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Thermal Response of a Lightweight, Gas-Fusion Mirror Blank

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Introduction

The purpose of this paper is to illustrate the rapid response of lightweight mirror blanks to small thermal perturbations and also to show how a Zernike polynomial representation of an optical surface can be helpful in analyzing the time varying deformations of the surface. In this work, a localized thermal load was introduced into the back of a lightweight mirror blank while the front surface was monitored interferometrically. Interferograms were taken every minute for the 14 minute application of the load and then continued for another 24 minutes to show the thermal relaxation of the blank.

As a result of the qualitative analysis of the data, it is apparent that the thermal time constant of a lightweight mirror blank is proportional to the face plate thickness rather than the total thickness as in the case of a solid mirror blank. Further, because of the thin faceplates used in lightweight mirrors, the relaxation time is only marginally greater than the time under thermal load.

Objective

It was the objective of this work to perform a simple test that would show the thermal time constant of a lightweight mirror is quite rapid. It was also recognized that this is not an easy test to perform unless the test is set up properly. Because the thermal change in figure was not expected to be large, precautions had to be taken to insure that changes in mounting conditions and/or the test apparatus did not influence the results of the thermal test.

Another objective of this experiment was to illustrate the ease with which the Zernike polynomial representation of a surface allows the pertinent temporal deformation data to be extracted from the experiment and displayed in a meaningful way. The results of this experiment are illustrated entirely in terms of the Zernike components of the surface that did, or did not, change with time under the thermal load.

Approach

A Hextek borosilicate glass, lightweight mirror blank 18" in diameter and 3.5" thick had been slumped to a radius of 96" and polished spherical. The mirror blank was then supported on its backplate on 3 points at approximately the 7/10ths zone. The mirror was placed in a face up condition under a digital phase measuring interferometer located at its center of curvature. In order to introduce the thermal load, a 660 ohm resistor was attached to the center of the rear plate of the mirror blank using thermally conductive grease.

At t = 0, the resistor was connected across a 110 volt AC source and the interferometer was used to capture an interferogram every minute. After 14 minutes of thermal load, the resistor was disconnected while the interferometer continued to take data once a minute for another 24 minutes. Each interferometrically obtained OPD file was stored to disk for analysis at the conclusion of the experiment.

Because the mirror was supported at just 3 points, it would be difficult for the mount to introduce any changing forces or add any moments as the mirror changed shape under the thermal load. Further, since glass has a low thermal conductivity, little if any heat would ever got to the 3 support points and thus it is felt that the mirror to interferometer distance remained essentially constant during the experiment so that the focus change we observed was due only to mirror deformation.

Data Reduction

Once the raw data was taken and stored to disk, each set of OPD data was retrieved and fit to a 36 term set of Zernike polynomials[1]. Appropriate polynomial coefficients were then plotted as a function of time to display the temporal behavior of the mirror. Since the heat load was applied to the center of the rear plate, the expected deformation was rotationally symmetric. Figure 1 shows the coefficient values of the 3 lowest order rotationally symmetric Zernike terms plotted against time for the duration of the 38 minute experiment.

In Figure 2, we show the coefficients of the next 3 higher order rotationally symmetric terms plotted against time with a 20 times expanded scale for the coefficient values. Clear temporal changes are apparent in the highest order terms even though the magnitude of these coefficients is of the order of $\lambda/50$.

If the mount were introducing errors, we would expect to see time varying errors with a 3θ symmetry due to the 3 point mounting scheme. In Figure 3 we have plotted the sin and cos 3θ Zernike coefficients versus time. To the level of noise in the experiment and to the level where there was obvious temporal change in the symmetric terms, there is no change in the values of the lowest order 3θ terms.

