature. The difference of strain between glass and PZT can be indicated as $\Delta\varepsilon = (\alpha_1 - \alpha_2)\,\Delta T$, where α_1 and α_2 is the thermal expansion coefficient for PZT and glass material respectively. The response of the surface displacement ΔW to the change of ambient temperature ΔT is $\Delta W/\Delta T$, which is defined as temperature sensitivity coefficient in this paper.

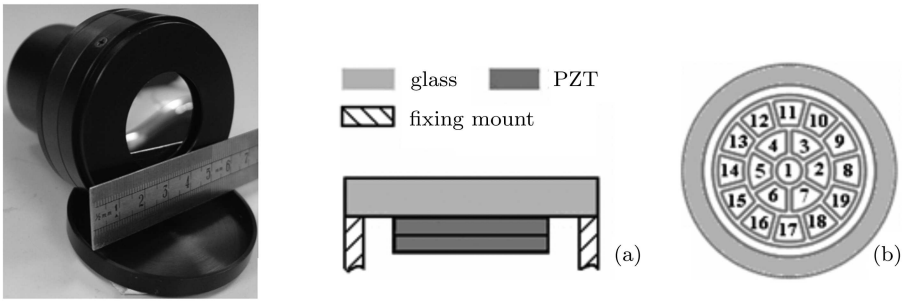


Fig.1. 20-actuator bimorph deformable mirror (left). Structure of the bimorph (right): (a) lateral view of layers and fixing mount, (b) arrangement of 1–19 discrete electrodes.

A Shack–Hartmann wavefront sensor (S–H) with 60 mm clear aperture is adopted to measure the surface shape of bimorph. The experimental layout is shown in Fig.2. Wavelength of the light source in S–H is 0.65 μm. Collimated light generated by S–H reaches the bimorph surface and is reflected back to the sensor again. Wavefront slopes in both X and Y directions are detected and outputted to a computer. Test and analysis are limited in the 30 mm effective aperture of bimorph, which corresponds to 16×16 central subapertures array of S–H. And all electrodes are suspended to ensure a static measurement condition.

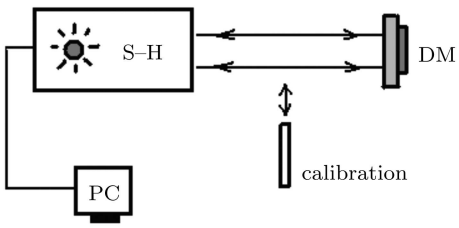


Fig.2. Experimental layout.

One method to measure temperature sensitivity coefficient is to lay the deformable mirror in a temperature-controlled cabinet. The detecting end of the cabinet is sealed by a glass window. But problem is that the thermal characteristic of the glass window is unknown and instable. So a modified scheme is adopted in this experiment as follows.

All the apparatuses, including S–H, calibration and bimorph, are put in a temperature-controlled cabinet. And it's assumed that thermal instability of the calibration mirror itself can be ignored.

The test is taken at four discrete points: 13°C, 16°C, 20°C and 25°C. At each of these temperature points, results are obtained from the mean of multiple measurements. Time interval between each temperature change and measurement is long enough to make all the apparatuses stable in new ambient.

To separate thermal instability of S–H from that of the bimorph surface, S–H is calibrated only once at 13°C (calibrated wavefront see Fig.3(a)). After each change of temperature, the calibration mirror is measured first. And the surface displacement of the calibration manifests the change of inner structure of S–H caused by ΔT. Results outputted by S–H are shown in Figs.3(b–d). With the increment of testing temperature, the calibration surface shows a small change and this tiny displacement is removed from bimorph surface testing results. Thus we can obtain the temperature sensitivity coefficient $\Delta W/\Delta T$ of bimorph, based on the surface shape of calibration at 13°C.

The surface shape of bimorph at each testing temperature is shown in Fig.4. And their corresponding peak-to-valley (P–V) and root mean square (RMS)

are plotted in Fig.5. The initial surface of bimorph at 13°C manifests itself as an irregular shape of saddle, with P–V = 1.06 μm, RMS = 0.22 μm. This shape is formed by the residual strain, which is correlative with the whole process flow and the temperature at which bimorph is bonded. With the increment of testing temperature, a centrosymmetric bulge is found on the bimorph surface. When it reaches 25°C, P–V = 1.85 μm, RMS = 0.48 μm.

