AN007

Using a Membrane DM to Generate Zernike Modes

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Membrane DMs have been used quite extensively to impose a known phase onto a beam for applications like testing wavefront sensors and generating Kolmogorov phase screens. Most of the time, users are interested in how well a membrane DM will compensate Zernike polynomials. To address this question, we performed a simple simulation in Matlab, the results of which we present here.

Zernike Numbering

In this document we are using the ordering put forth in D. Malacara's Optical Shop Testing in which the Zernike terms are sorted first by their order (n) and then by their l term. Table 1 shows Zernike order through the third-order terms. Appendix B below shows the terms. In this study we neglected piston.

Table 1 – Order of the Zernike Terms

Order	n	l	Name
1	1	-1	X-Tilt
2	1	1	Y-Tilt
3	2	-2	90° Astigmatism
4	2	0	Focus
5	2	2	45° Astigmatism
6	3	-3	Y Trefoil
7	3	-1	Y Coma
8	3	1	X Coma
9	3	3	X Trefoil

Matrix Fitting

Figure 1 shows the actuator patterns we used in this testing. We first generated influence functions for four different deformable mirrors on a 128x128 pixel grid with about a 0.21-mm spacing such that the DM aperture was represented with a small guard-band. Our 1" membrane deformable mirrors have about 10 microns of focus throw on average, so we normalized the influence functions such that the sum of all of the commands produced 10 microns of focus throw over the aperture. We then limited our simulation to only use the inner 80% of the mirror since the edges are typically poorly controlled.

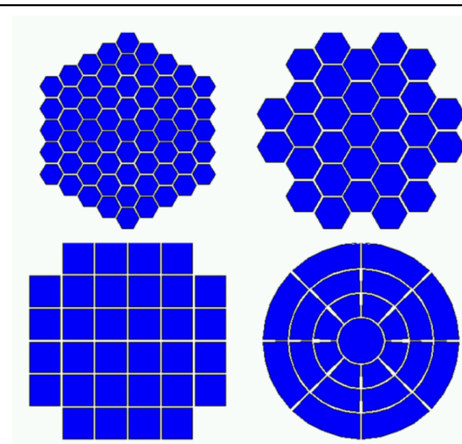


Figure 1 - Four patterns of deformable mirror actuators used in the Zernike fit testing

We sampled the central section of each of the influence functions with about 300 points and created a "poke" matrix in phase space. We inverted that matrix to create a phase-space control matrix. We then generated a phase profile of each of the first 40 Zernike terms and sampled it at the same 300 sample points to create a phase vector. By multiplying the phase vector by the control matrix we were able to obtain weights (aka forces) for each of the influence functions.

We then scaled the forces such that they were between 0 and 1 by subtracting the minimum and then dividing by the maximum. We did not allow any negative forces because the electrostatic actuators on the membrane DMs can only pull on the membrane and cannot push (the effective pushing force is obtained from the tension in the membrane). We then created the phase profile by adding together each of the weighted influence functions. To better see the desired aberration, we also removed the focus term that is the bias condition of the membrane deformable mirror. Figure 2 shows one example result in which we used the annular actuator deformable mirror to generate 90° astigmatism.

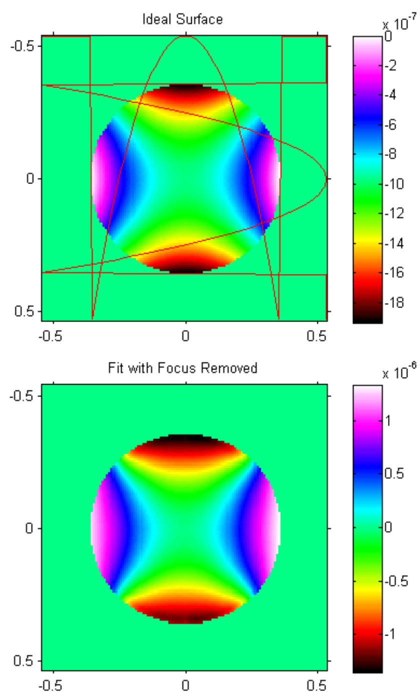


Figure 2 - Result obtained for using the annular actuator deformable mirror to create 90-degree astigmatism

Once we had obtained the phase surface that best created the desired aberration, we did an overlap integral decomposition of the generated phase profile with the each of the 40 Zernike terms. This was done for each mirror for each of the 40 Zernike terms. Figure 3 shows the results obtained from the 25-channel annular actuator deformable mirror. The focus bias was not removed for in these results, so there is a Zernike 4 term in all of the results.

