Active Thermal Figure Control for Large, Lightweight Honeycomb Mirrors in Vacuum and Space

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1. ABSTRACT

Active figure control of lightweight glass honeycomb mirrors will be valuable for making the on-orbit operation of large space optics more precise, lighter, more cost effective, and more thermally stable. Key applications will include very high contrast imaging of extrasolar planets and large scale vacuum test optics, whose optical quality must be controlled for better quality than the space systems under test.

The concept presented here relies on the low but finite thermal expansion of honeycomb mirrors made from fused silica, a material commonly used for precision lightweight space optics. The figure is controlled by varying the temperature of the faceplates and individual rib elements. Resistive heating is balanced in a servo control loop against radiative loss to cold fingers inserted in each honeycomb cell. Preliminary finite element models indicate that for a mirror with n cells up to n Zernike modes can be corrected to better than 90% fidelity, with still higher accuracy for the lower modes. An initial demonstration has been made with a honeycomb mirror of borosilicate glass. Interferometric measurements show a single cell influence function with 300 nm stroke and ~5 minute time constant.

2. RATIONALE

Glass honeycomb mirrors have long been the preferred choice for space optical systems operating at the optical diffraction limit, because of their high thermal and mechanical stability. Alternate primary mirror materials with higher elastic modulus can be used for smaller optical systems or for reduced quality. The beryllium segments for the JWST, for example, are aimed at diffraction-limited performance down to 2 μm wavelength. However, for large systems to be diffraction limited in the optical (λ=0.5 μm), glass honeycomb technology is likely to be preferred. But even glass has a performance limit—for example the HST primary has astigmatism that varies slowly over a range of 25 nm (Lallo et al, 2006). Active control of the wavefront would allow the highest optical quality to be maintained, even for systems with a much lighter build than HST, by compensating for gravity release effects and support force errors in space. It would also allow construction of "super diffraction-limited optical systems," as are needed for ultra-high contrast imaging to image extrasolar planets.

At present the only option for correcting primary aberrations is to add optics to relay a pupil image onto a separate deformable mirror and to recreate the original image. The concept we propose makes the correction directly at the glass-honeycomb primary mirror. This has several advantages

1) Higher throughput and simpler—no additional optics needed
2) Simple and lightweight translates to lower costs/lower mass
3) No cross coupling of phase into amplitude errors—limits spectral bandwidth for very high contrast imaging. This is very important for exoplanet detection
4) no increased field aberrations from the added relay

Many future astrophysics missions will be able to take advantage of precise optical wavefront prescription and/or the stability of thermally controlled honeycomb mirrors. Examples are exoplanet imaging, high spatial resolution UV and visible imaging (JDEM, Large Ultraviolet/Optical Telescope), or missions aimed at extreme astrometric stability (OBSS Origins Probe mission concept). The resistive heating control system described here has the potential to both lower the costs and improve the performance of these types of missions. It would also reduce the risk, since it works by combining two technologies—glass honeycomb mirrors and thermal control—that are already at very high TRL levels.

3. THERMAL ACTUATION CONCEPT

Conventional glass honeycomb mirrors for space obtain their thermal stability by use of very low or zero expansion glasses. Fused silica (coefficient 5×10^{-7}/C) and its titania doped form (ULE— coefficient $\leq 10^{-8}$/C) are both well-established and commonly used (Hobbs et al, 2003). Our strategy is to take advantage of silica's small coefficient to induce small wavefront corrections by differential thermal expansion. Accurate thermal controls will be added, on the scale of the honeycomb cells. This approach avoids the difficulties of primary mirror actuation by piezo or electrostrictive actuators, which arise because their relatively high expansion coefficients would compromise the natural stability and rigidity of glass honeycomb structure. Low order thermal control of a telescope primary has been tested by Lardiere et al. (2000), and of a silicon plate by Vdovin and Loktev (2002).

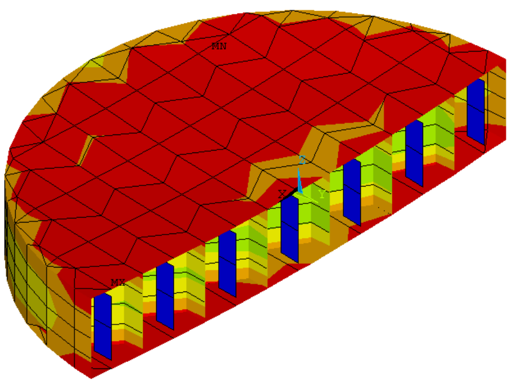

Figure 1: Preliminary finite element model with 37 cells. Color coded for equilibrium temperatures; when the cold fingers are held isothermal and 3.5 W are dissipated across the mirror heaters, the face temperature (red) is 5°C warmer than the cold fingers (blue).