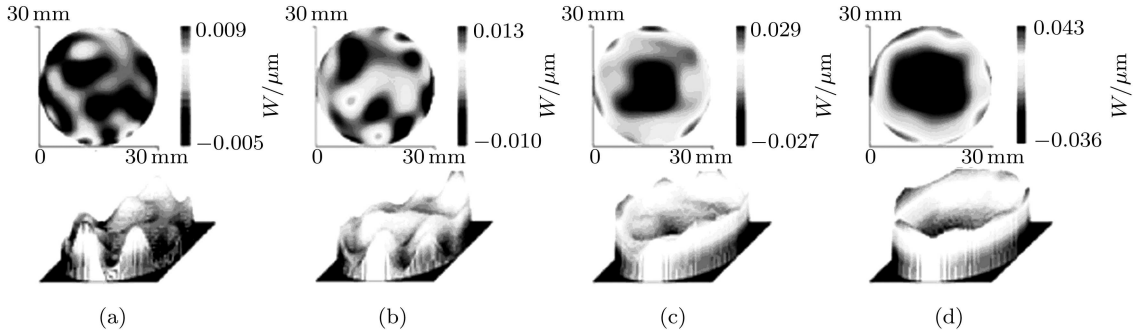


Fig.3. Surface displacements of calibration mirror measured by S–H. (a) 13°C RMS = 0.002 μm, PV = 0.014 μm; (b) 16°C RMS = 0.004 μm, PV = 0.023 μm; (c) 20°C RMS = 0.011 μm, PV = 0.055 μm; (d) 25°C RMS = 0.02 μm, PV = 0.079 μm.

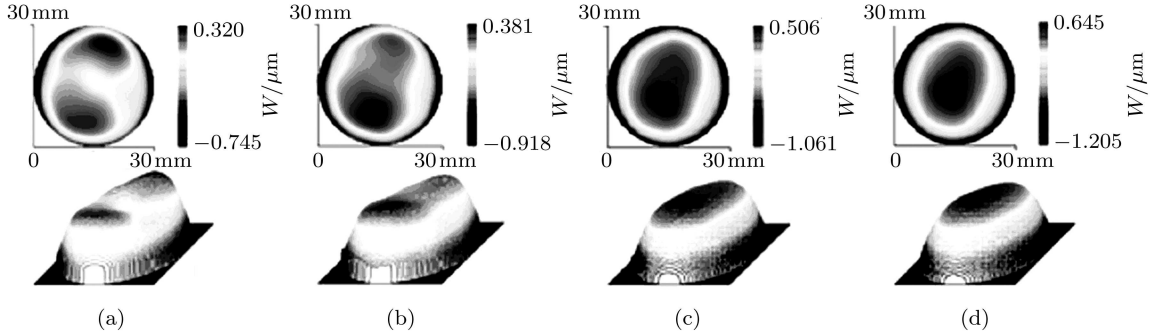


Fig.4. Surface displacements of bimorph measured by S–H. (a) 13°C, (b) 16°C, (c) 20°C, (d) 25°C.

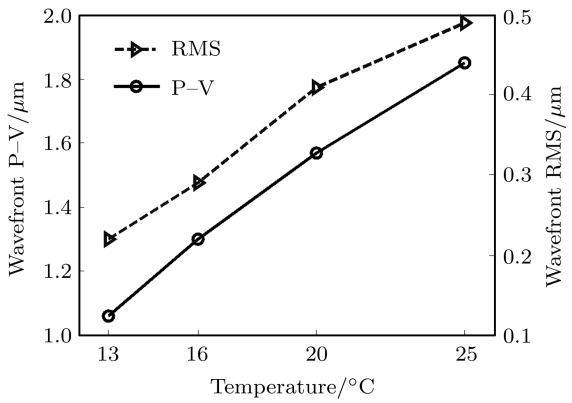


Fig.5. Variation of surface P–V and RMS of bimorph as a function of the ambient temperature.