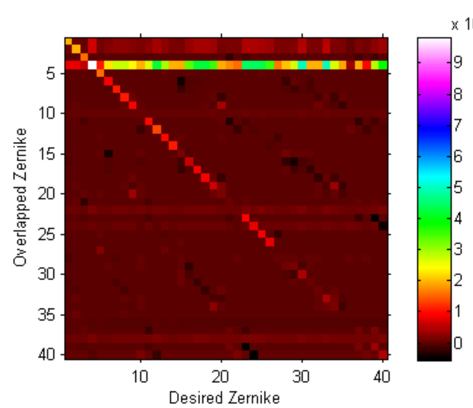


Figure 3 - Results of decomposing the attempt to create Zernike terms using a 25-actuator annular deformable mirror without removing the focal bias.

To determine the ability of each mirror to create each mode, we looked at the diagonal of the matrix relating desired Zernike term to the overlapped Zernike result. Figure 4 shows the results plotted on a log-scale with the vertical axis limited to 0.1 microns. There were several different trends identified in this experimentation. First, we found that the annular actuator grid was better than all the others at some patterns, but was much worse at others. The annuli were segmented into eight pieces, so the aberrations that matched well to this arrangement of actuators were much better, while those with other angular content (60° angles for example) were much worse. We also were surprised by the 61-actuator device doing more poorly at representing the desired patterns than the lower actuator counts. We have not completed our investigation into why this was the case, but will update our application note when we complete this investigation.

In the future, we would like to try a metric-based strategy for achieving this result in which we search through actuator space to maximize the DM's overlap integral with each of the desired Zernike terms to see if the results are any better.

Metric Searching to Maximize Zernike Overlap Integral

After doing the matrix-based fitting, we implemented a genetic search algorithm to maximize the overlap integral between a deformable mirror shape and a given Zernike term. We implemented the Guided Evolutionary Simulated Annealing (GESA) algorithm in which a set of families of solutions are tried and the best solution becomes the parent for the next generation. Each child of the parent is generated as a random perturbation of the parent with a