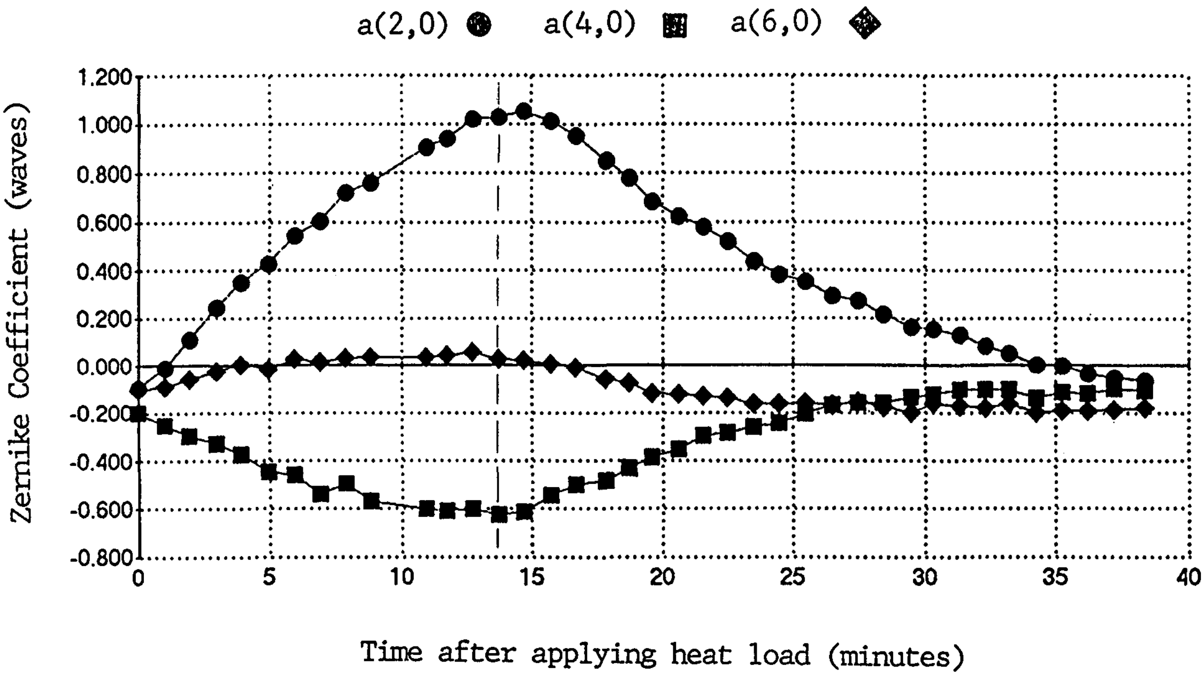


Fig. 1 Values of the 3 lowest order, rotationally symmetric, Zernike polynomial coefficients showing the mirror surface deformation with time, first under thermal load for 14 minutes (up to dashed line), and then after removing the thermal load.

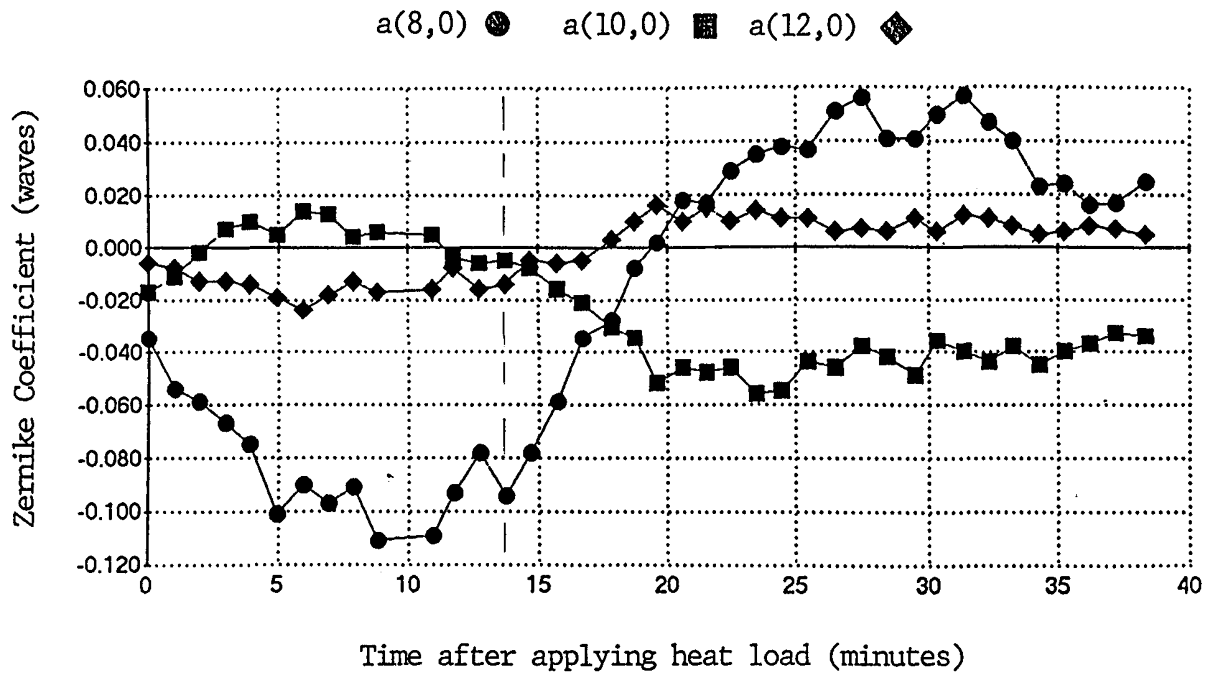


Fig. 2 Values of the next 3 higher order, rotationally symmetric Zernike polynomial coefficients for the same conditions as in Fig. 1. Notice the coefficient scale change of 20x.