To find out the components of this surface displacement, the results outputted by S–H are decomposed based on Zernike aberrations. Figure 6 (left) shows the distribution of P–V of 3–35 order Zernikes at the four temperature points. Specially, P–V of defocusing, astigmatism, coma and spherical aberration are listed in Fig.6 (right).

It can be seen from Fig.6 that, defocusing contributes the most part to the displacement and it is most sensitive to ΔT. In the range from 13°C to 25°C, P–V of defocusing varies 1.37 μm whereas that of any other Zernike order is small than 0.15 μm. The difference in P–V change comes from the centrosymmetric structure and fixing method of the mirror. So, it's more reasonable to substitute the total surface displacement with the P–V of defocusing in temperature sensitivity coefficient. Then we obtain the mean of it: $\Delta W_{\mathrm{defocus}}/\Delta T = 0.11\,\mu\mathrm{m}/^{\circ}\mathrm{C}$.

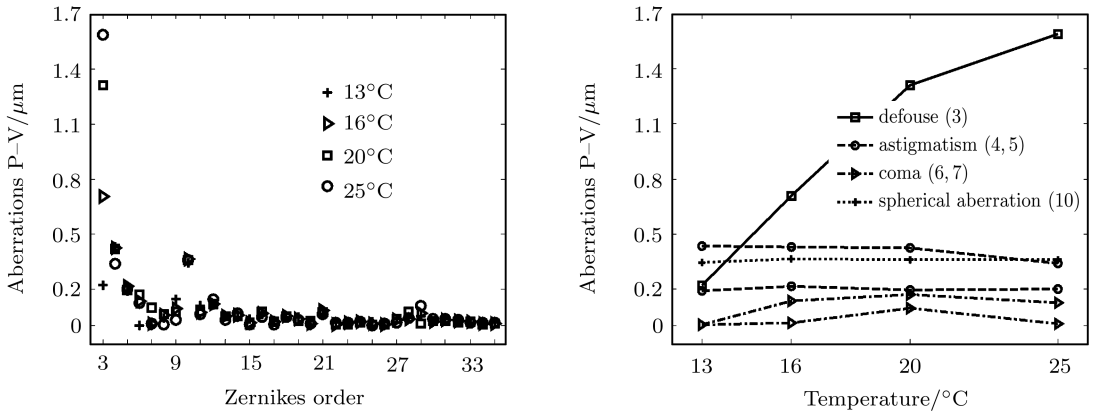


Fig.6. P–V of 3–35 order Zernikes decomposed from the surface displacement of bimorph on various temperature (left); those of defocus, astigmatism, coma and spherical aberration (right).

The surface flatness of a bimorph is influenced by many factors, among which there are several factors which can be optimized, such as the thickness ratio and material parameters of each layer. According to the actual device, a model is built up in Algor finite element software to analyse the influence of the thickness ratio, thermal expansion coefficient and Young's modulus on thermal stability of the bimorph.

There are three thin layers in the thickness direction of the model, one layer of glass and two of PZT. The conducting films and glue between each two layers are ignored (for the thickness of them is at the magnitude of μm). The boundary is set as elastic contact to simulate the action of fixing glue layer. Mesh of the model and the surface displacement of bimorph when $\Delta T = 1°\mathrm{C}$ are shown in Fig.7. The defocusing P–V of this shape is $0.14\,\mu\mathrm{m}/°\mathrm{C}$. It fits well with the testing result $0.11\,\mu\mathrm{m}/°\mathrm{C}$, which verifies the accuracy of our finite element model.

Assume that subscript 1 refers to the active PZT layer and 2 to the passive glass layer, E indicates Young's modulus and t indicates thickness. The calculated results of the influence of t, α and E on temperature sensitivity coefficient $\Delta W/\Delta T$ are shown in Figs.8–10. For each parameter P, $\Delta W/\Delta T$ is calculated not only as a two-dimensional function of P_1 and P_2, also functions of P_1 or P_2 separately. From these figures, one can see the global behaviour of $\Delta W/\Delta T$ on various parameters of all materials, and the single influence of each material. The latter has special reference to the case when one material is determined and the others need to be chosen.