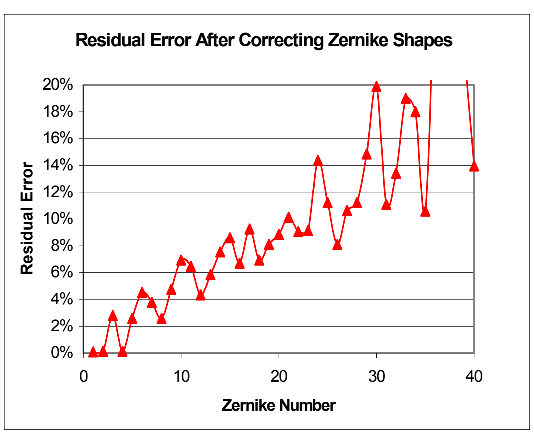

***Figure 2:** Thermally induced fractional residual errors for Zernike terms.*

The control geometry we propose will use a combination of resistive heating and radiative cooling. Normally these would be balanced, but in order to achieve local expansion or contraction, the heater power will be altered. The resistive heaters will be deposited or glued to the internal rib and faceplate surfaces. Radiative cooling will flow to cold fingers inserted into each honeycomb cell and around the perimeter wall. The neutral state of the mirror will be one in which a steady state heat flow is established. To control edge effects, the back outer face will be insulated, and the front mirrored surface will have low emissivity and thermal coupling. The temperature of the different surface elements will be measured by thermistors and used as input to the thermal control servo.

A preliminary small-scale model of a 37-cell honeycomb mirror, using thermal finite element code, has been made (shown in Fig. 1). It is 30-cm in diameter and 5-cm thick overall. In the steady state the face sheets are 5°C warmer than the cold fingers for a total heat flow of 3.5 W. The mirror would be null figured in this state. When the heaters are adjusted to induce small distortions, wavefront amplitudes ≥ 300 nm peak-to-valley can be realized for up to the first 11 Zernike modes, and ≥100 nm for the first 30. The residual errors (shown in Fig. 2) range from a few percent at the lowest modes, and rise to 10% at mode 22. The calculated time constant is 30 minutes.

4. LABORATORY DEMONSTRATION

The principles of thermal actuation have been demonstrated with a single actuator implemented in a borosilicate honeycomb mirror. The 60-mm thick, 18″ diameter mirror (loaned to us by Richard Wortley of Hextek Corp) has 61 cells, is about 65 mm in diameter, and is polished as an optical flat. The backplate holes, in 4 cells near the center, were enlarged to 35-mm diameter for the experiment and radiative cooling fingers were installed to project into these holes, without touching the glass. These can be seen through the uncoated front face plate in Figure 3. The fingers are flat plates with the sides facing a Y shaped intersection of the hexagonal cell walls coated for high thermal emissivity; the outward facing sides are insulated to limit the cooling influence. Resistors were attached with thermally conducting silver epoxy to the three ribs forming the central Y intersection. The temperature of the mirror surface was measured by a thermistor.

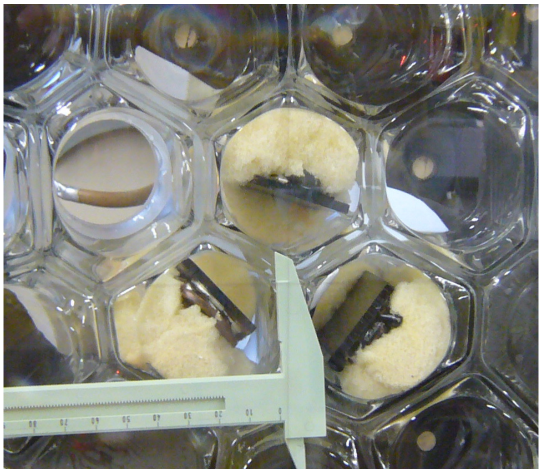

Figure 3. *Detailed view of honeycomb mirror cells with cooling fingers inserted through the hole in the back plate, seen through the face plate.*