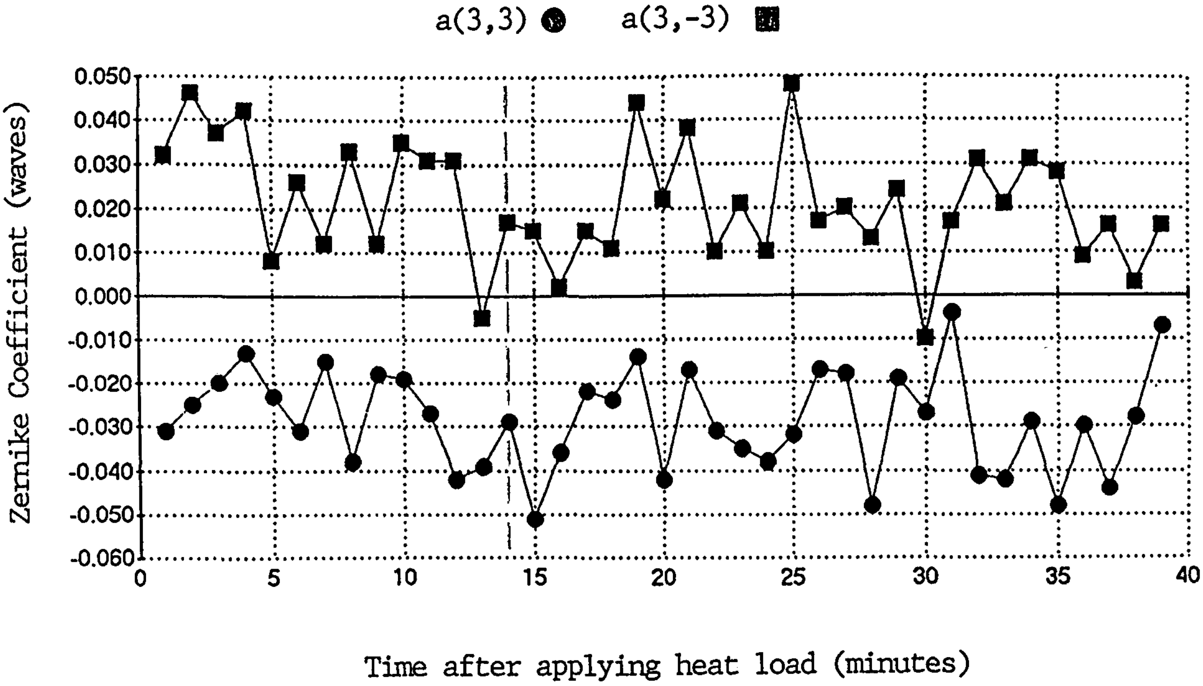


Fig. 3 Values of the 2 lowest order, non-rotationally symmetric, 3θ Zernike polynomial coefficients over the duration of the test. Note the further 1.6x scale change.

Notice that the sin terms are positive and the cos terms negative indicating that the mirror support points were lined up to match the highs of the sin 3θ component and the cos terms show the sag of the mirror between support points at the $\lambda/30$ level. Of course, to be sure this is a mount induced error, the mirror should be rotated with respect to the mount and remeasured to see if the 3θ error followed the mirror or stayed aligned with the mount[2].

A final approach to plotting the data is illustrated in Fig. 4. Here we subtracted the Zernike coefficients at time = 0 from the low order rotationally symmetric coefficients at all later times. Since the rotationally symmetric coefficients were not zero to begin with because the mirror figure was not perfect as can be seen in Fig. 1 at t = 0, it is a little difficult to see how closely the mirror figure returns to its initial value.

By subtracting the t = 0 coefficients as in Fig. 4, all the low order symmetric coefficients start at zero and then change with time. By the end of the experiment, it is quite easy to see how closely each term has returned to its starting point. It appears in this Figure that the higher order terms, even though they are smaller in magnitude, do not return to zero as quickly as the low order coefficients.