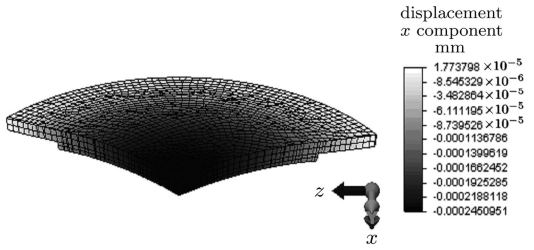
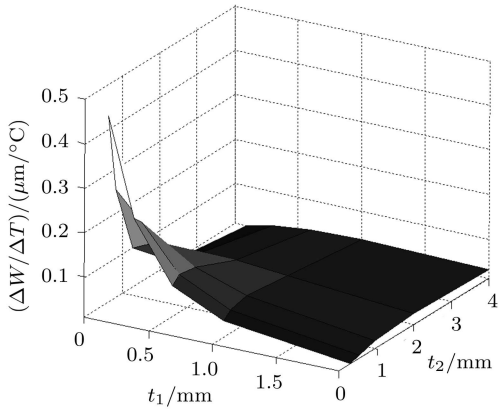


Fig.7. Mesh of the finite element model and the surface displacement of bimorph when $\Delta T = 1°\mathrm{C}$.



(a)

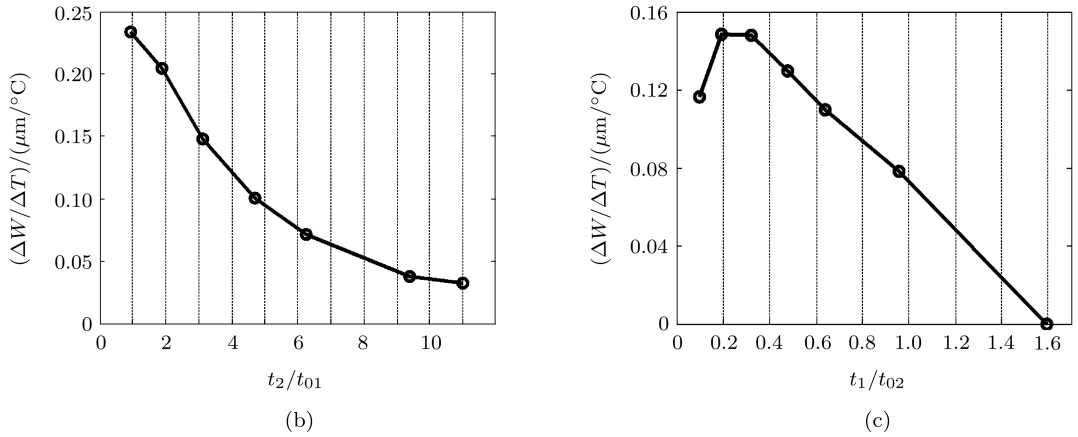


Fig.8. Variation of $\Delta W/\Delta T$ as a function of thickness t_1 and t_2 (a), t_2/t_{01} (b), t_1/t_{02} (c).