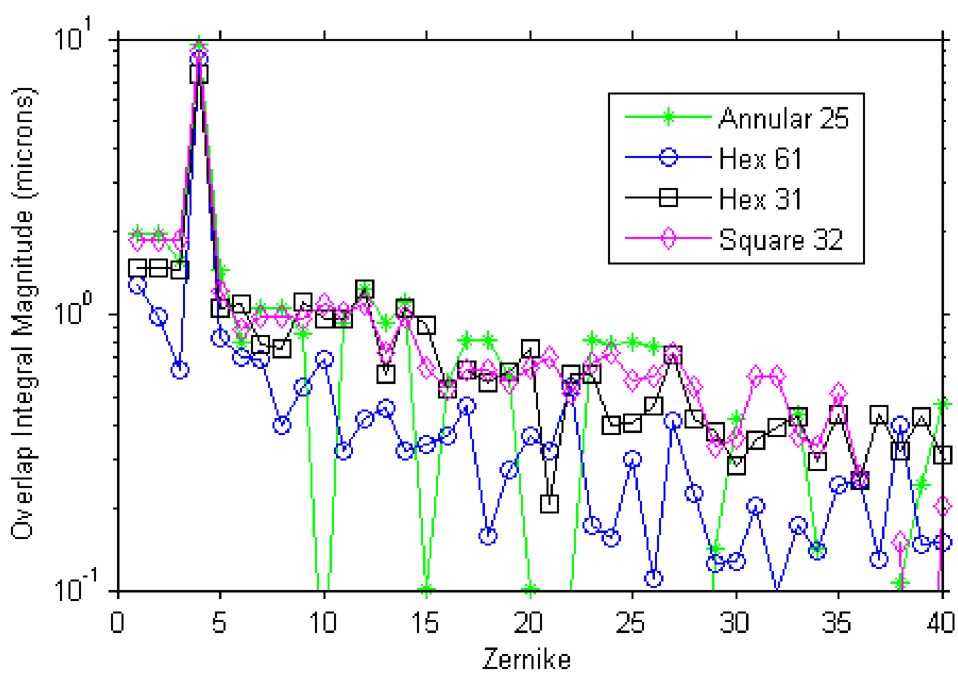


Figure 4 - Magnitude obtained for each of the first 40 Zernike terms with each of the deformable mirrors.

uniform random number generator with a radius equal to the maximum throw of the device initially. The random radius was reduced by a simulated annealing factor each iteration.

We used 10 families of solutions with a 98% simulated annealing factor per generation. Each family had as many children as it had actuators. We propagated at least 150 generations, but as many as 3 times the number of actuators. We limited the used area of the deformable mirror to the 80% radius of the device and the throw of the entire device to 10 microns of focus. We also extended our search to include the 59-actuator annular DM and the 61-actuator square grid DM shown in Figure 6. We also extended our search to 60 Zernike terms for the higher actuator count pad array patterns. We only considered positive amplitude Zernike terms in this test.

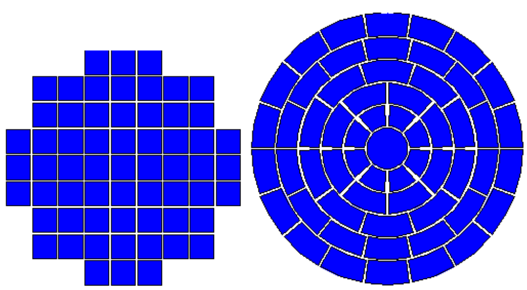


Figure 6 - Higher Actuator Count DM Pad Arrays

We did not try to minimize any of the other Zernike terms during our search, so we did see some coupling to higher-order terms to maximize the desired term. For example, with the 25-actuator annular DM (center actuator and 3 rings of 8 segments), we found the focus-removed x-tilt term with maximum overlap integral to the Zernike term was the

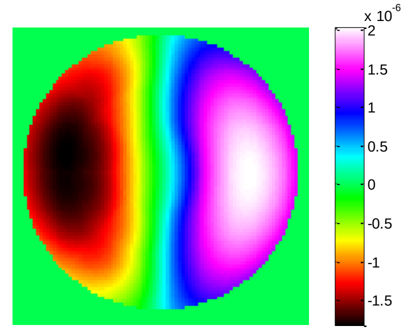


Figure 5 - Best focus-removed x-tilt term from the 25-actuator annular pad array.

shape shown in Figure 5. Figure 7 shows the decomposition of the non-focus-removed tilt term. This decomposition clearly has a large tilt term (the #1 Zernike), but also significant focus due to the nature of the membrane DM and some trefoil and x-coma.

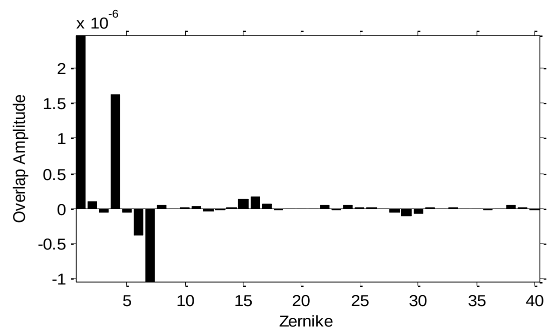


Figure 7 - Zernike decomposition of the best x-tilt term obtained from the 25-actuator annular pad array using the GESA search.