In the experiment, the cooling mechanism consisted of ice water circulated through pipes soldered to the three cold fingers; heating was achieved by powering the resistors. The figure was measured with a 4D vision phase-shifting interferometer over a 145-mm diameter circular aperture, offset slightly from the test cell. Figure 4 shows a sequence of measurements of the surface figure. Initially the glass was in thermal equilibrium (all measurements are shown with reference to this equilibrium figure). The first frame of the equilibrium surface thus appears completely flat. The resistor power at this point was turned on at 200 mW, which produced a 150 nm peak surface actuation after 10 minutes (frame 5), with a surface temperature increase of 2.0°C. When ice water was circulated to the cooling fingers and the power dropped to 100 mW, the surface was restored to within 10 nm rms of its original equilibrium figure (frame 8). The power was then turned off, and after a further 6 minutes, a 130-nm depression caused by cold finger cooling was recorded in the last frame. From these measurements we were able to characterize the single cell influence function as having a full width at half maximum of 60 mm, a response time constant of around 6 minutes and an actuation rate of about 50 nm/°C. This rate can be compared with the expansion of a simple rod of borosilicate glass with the same expansion coefficient of 3.2×10^{-6}/°C and length of 60 mm (equal to the thickness of the mirror). This would expand ± 96 nm about its neutral center, if heated 1.0°C. The smaller expansion measured for the mirror faceplate arises because of the mechanical constraint of the neighboring unheated ribs and face sheets.

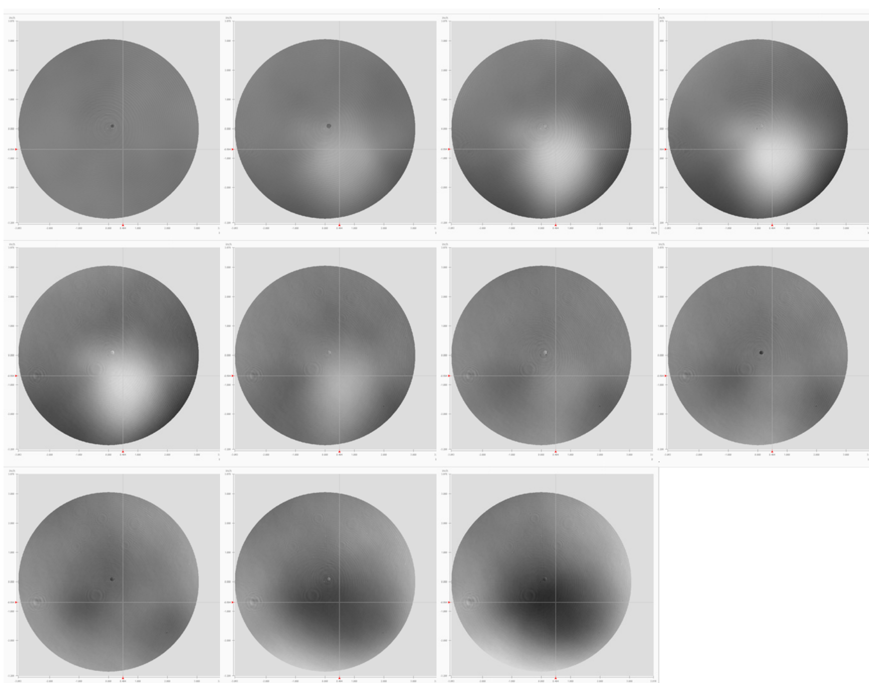

Figure 4. *Metrology of 145-mm diameter region covering one thermally controlled cell of a borosilicate mirror. The surface figure is shown by gray scale from -130 nm (black) to +150 nm (white). The actuator maximum corresponds to the 200 mW heating of three adjacent ribs, the minimum to the radiative cooling to the cold fingers at 0°C.*

5. FUTURE PLANS

We plan to validate the models and the control concept with a 0.4-m prototype honeycomb mirror with thermal control. The 61-cell blank will be made of borosilicate honeycomb by Hextek. It will be fitted with 250 heater elements and thermistors, before being figured as a 1.5-m radius sphere. The finned cold-fingers will be cooled individually with liquid from a refrigerated recirculator system (0.01°C control). Testing from the center of curvature will again be with a 4D Vision phase-shifting interferometer. Measurements will be taken of:

1) the control time constant
2) the power dissipation for initial steady flow state
3) the temporal stability of control
4) the power vs amplitude as a function of Zernike mode amplitude
5) the stability against external thermal perturbation

Good control up to the first 50 Zernike coefficients is projected, which (for the coronagraphic application) will allow the suppression of weak speckles out to ~ 4 λ/D in the focal plane. The larger system models will be refined on the basis of the prototype experience. Critical tests of the control accuracy for high contrast imaging will then be undertaken by combining the test mirror with coronagraphic optics. One test will be made with the AHA suppression system being developed by John Codona (these proceedings and Codona and Angel, 2006). Another will be with the PIAA optics recently demonstrated by Guyon and Pluzhnik (2006) to give suppression of the optical star halo to 10^{-6} at an angular separation of 2 λ/D. In this demonstration, the wavefront was corrected by a small MEMS deformable mirror. The prototype proposed here would be used to make a first test of achieving such contrast in a full system that includes a directly corrected primary mirror. At 40-cm diameter the primary would be far larger than the optics used in any previous high-contrast lab test, and the combined operation would make a major advance toward a practical coronagraphic space telescope.

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