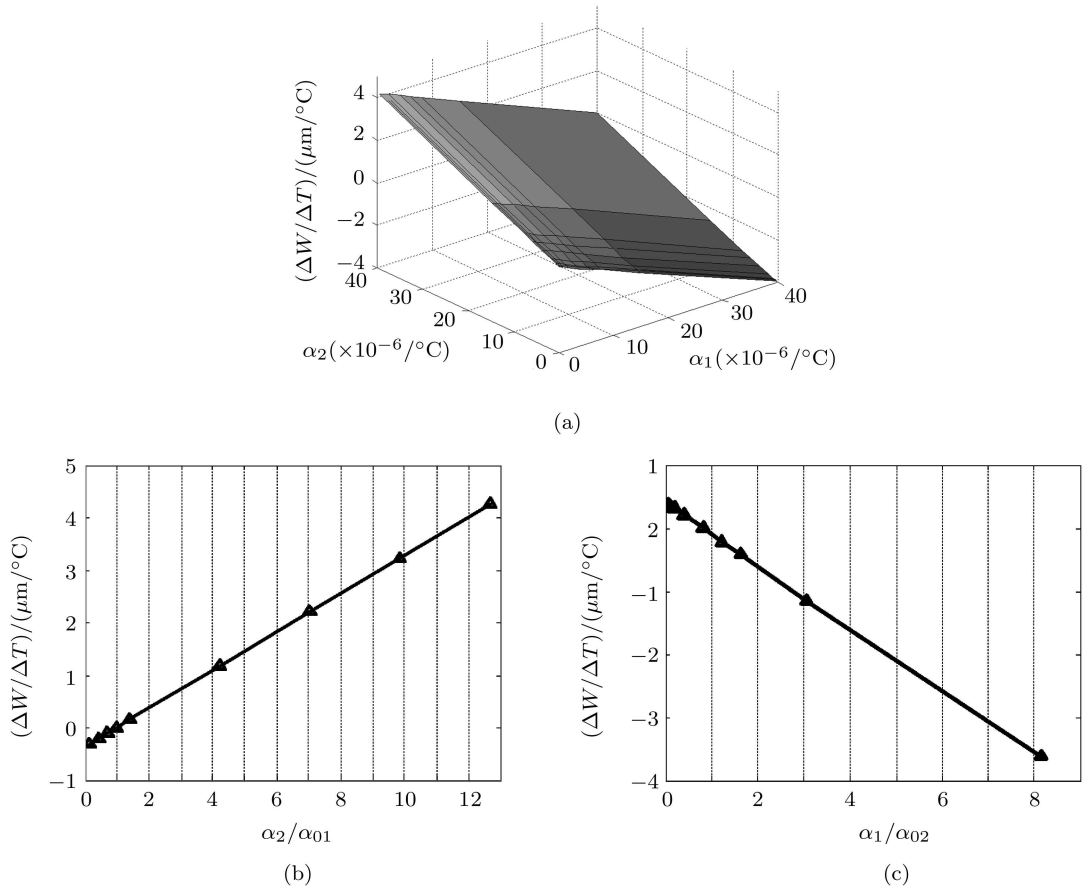


Fig.9. Variation of $\Delta W/\Delta T$ as a function of thickness α_1 and α_2 (a), α_2/α_{01} (b), α_1/α_{02} (c).

When the influence of parameter P is analysed for glass layer, $P_1 = P_{01}$ and P_2 varies through a certain range to calculate the surface displacement of bimorph at $\Delta T = 1^\circ$C. Subscript 0 refers to the parameters for actual device: $t_{01} = 0.3\,\text{mm}$, $t_{02} = 0.94\,\text{mm}$; $\alpha_{01} = 3.5\times10^{-6}/^\circ\text{C}$, $\alpha_{02} = 4.92\times10^{-6}/^\circ\text{C}$; $E_{01} = 7.5\times10^{10}\,\text{N/m}^2$, $E_{02} = 7.14\times10^{10}\,\text{N/m}^2$. Then, a similar process is taken by changing P_1 with $P_2 = P_{02}$. For different parameters, the variation range and sampling number are different: $t \in (0.1t_0, 4t_0)$, $\alpha \in (0.1\alpha_0, 10\alpha_0)$, $E \in (0.1E_0, 10E_0)$.

Thickness of each layer may be the first parameter needed to be determined when designing a bimorph. It should be considered on available technology and other characteristic of the device, such as thermal stability and response sensitivity to controlling voltage.[7]