Metric Search Resutls

Figure 8 shows the results of the Zernike overlap metric search. The results were very similar in nature to the matrix-based results presented above. The mirror was again clearly better at low spatial frequency terms

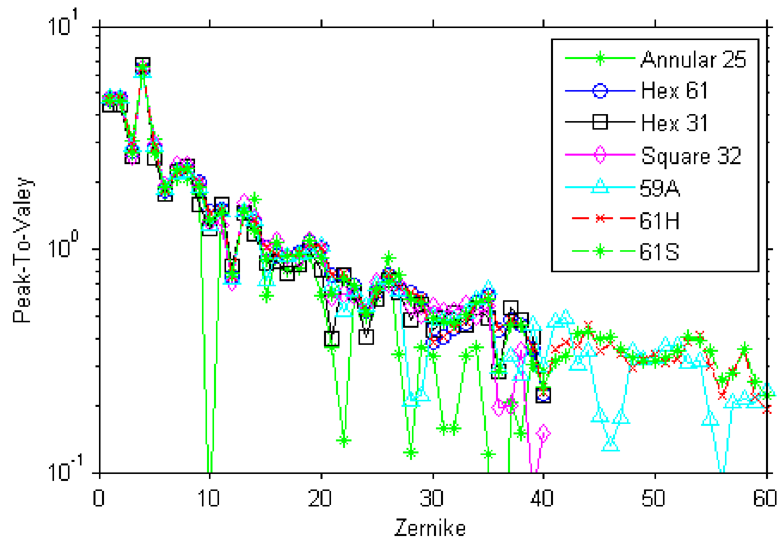


Figure 8 - Peak-to-valley amplitude of each of the Zernike terms tested for each of the pad arrays tested.

than it was at higher spatial frequency terms. The pad array patterns that appeared to do the best at creating all the different Zernike terms were the 61-actuator hex and square grid patterns. The 25 and 59 actuator annular patterns were the worst in our testing due primarily to significant drop-outs on some Zernike terms.

We did some analysis to determine the reason the 25-actuator annular DM did so poorly in representing the Zernike terms in some of the cases. We started with the lowest order term that was doing poorly, which was the 10th Zernike term. Figure 9 shows the shape of the Zernike term and the actuator pattern. The problem clearly stems from the fact that the actuators line up exactly with the nulls in the Zernike term. We found a similar result in Zernike #21, the next poorly performing Zernike.

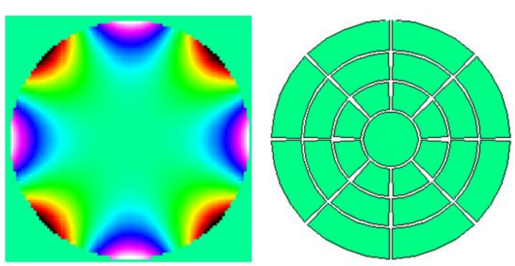


Figure 9 - Zernike 10 and the actuator pattern for the 25-actuator annular DM.

Zernike Amplitude Reduction Analysis

The result in Figure 8 clearly shows that the maximum amplitude of the Zernike term reduces with the Zernike number. The DM is not as able to excite higher order terms as well as it is lower order terms. To analyze this phenomenon we averaged the maximum amplitude of the Zernike terms with like radial powers for all the higher actuator count (>32) DMs. Figure 10 shows the results as both linear and log-scale plots. The average amplitude falls-off as a -1.6 power law.