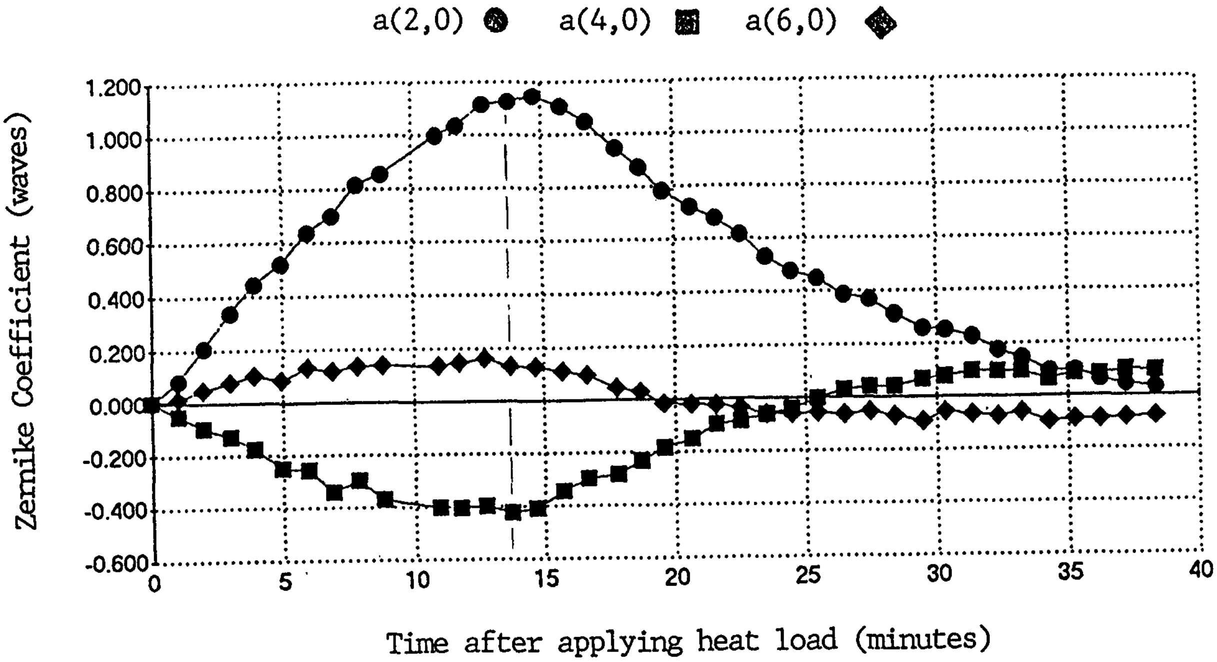
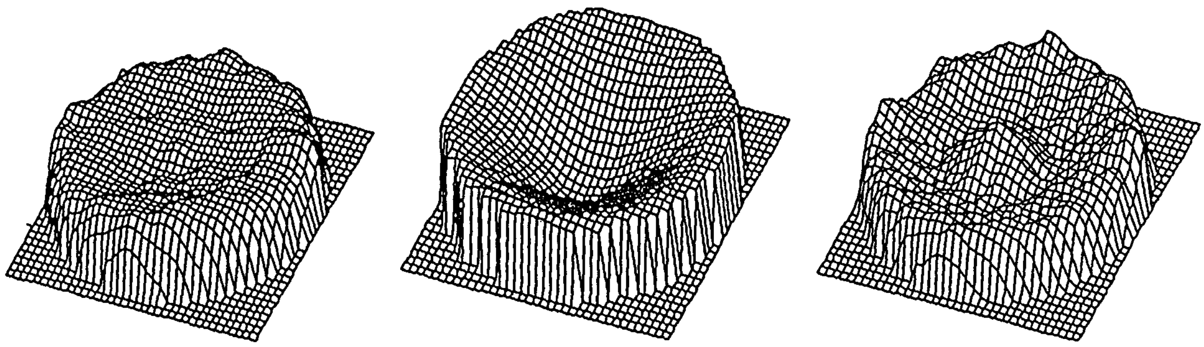


Fig. 4 Values as plotted in Fig. 1 with the exception that in each of the 3 cases, the value of the t = 0 coefficient was subtracted from each of the subsequent values. This has the effect of removing the initial residual figure error.

To illustrate how much information we can get out of the Zernike coefficients about what happened during the experiment, we have shown 3 isometric plots of the mirror figure in Fig. 5. The mirror at t = 0, with its reasonably error free surface is shown in Fig. 5a. Fig. 5b shows the figure just as we remove the heat load at 14 minutes and shows the obvious concavity produced by the heat load. The peak-to-valley and rms error have increased by about a factor of 5 but the features of the surface are lost to the change in power. At the end of the experiment the surface has returned to about where it was to begin with but with a residual high center as seen in Fig. 5c.