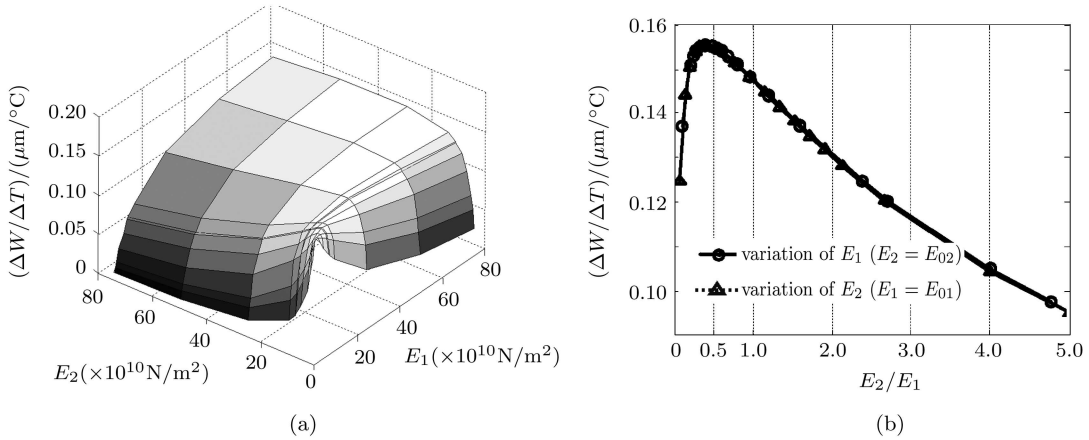


Fig.10. Variation of $\Delta W/\Delta T$ as a function of thickness E_1 and E_2 (a), E_2/E_1 (b).

Figure 8(a) shows the temperature sensitivity coefficient as a function of t_1 and t_2. When $t_1 = t_{01}$ (Fig.8(b)), $\Delta W/\Delta T$ reduces with the increase of t_2. The thicker glass layer is, the better thermal stability bimorph has. When $t_2 = t_{02}$ (Fig.8(c)), $\Delta W/\Delta T$ varies as a parabolic function of t_1/t_{02} and the peak appears at the point $t_1/t_{02} \approx 0.3$. That is to say, the structure of our present bimorph should be further optimized for better thermal stability. Certainly, the response sensitivity to controlling voltage should be also considered in this optimization. When $t_1/t_{02} > 1$, $\Delta W/\Delta T$ reduces rapidly with the increase of t_1. $\Delta W/\Delta T$ changes to zero until the stress caused by ΔT is not enough to afford bending of the thick PZT layer.

Thermal expansion coefficient is another material parameter which should be carefully chosen (Fig.9(a)). For the difference in radial dimension and fixing condition between glass and PZT, the influence of their thermal expansion coefficients on $\Delta W/\Delta T$ is different. In Fig.9(b), $\Delta W/\Delta T$ increases as a linear function of α_2 and at the point α_2/α_{01}=1, the surface displacement of bimorph is nearly zero. When α_2 gets bigger, the surface displacement becomes positive. Whereas the case is different in Fig.9(c) where $\Delta W/\Delta T$ varies in such a way that it is inversely proportional to α_1. The mirror surface sags towards PZT in the range of $\alpha_1 > \alpha_{02}$.

Young's modulus is not only determined by inherent attribute of material but also influenced by thickness and ambient temperature. It gets smaller when the layer of material is thinner or the temperature rises. But the change is very small in this paper and can be ignored.

Figure 10(a) shows the behaviour of temperature sensitivity coefficient as a function of E_1 and E_2. $\Delta W/\Delta T$ varies severely when E_1 and E_2 are small. From Fig.10(b) it can be seen that, $\Delta W/\Delta T$ has a certain value when E_2/E_1 is definite. This result fits well with the conclusion that has been obtained by numerical method in Ref.[8]. The peak of this curve appears at $E_2/E_1 = 0.4$. That is to say, when the Young's modulus of glass is 0.4 times as that of PZT, the bimorph surface varies most sensitively with the change of ambient temperature.

The surface instability of a bimorph is basically caused by distinction between the thermal expansion coefficients for glass substrate and PZT material. So the influence of ambient temperature on the surface flatness can not be ignored if only this distinction exists.

In this paper, the thermal stability from 13°C to 25°C of a 20-actuator bimorph deformable mirror is tested by a Shack–Hartmann wavefront sensor. Experimental results show that, the surface P–V of bimorph increases nearly linearly with the ambient temperature. The ratio is 0.11 μm/°C and the major component of surface displacement is defocusing, compared with which, astigmatism, coma and spherical aberration contribute very small. Besides, a finite element model is built up to analyse the influence of thickness, thermal expansion coefficient and Young's modulus of materials on the thermal stability. Calculated results show that, bimorph has a better thermal stability when the thicknesses of glass and PZT layers are both bigger. And when the thickness ratio of glass to PZT is 3 and Young's modulus ratio is ap-

proximately 0.4, the surface instability behaviour of the bimorph manifests itself most severely.

In general, thermal stability of a bimorph is determined by thermal expansion coefficient. But analysis on the influence of thickness and Young's modulus can also give actual application a valuable reference.

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