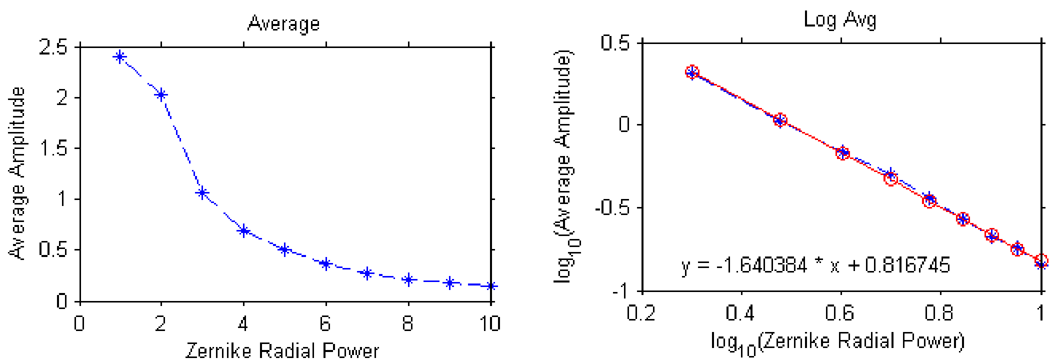
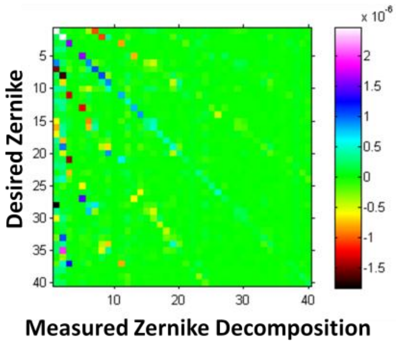


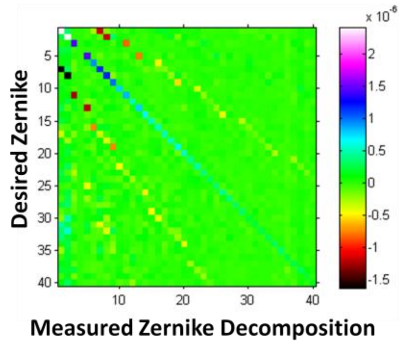
Figure 10 - Analysis of the Average Maximum Amplitude with respect to Zernike Radial Power

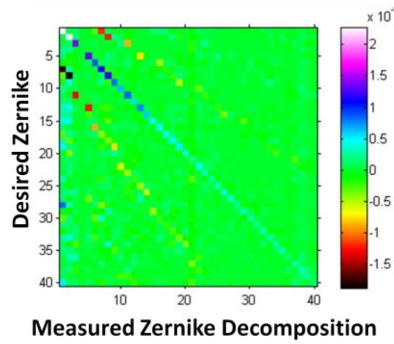
Conclusions

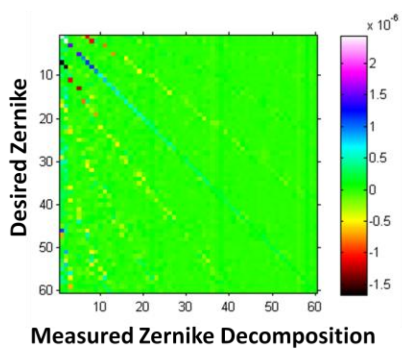
Membrane DMs are extremely good at creating focus, but can create other Zernike terms with good fidelity and reasonable amplitude, especially considering that the imposed aberration on the wavefront is double the amplitude of the deformable mirror.

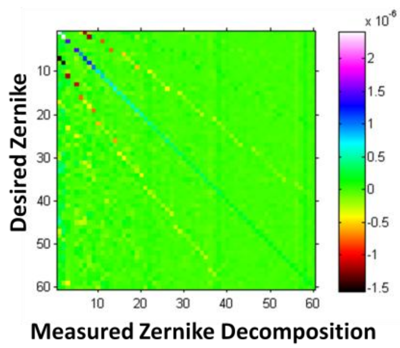
Appendix A: Complete Matrix Search Results with Focus (Zernike 4) Removed

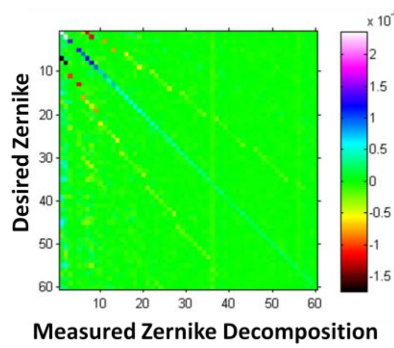












Appendix B: Zernike Terms and Numbering