While we can certainly tell the mirror figure got worse and in what direction using the isometric maps, we do not know the high center at the end is due to the non-zero a(4,0) term that did not recover as quickly as the focus, a(2,0), term. Nor is it possible to tell any thing about the higher order terms or the 3θ terms from the isometric views or the numerical data that goes with them. Even to get a subjective feeling for the time varying part of this experiment, we would have had to plot a whole series of these isometric views. To quantify the changes in a meaningful way and to get a feel for the thermal time constant would have been very difficult. On the other hand, the coefficients plotted in Figs. 1, 2, 3 and 4 give a very complete picture of how smoothly the changes were with time and about how much noise was in the data due to external environmental conditions.

0.085λ rms 0.62λ p-v ¦ 0.67λ rms 2.72λ p-v ¦ 0.086λ rms 0.56λ p-v



a) b) c)

Fig. 5 Three isometric views of the figure error in the mirror blank, a) at t = 0, b) at t = 14 minutes when the thermal load was removed and c) at t = 38. Note that Fig. 5b has been rescaled by about 4x relative to a) and c).

Results

During the time of the applied heat load, the back plate of the mirror expanded forcing the mirror concave as evidenced in both the positive a(2,0) coefficient in Fig. 1 and the isometric view in Fig. 5b. In addition, the concentrated heat load, due to the poor thermal conductivity of glass caused a local low and relatively higher 7/10ths zone as indicated by the negative a(4,0) or spherical aberration coefficient and positive a(6,0) term. Overall, the symmetrical figure change was somewhat complex in that there were contributions for terms up to 12th order. As expected, however, each higher order term was less large than the next lower order term and alternated in sign indicating a coherent addition of the error in a very localized low in the vicinity of the heat load.

At the same time, the lowest order 3θ coefficients were constant with time to the order of λ/50 peak-to-valley, the approximate noise level of the experiment. This indicated to us that the 3 point support was not influencing the experiment and that the symmetric heating was not introducing local asymmetries in the figure.

In Fig. 4, where we have removed the effects of the initial figure errors in the mirror, we can see that the mirror continued to get progressively more concave with the application of the heat load although we may have been trying to heat the mirror faster than we could transfer the heat. Within a minute of removing the heat, however, the effects of the heating were reversing and the figure was returning to that at the beginning of the experiment.

If a thermal time constant can be defined as when the system returns to within 37% of the initial condition, the time constant for this mirror blank with a facesheet thickness of 8 mm was about 12 minutes, almost an order of magnitude shorter time than would be calculated for a solid blank of the same dimensions. Recall that the thermal time constant is essentially independent of the coefficient of expansion, only the magnitude of the deformation depends on the coefficient of expansion.

While the lowest order term returned to its starting value within 24 minutes after removing the heat load, the higher order terms did not return as quickly due to the heat still redis-tributing itself throughout the mirror. The actual rms figure error had returned to its initial value in the 24 minutes.

Conclusions

We have shown how relatively quickly a light weight mirror blank recovered from an externally applied localized thermal load. The recovery, in addition to being rapid, did not give any indication of hysteresis or permanent change in figure. Further, there was no evidence of thermally induced asymmetric errors coincident with the 3 support points.

We have also shown the value of analyzing temporal changes in figure by the use of Zernike polynomial coefficients. The coefficients show precisely which spatial frequencies of figure error are changing as a function of time and by how much. Once the Zernike coefficients have been calculated, they are easily transferred from the analysis package to a spread sheet for editing and plotting as a function of independent variable.

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[1] D. Malacara, *Optical Shop Testing*, 1st ed., John Wiley & Sons, New York (1978), Table A2.2, p. 493. This is the set of Zernike polynomials used in this paper along with the "n,m" notation used in this reference so that the symmetry properties of the particular polynomial term are immediately obvious. To see the 3-D form of each term, see C-J. Kim and R. R. Shannon, "Catalog of Zernike Polynomials" in *Applied Optics and Optical Engineering*, Vol. X, R. R. Shannon and J. C. Wyant, eds., Academic Press, San Diego, CA (1987), pp. 193-223. This set of Zernike polynomial terms is numbered sequentially for historical reasons in a manner that made it easy to write computer code involving these terms. Also note that the normalization of this set of Zernike polynomials is different from that used in most commercial software used in conjunction with phase measuring interferometers, although this will not affect most applications unless new software is written.

[2] R. E. Parks, "Removal of test optics errors", *Proc. SPIE, 153*, 56-63 (1978).